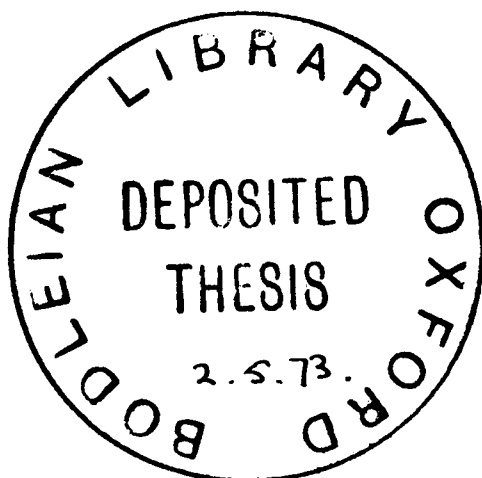


Electromagnetic Properties of  
Light Proton-Rich Nuclei

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## 0. Abstract

An experimental study of electromagnetic transition rates of some proton-rich nuclei of the sd shell was made.

In order to perform the neutron-gamma coincidence measurements necessary to study these nuclei an associated  $\gamma$ -ray neutron time of flight spectrometer was constructed. The neutron detector has an annular shape and is divided in four quadrants, which are filled with NE213 liquid scintillator. The detector is viewed by eight XP1040 photomultiplier tubes (two per quadrant) and the neutron events in the scintillator are identified by means of pulse shape discrimination. The fast timing pulses are derived from constant fraction pulse height discriminators, thus enabling the use of wide dynamic ranges in both the neutron and the  $\gamma$ -ray detectors. The time resolution of the system, when the  $\gamma$ -detector is a large volume Ge(Li) crystal ( $82 \text{ cm}^3$ ), is approximately 6 ns (FWHM).

The decay modes and branching ratios of states in  $^{37}\text{Ar}$  up to 3.60 MeV excitation energy have been determined using the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction. A new level at  $E_x = 3184 \pm 3$  keV excitation energy has been found. The decay of the  $7/2$ , 3535 keV state has also been observed. Using the Doppler shift attenuation method (DSAM) F-values for some levels in  $^{37}\text{Ar}$  and  $^{35}\text{Cl}$  were measured by means of the reactions  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  and  $^{35}\text{Cl}(p,p')^{35}\text{Cl}^*$ . The lifetimes deduced were (in fs) :  $\tau(1409) = 370^{+190}_{-110}$ ,  $\tau(2489) = 88 \pm 24$  and  $\tau(2795) < 8$  in  $^{37}\text{Ar}$ ; and  $\tau(2646) = 83 \pm 21$  and  $\tau(2695) = 11 \pm 7$  in  $^{35}\text{Cl}$ . The data provide further evidence that the commonly

used stopping power theory is in error under certain circumstances and a discussion of the reliability of the DSAM measurements is presented.

Further investigations have been made on the nucleus  $^{18}\text{Ne}$ , which was populated by means of the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction. The first excited  $0^+$  state was definitely located at  $E_x = 3576$  keV excitation energy and the lifetimes of both this level and the  $4^+$  state at  $E_x = 3376$  keV were measured with the Doppler shift recoil-distance method. The values obtained were (in ps) :  $\tau(3376) = 4.4 \pm 0.6$  and  $\tau(3576) < 6$ . Angular correlation measurements of the  $\gamma$ -decay of the  $2^+$  level at 3616 keV were also made. As a result, the strength of the cross over branch of this state to the ground was observed to be  $(12.5 \pm 2.5)\%$  and the E2/M1 mixing ratio of the  $3616 \rightarrow 1887$  transition was also determined, yielding the value  $\delta = +0.03 \pm 0.09$ . These results are compared with current theoretical calculations.

Decay modes and lifetimes of low-lying levels in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  were investigated by the Doppler shift attenuation method using the  $^{28}\text{Si}(^3\text{He},n)^{30}\text{S}$  and the  $^{32}\text{S}(^3\text{He},n)^{34}\text{Ar}$  reactions, respectively. The lifetimes measured were (in fs) :  $\tau(2210) = 310 \pm 75$ ,  $\tau(3402) = 160 \pm 45$  and  $\tau(3664) > 1400$  in  $^{30}\text{S}$ ; and  $\tau(2090) = 150 \pm 50$ ,  $\tau(3286) = 120 \pm 65$  and  $\tau(4513) = 300 \pm 80$  in  $^{34}\text{Ar}$ . These results are compared with theoretical calculations. A comparison of the E2 decay strengths in masses 30 and 34 is also made to test the isospin dependence of electromagnetic transitions.

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## Contents

|                                                             | page |
|-------------------------------------------------------------|------|
| 0. Abstract                                                 | i    |
| Acknowledgements                                            | iii  |
| 1. Introduction                                             | 1    |
| 1.1 Motivation                                              | 1    |
| 1.2 Plan of thesis                                          | 3    |
| 2. Experimental Methods                                     | 5    |
| 2.1 Neutron-gamma coincidence measurements                  | 5    |
| 2.1.1 The neutron time of flight (TOF)<br>selection method  | 5    |
| 2.1.2 Neutron detection                                     | 6    |
| 2.1.3 The neutron detector                                  | 9    |
| 2.1.4 Pulse shape discrimination                            | 14   |
| 2.1.5 Further associated electronics                        | 18   |
| 2.1.6 Performance tests                                     | 23   |
| 2.2 The measurement of nuclear lifetimes                    | 27   |
| 2.2.1 Introduction                                          | 27   |
| 2.2.2 The Doppler shift attenuation<br>method (DSAM)        | 28   |
| 2.2.3 The Doppler shift recoil-distance<br>(plunger) method | 35   |
| 2.2.4 Description of the plunger apparatus                  | 39   |
| 3. Electromagnetic Deexcitation Theory and<br>Data Analysis | 42   |
| 3.1 Angular correlation theory                              | 42   |

|                                                                      |     |
|----------------------------------------------------------------------|-----|
| 3.2 Geometry corrections and data analysis                           | 49  |
| 3.2.1 Corrections due to finite size<br>of detectors                 | 49  |
| 3.2.2 Data analysis; spin and mixing<br>ratio determination          | 51  |
| 3.3 Gamma transition widths in isospin<br>multiplets                 | 57  |
| 4. The Decay Scheme and Lifetime Measurements<br>in $^{37}\text{Ar}$ | 65  |
| 4.1 Introduction                                                     | 65  |
| 4.2 Energy determinations and decay scheme                           | 66  |
| 4.3 DSAM lifetime measurements                                       | 71  |
| 4.4 Discussion of the reliability of DSAM<br>measurements            | 76  |
| 5. Study of $^{18}\text{Ne}$ Gamma Decay                             | 84  |
| 5.1 Introduction                                                     | 84  |
| 5.2 The location of the first excited $0^+$<br>state                 | 86  |
| 5.3 The decay of the 3616 keV level                                  | 89  |
| 5.4 Lifetime measurements                                            | 93  |
| 5.4.1 The 3376 keV level                                             | 93  |
| 5.4.2 The 3576 keV level                                             | 96  |
| 5.5 Discussion of results                                            | 98  |
| 6. Spectroscopy of $^{30}\text{S}$ and $^{34}\text{Ar}$              | 102 |
| 6.1 Introduction                                                     | 102 |
| 6.2 The $^{30}\text{S}$ nucleus                                      | 103 |
| 6.2.1 Decay scheme                                                   | 103 |

|                                                                              |     |
|------------------------------------------------------------------------------|-----|
| 6.2.2 Lifetime measurements                                                  | 105 |
| 6.3 The $^{34}\text{Ar}$ nucleus                                             | 108 |
| 6.3.1 Decay scheme                                                           | 108 |
| 6.3.2 Lifetime measurements                                                  | 112 |
| 6.4 Discussion                                                               | 113 |
| 6.4.1 The $^{30}\text{S}$ and $^{34}\text{Ar}$ results                       | 113 |
| 6.4.2 The E2 transition strengths in<br>mass 30 and mass 34 isospin triplets | 116 |
| 7. List of Publications                                                      | 121 |
| 8. References                                                                | 122 |

## 1. Introduction

### 1.1 Motivation

Much experimental and theoretical effort has been channelled into the field of Nuclear Physics for the past twenty years. Extensive investigations have been made of light nuclei of the p and the sd shells. Both basic and phenomenological theories have <sup>been</sup> developed in an attempt to understand the different nuclear configurations which are possible.

The electromagnetic transition probabilities are very sensitive to the wave functions describing the various nuclear states. This arises from the fact that the laws of electromagnetism are well understood and provide a rigorous quantitative description of phenomena over the entire range of physical dimensions in our universe. Therefore, the uncertainties involved in the calculation of matrix elements arise solely from our incomplete knowledge of the nuclear wave functions.

Typical electromagnetic properties of nuclei are lifetimes, branching ratios and mixing ratios of multipole transitions. The determination of branching and mixing ratios involves the measurement of angular distributions of  $\gamma$ -rays originating from the decay of excited states. For lifetime measurements an adequate "clock", such as the slowing down time of ions recoiling in solids or gases, or the time of flight of recoiling nuclei over a measurable distance, is required. The combination of all these three quantities allows the determination of

electromagnetic transition matrix elements to be made. Also, by comparing the measured transition rates with their single particle Weisskopf estimates (Wi60) conclusions about the single particle or collective nature of these transitions may be drawn. Thus the study of gamma deexcitations in nuclei is a highly useful experimental tool of Nuclear Structure.

The sd shell has been extensively studied in recent years, but the amount of experimental investigations referring to the electromagnetic properties of proton-rich nuclei has been considerably less than that concerning their mirrors. Further, few tests of the isospin dependence of electromagnetic transition matrix elements throughout whole isospin multiplets have so far been performed. This is due to the difficulty of preparing proton-rich nuclei in a way which favours the study of  $\gamma$ -decay modes. The neutron emitting reactions are usually the reactions in which this may occur. However, problems existed in the development of neutron detectors of comparable energy resolution and detection efficiency to the charged particle detectors, which have delayed the investigations of  $\gamma$ -deexcitations of proton-rich nuclei. Such a neutron detector, which allows individual nuclear level selection by neutron time of flight techniques, has now been constructed. Its use in experimental Nuclear Physics and the study of electromagnetic properties of some proton-rich nuclei of the sd shell are the subject of this thesis. The results obtained are discussed in terms of current models.

## 1.2 Plan of thesis

The experimental methods employed in the Nuclear Structure studies presented in this work are referred to in chapter 2. A description of the Oxford associated  $\gamma$ -ray neutron time of flight spectrometer together with the electronics it requires and the set up procedure is made in section 2.1. In section 2.2, the Doppler shift attenuation method (DSAM) and the Doppler shift recoil-distance (plunger) method, both used in connection with the determination of nuclear lifetimes, are discussed.

In chapter 3, the phase-consistent treatment of  $\gamma$ -angular distributions due to Rose and Brink (Ro67) is discussed, and its application in terms of the experimental arrangement designated "method II" (Litherland and Ferguson (Li61) ) is shown. The introduction of isospin formalism and a derivation of the isospin dependence of transition matrix elements is also presented.

In chapter 4 the decay scheme and DSAM lifetime measurements in the nucleus  $^{37}\text{Ar}$  are reported. As a result of these measurements, a general discussion of the reliability of DSAM lifetime determinations has been included in chapter 4. A critical analysis of the lifetimes measured in this work using the DSAM is also presented.

Nuclear shell-model calculations are usually particularly successful near closed shells. Mass 18 has been a traditional field of shell-model applications due to its closeness to the doubly magic  $^{16}\text{O}$  nucleus. However, it has also become apparent that collective effects play already an important rôle at the beginning of the sd shell. The

angular correlation and plunger lifetime measurements in  $^{18}\text{Ne}$

were performed in order to complete the experimental information about the low-lying levels in mass 18. The results obtained and their comparison with theoretical calculations are presented in chapter 5.

Finally, chapter 6 is devoted to the study of two lesser known proton-rich nuclei,  $^{30}\text{S}$  and  $^{34}\text{Ar}$ . Very little information about  $\gamma$ -decay modes was available in the case of  $^{30}\text{S}$ , prior to our investigations. In the case of  $^{34}\text{Ar}$ , however, no information about electromagnetic properties was found at all. The abundant measurements made on their mirrors and the existence of recent shell-model calculations of transition rates covering the mass region 30-35, make the investigation of the decay schemes and lifetimes of excited states of  $^{30}\text{S}$  and  $^{34}\text{Ar}$  interesting. A comparison of the E2 decay modes of the isospin triplets in mass 30 and mass 34 is also presented in this chapter.

## 2. Experimental Methods

### 2.1 Neutron-gamma coincidence measurements

#### 2.1.1 The neutron time of flight (TOF) selection method

For the study of  $\gamma$ -rays associated with particle emitting reactions, particle detectors with good energy resolution are required. The  $\gamma$ -decay of specific excited states in the final nuclei can only be studied selecting the individual particle groups which populate these states.

For charged particles this selection can easily be achieved and detectors, such as the silicon surface barrier counters, have extensively been used in Nuclear Structure studies of the charged particle- $\gamma$  ray coincidence type. For the neutron emitting reactions however, the surface barrier detectors cannot be used as neutrons have zero electric charge. Thus, a neutron detector with comparable performance to the charged particle ones is needed.

The main features of such a detector are that it must provide reasonably good energy resolution, have high detection efficiency and good timing characteristics, provide good discrimination against a strong  $\gamma$ -ray flux and bear high count rates.

The good energy resolution requirement motivated the choice of a detector employing time of flight techniques for individual group selection. A different possibility would have been a  $^6\text{LiI}(\text{Eu})$  scintillator (Mu 58), however in addition to difficulties arising from the presence of strong neutron and  $\gamma$ -ray fluxes accompanying nuclear

reactions, large  ${}^6\text{LiI}(\text{Eu})$  crystals were in 1969 still of an "untried nature" (Be69). In the time of flight method one measures the time spent by the neutrons to travel from the target to the detector, obtaining in this way a measurement of the energy of the various neutron groups emitted. The timing characteristics of a detector employing this technique must therefore be very good and the flight path will be chosen in accordance to the energy of the outgoing neutrons. However, a compromise between good detection efficiency and good timing characteristics must be made. On one hand a thick detector is required for reasons of detection efficiency, while on the other hand the thickness must be kept as small as possible in order to minimise the time spread due to the neutron time of flight within the detector. Because of these considerations, it was decided to build a neutron detector of thickness 4.4 cm using an organic liquid scintillator type NE213 (Nuclear Enterprises Ltd.). NE213 has a high detection efficiency and has been in use in fast neutron spectroscopy since approximately 1960 (Ba60). Further, it has good pulse shape discrimination (P.S.D.) characteristics. The P.S.D. properties of scintillators for use with fast neutrons are very important because of the discrimination needed against the  $\gamma$ -radiation accompanying the neutron emitting reactions.

### 2.1.2 Neutron detection

The liquid scintillator NE213 is a binary system consisting basically of xylene ( $\text{C}_6\text{H}_4(\text{CH}_3)_2$ ) in which

several activators are dissolved. Its density is 0.874 (Nu70). NE213 is suited for pulse shape discrimination techniques because the shape of the output pulses generated depends on the nature of the detected particles. The emission decay of NE213 involves two components: a fast one ( $\sim 5$  ns) and a slow one ( $\sim 120$  ns) and the relative importance of both components in the output pulse varies with the ionizing power of the incident radiation (Pe62).

Neutrons are detected mainly via elastic scattering from protons. However, alpha emission from  $^{12}\text{C}(n,\alpha)^9\text{Be}$  and  $^{12}\text{C}(n,n')^3\alpha$  reactions will also become important for neutron energies above  $\sim 8$  MeV though the contribution to the light output coming from the  $\alpha$ -particles and carbon recoils is small (Ba61). The detector is also exposed to an incident flux of  $\gamma$ -rays which produce Compton electrons in the scintillator and will therefore be detected too. The use of NE213 for pulse shape discrimination is based on the fact that the activation produced in the scintillator by a proton recoiling is quite different from the activation produced by a Compton electron. The mechanisms leading from the initial activation to the final light emission are more or less understood, and we follow Laustriat (La68) in the discussion presented below.

In the case of a proton recoiling in the scintillator a track of excitations and ionizations is created - the ionizations producing secondary electrons that may or may not get out of the track. The fast secondaries, when going out of the track, induce further activation in the

neighbouring medium mainly in the form of "spurs" and "blobs", as it is schematically shown in fig.2.1a. The slow secondaries remain inside the track and increase the initial activation. There is then a region of high activated species - track, spurs and blobs, and a region of low concentration of species in the vicinity of the track.

For the Compton recoil electrons, which behave like fast secondaries, there is no track and the high concentration region consists of spurs and blobs only. The excited states will decay by intramolecular processes such as dissociation and internal conversion to the lowest excited singlet and triplet states. Scintillation is due to radiative deexcitation of the lowest singlet states. There is an additional step involved - the energy transfer from singlet states of the solvent to the singlet states of the solute, but which for usual concentrations is fast enough not to modify the emission. Some of the singlets are produced very rapidly (by internal conversion) and give rise to a prompt emission - responsible for the fast component. Other singlets however, arising from triplet-triplet interactions, are retarded in their formation and thus give rise to a delayed emission - responsible for the slow component. These triplet-triplet interactions are more likely to occur in regions where the concentration of activated species is high, i.e. in the track in the case of protons, and spurs and blobs for both protons and Compton electrons. The presence of oxygen in the liquid

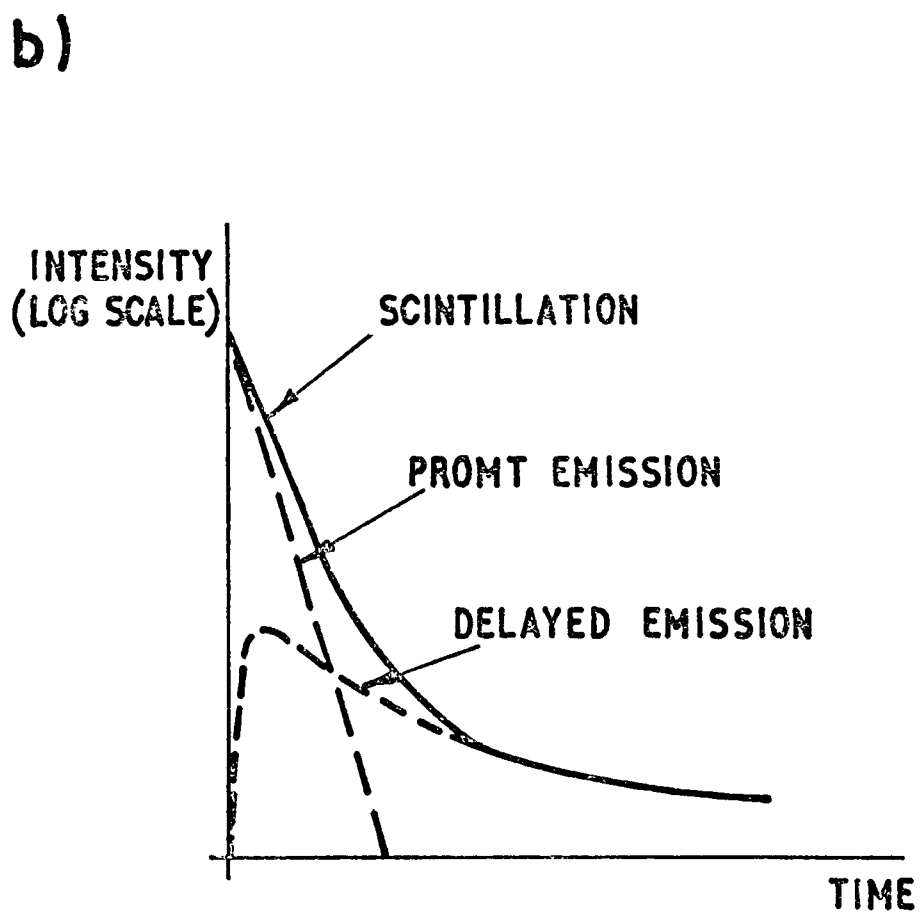
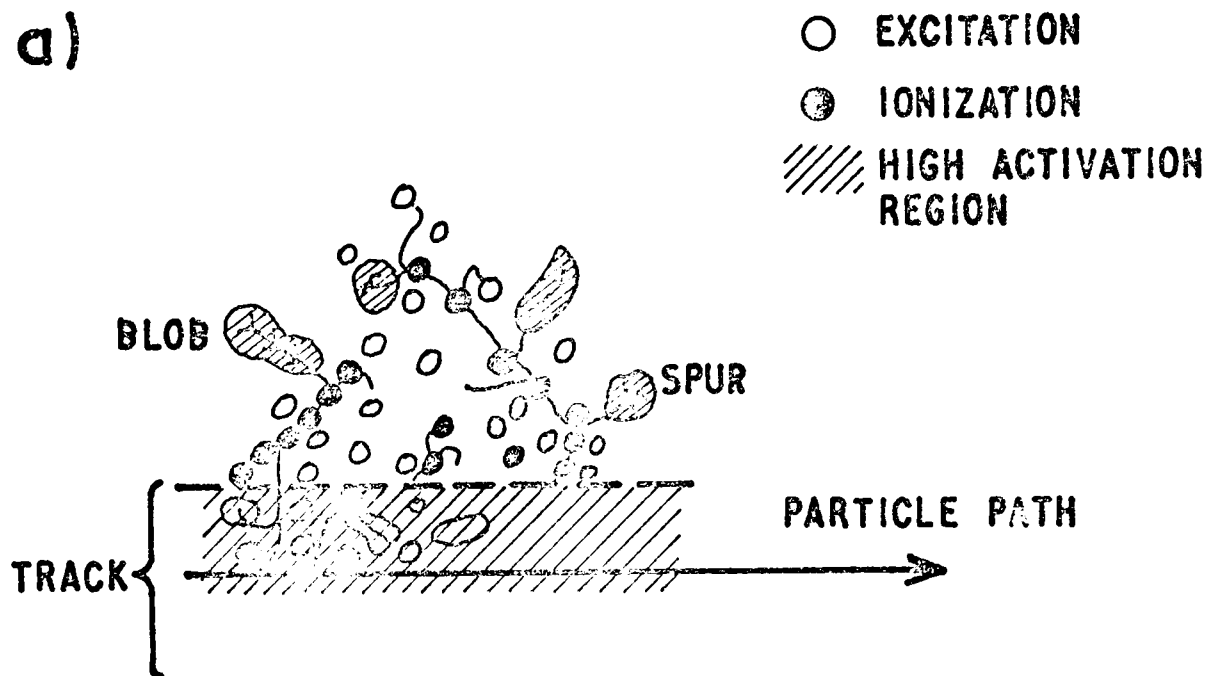


Fig.2.1 - The activation induced by a charged particle recoiling in the scintillator and the resulting output pulse.

scintillator has the effect of considerable quenching of the triplet states reducing the delayed emission and modifying its decay. Great care must therefore be taken to remove dissolved oxygen from the scintillator (see section 2.1.3). The output pulse from the scintillator is schematically shown in fig.2.1b.

The prompt and delayed emissions are properties of the scintillator and therefore have decay laws which are independent of the type of the ionizing particle; their integrated intensities however, depend strongly on the stopping power and charge of the exciting particle - this fact is mainly due to the initial quenching of excited states in regions of high excitation. It follows then that the relative importance of the fast and the slow components of the scintillation will depend on the detected particles, as the high excitation regions created by recoiling protons or electrons differ appreciably in nature.

In the case of neutrons a big fraction of the light output is emitted in the delayed emission, while for  $\gamma$ -rays most of the light is coming from the prompt emission. Laustriat (La68) quotes the values of the ratio of the prompt to the delayed emission as being 6.5 for  $\gamma$ -rays (from  $^{60}\text{Co}$ ) and 1.2 for fast neutrons (from a Ra-Be source) in the case of a stilbene crystal (which has P.S.D. properties comparable to those of NE213 (Nu70) ).

### 2.1.3 The neutron detector

The neutron detector was chosen to have an annular geometry so that it could be positioned at either  $0^\circ$  or

$180^\circ$  with respect to the charged particle beam incident upon the target. The detection of the outgoing particles on the beam axis greatly simplifies the analysis of angular correlation experiments (cylindrical symmetry) and the number of magnetic substates of the levels populated in the final nucleus is restricted, see chapter 3. However, as the detector has a finite size, its angular acceptance has to be small in order not to let the population of further magnetic substates (which otherwise would not be allowed by the restriction of on-beam axis detection) to be significant. Generally this was found to be the case provided the value of  $\theta_c$ , the half angle of the cone subtended at the target by the detector, is less than  $\sim 10^\circ$  (Ha66). We refer to chapter 3 for a discussion of these points.

In most experiments, a neutron flight path of 2 m is a reasonable compromise between background count rate and neutron energy resolution. The restriction on the angular acceptance of the neutron detector limits then its outside radius to a value of about 35 cm. To allow the beam line if necessary to pass through the detector in the geometry we have chosen, the inside radius of the detector then measures 8 cm. The solid angle subtended at the target by such an annular counter is 92 mstr at 2 m distance.

As outlined in section 2.1.1 the choice of thickness of a neutron time of flight spectrometer results from a compromise between detection efficiency and good timing properties. Furthermore, while at lower neutron energies

the neutron energy resolution and detection efficiency improve, for given values of flight path and detector thickness, the discrimination of neutrons against  $\gamma$ -rays is more difficult and the time spread due to the detector thickness increases. As a result of these considerations the neutron detector thickness was chosen to be 4.4 cm. If not impossible for other reasons the beam energy is then selected such as to produce the neutron groups of interest with energies ranging between 1 and 4 MeV. The time spread due to neutron flight within the counter is then 3.2 ns and 1.6 ns for 1 MeV and 4 MeV neutrons, respectively. As the overall time resolution of the neutron spectrometer when used in conjunction with a  $\gamma$ -ray Ge(Li) detector is of the order of 6 ns (see section 2.1.6) the neutron energy resolution obtained with this instrument is 8% at 1 MeV (80 keV) and 15% at 4 MeV (600 keV) neutron energy. The detection efficiencies obtained with the detector (consisting of 4.4 cm of NE213) are for the same range of neutron energies between 62% and 35%, at zero detector bias. The calculation of these efficiencies is based on the assumption that the presence of carbon in the scintillator is only reflected in an increase of the effective neutron path length by means of elastic scattering. Also, for zero detector bias, multiple neutron-proton scattering can be assumed to occur in a sufficiently small time interval so that only a single event is detected. The total n-p and neutron elastic scattering cross-sections used in the efficiency calculations were taken from Marion and Young (Ma68) and Hughes and Harvey (Hu55). The above

neutron energy resolution and detector efficiencies are quite adequate for Nuclear Structure studies by n- $\gamma$  coincidence measurements.

The annular neutron detector was designed to consist of four quadrants, each quadrant being viewed by two 11 cm photocathode diameter Mullard XP1040 photomultiplier tubes as shown in fig.2.2. This design has two advantages: (i) each quadrant is independent from the electronics point of view (pulse shape discrimination and timing) the only concern being the matching of the photomultiplier tubes in pairs; and (ii) each quadrant can be pivoted about an axis normal to its symmetry plane by an angle of up to  $12^{\circ}$ . In this way the shape of the detector can be adjusted such as to approximate closely an isochronous surface of which the target is the centre, and thus eliminate differences in flight times due to "bad geometry". The optimum angle setting depends of course on the flight path and on the reaction kinematics. Each quadrant has also a small viewing window so that a light pulser can be used for testing purposes.

The detector quadrants are made of aluminium and have been painted inside with a white reflecting paint to increase the optical efficiency. Each quadrant was then filled with NE213 liquid scintillator and the dissolved oxygen was removed by displacement with nitrogen, to prevent the undesirable quenching effects of oxygen mentioned in section 2.1.2. The Photomultiplier (PM) tube faces were optically coupled to the quadrant windows with silicone grease. Each PM tube is shielded from stray magnetic fields

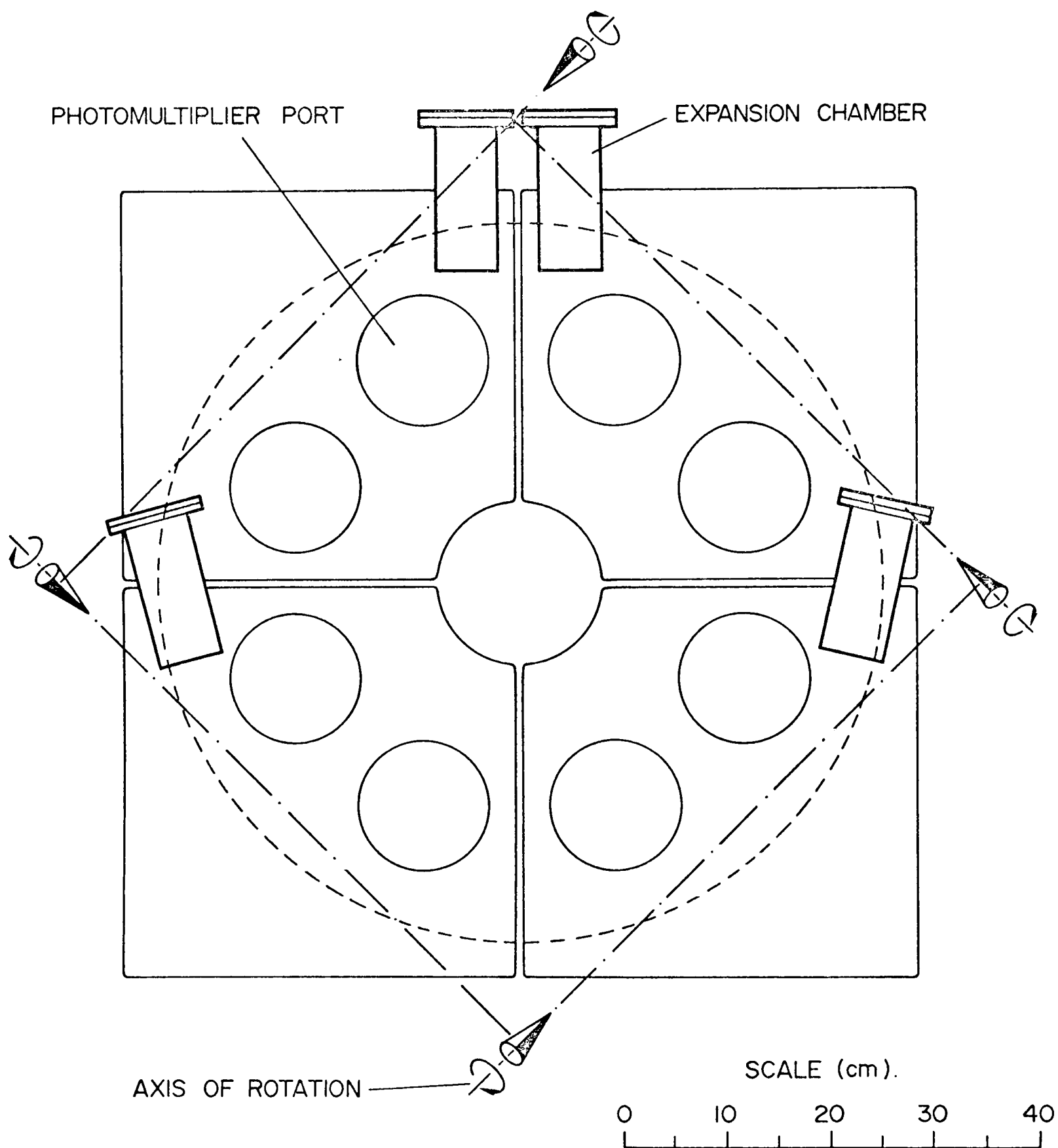
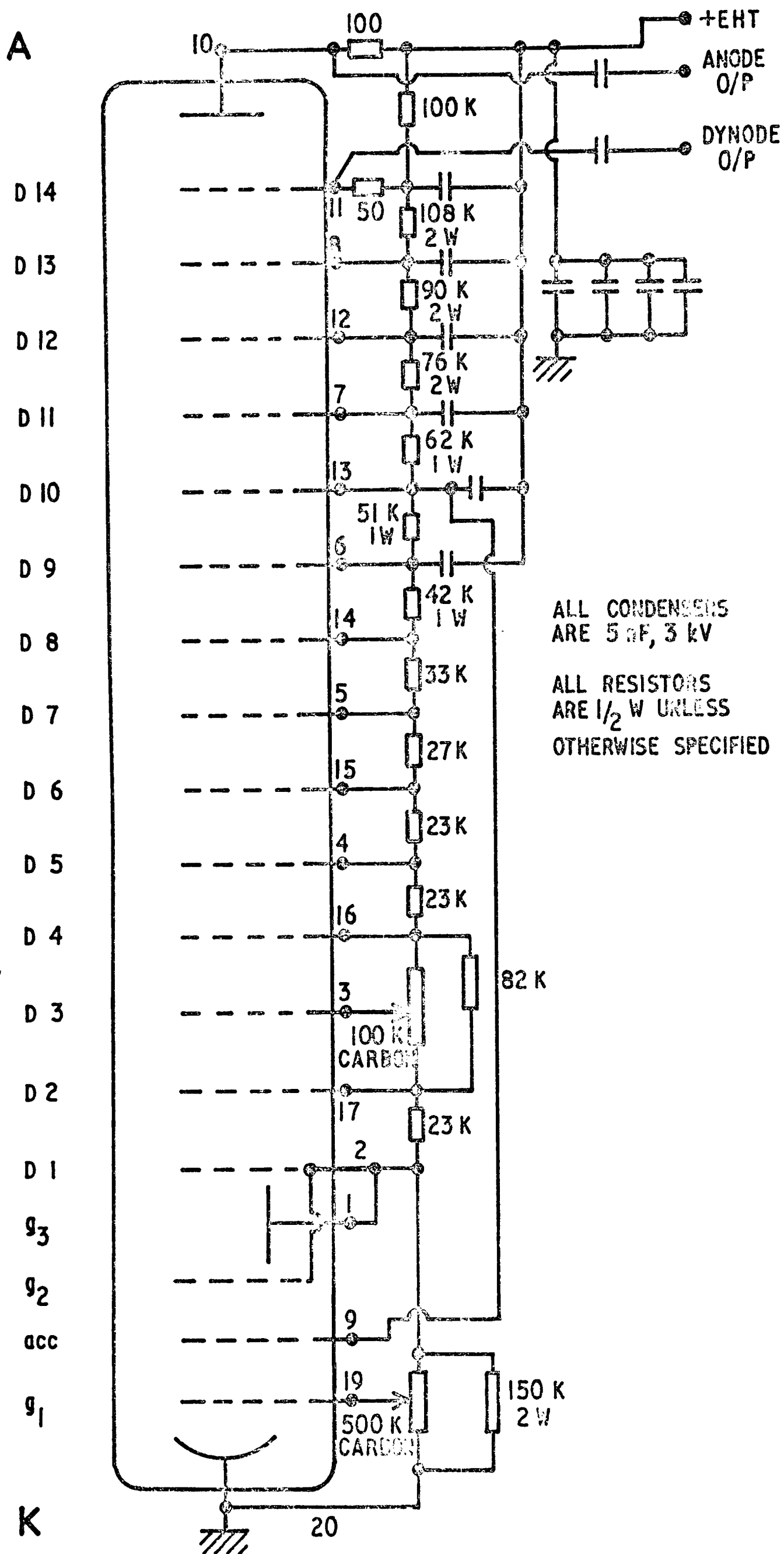


Fig.2.2 - Schematic diagram of the neutron detector.

with  $\mu$ -metal and is located in a light-tight brass case, to which the dynode chain assembly is attached. Also, each PM tube is powered by a separate high voltage power supply. The dynode chain assembly used with the XP1040 PM tube both for pulse shape discrimination (PSD) and timing purposes is shown in fig.2.3. The chain draws 3 mA at 2.5 kV bias and was designed to provide the voltage distribution recommended by Mullard for fast timing purposes. The fast timing signal is taken from the anode by means of a 100  $\Omega$  anode load resistor. The anode signals from the two PM tubes viewing each quadrant are then added in a 100  $\Omega$  input impedance resistive adder. 100  $\Omega$  was chosen for the timing signals to match the impedance of the cables connecting the target area to the control room. A linear signal for PSD purposes is provided by the 50  $\Omega$  dynode load resistor of dynode 14. The dynode signals from the two PM tubes on each quadrant are similarly added in a 50  $\Omega$  input impedance resistive adder. The neutron detector has therefore eight signal outputs, namely the four fast timing outputs from the anode adder units, and the four linear outputs for PSD purposes from the dynode adder units.

The light collection obtained with this photomultiplier arrangement is good. Test runs were made using a radioactive source, located at different places of the quadrant faces. The count rate was nearly constant over the quadrant areas, falling off by 20% only near the edges. Also, the balance of the four quadrants in detection efficiency was investigated. Test runs using different radioactive sources showed that the four quadrants had very similar character-



istics, and that their outputs could be made nearly equal with simple adjustments in the high voltage power supplies (see also section 2.1.6).

The neutron detector is mounted on wheels to make it easier to change the length of the neutron flight path. A photograph of the detector showing the four quadrants (pivoted by about  $6^\circ$ ) with the PM tube cases, dynode chain assembly boxes, anode and dynode pulse adders, high voltage power supplies and some of the associated electronics described in the following sections is presented in fig.2.4.

#### 2.1.4 Pulse shape discrimination

As discussed in section 2.1.2 the nature of the radiation entering the detector can be determined if a PSD method is used. This technique compares the slow component of the output pulse with the fast one. Of the various discrimination methods available (Be69), the charge comparison method as described by Sabbah and Suhami (Sa68) is the most suitable for a neutron time of flight spectrometer. In this method the charge contained in the fast component of the light output pulse is compared to its total charge. The charge comparison method shows very good performance at low energies, it is not too critical in use and set up<sup>and</sup> requires a small number of electronic units. It was found that the PSD characteristics of the dynode pulses as added in the resistor adders were only slightly poorer than those obtained with pulses taken directly from the last dynode of each PM tube. Therefore, associated with the neutron detector there are four pulse shape

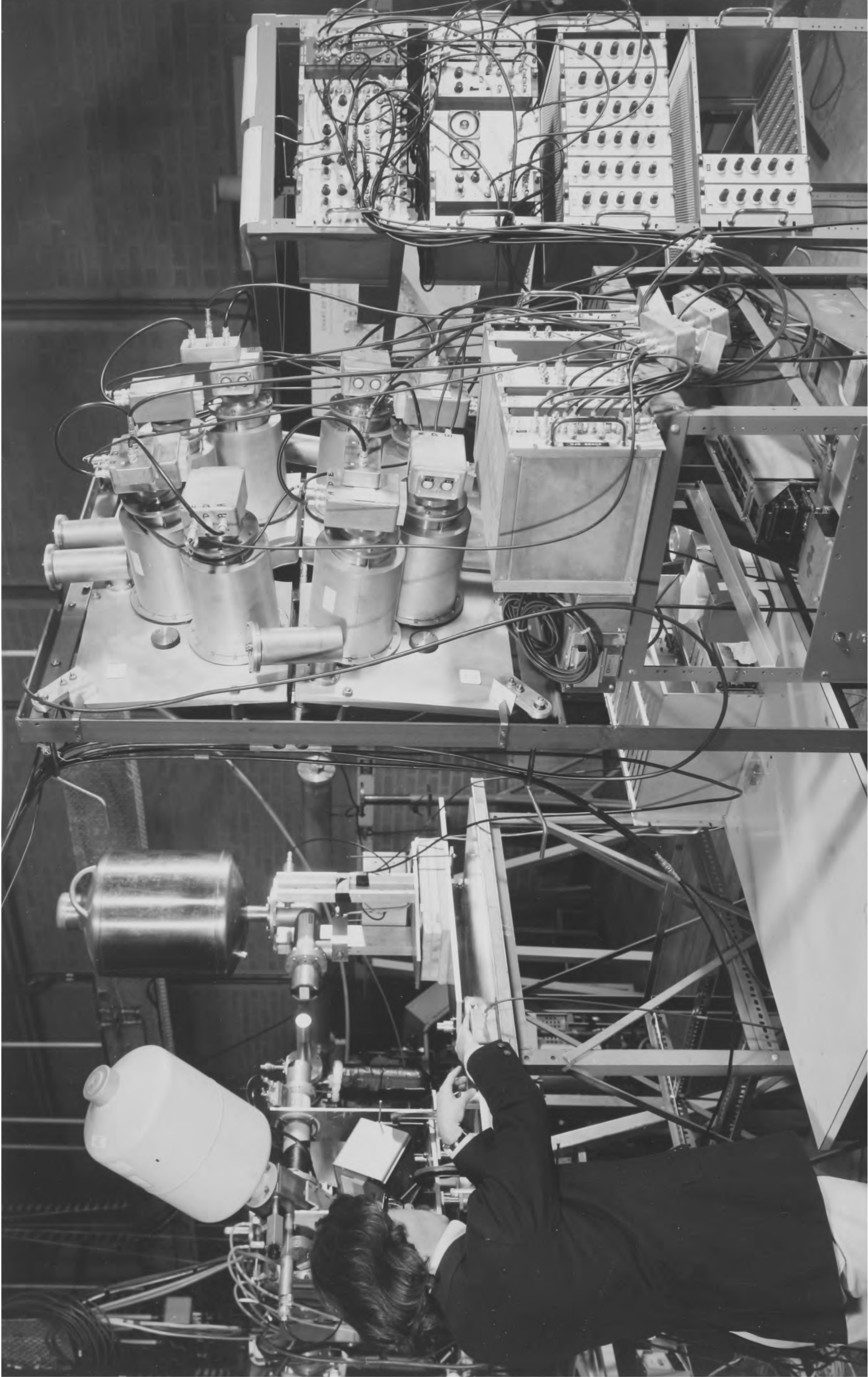


Fig. 2.4

discriminators (Elron, model PSD-N-1) - one for each quadrant - which are mounted in single width NIM modules. The PSD units can also be seen in fig.2.4 set up in a NIM's bin right below the detector quadrants.

The Elron pulse shape discriminators have 50  $\Omega$  input impedance. Their internal block diagram is shown in fig.2.5 together with the typical waveforms at specific points of the circuit. The input pulse (A) is split by the RLC shaping network of constant input impedance. On the LR side of the circuit the pulse is pre-integrated (B) and its total charge fed via the buffer stage and  $D_2$  to the passive integrator. In the CR side of the circuit the pulse is differentiated (C) so that the total charge in this channel is zero. The positive and negative charges of the differentiated pulse are therefore equal and proportional to the charge contained in the input pulse up to the time  $t_0$ , which is determined by the decay of the input pulse and by  $T = CR$  ( $t_0 = 25$  ns in the case of NE213 pulses). The negative charge of the differentiated pulse (which is then a measure of the fast component of the input signal) is fed after a suitable amplification to the passive integrator by means of  $D_4$ . The delay of the buffer stage is set to  $t_0$  so that the pulses coming from the two channels will arrive simultaneously at the passive integrator. This passive integrator is a critically damped RLC circuit. The gain of the amplifier  $A_1$  is adjusted so that the final charge (D) is negative for  $\gamma$ -induced pulses and positive for neutron induced signals. The output of the passive integrator is amplified and fed into a low level

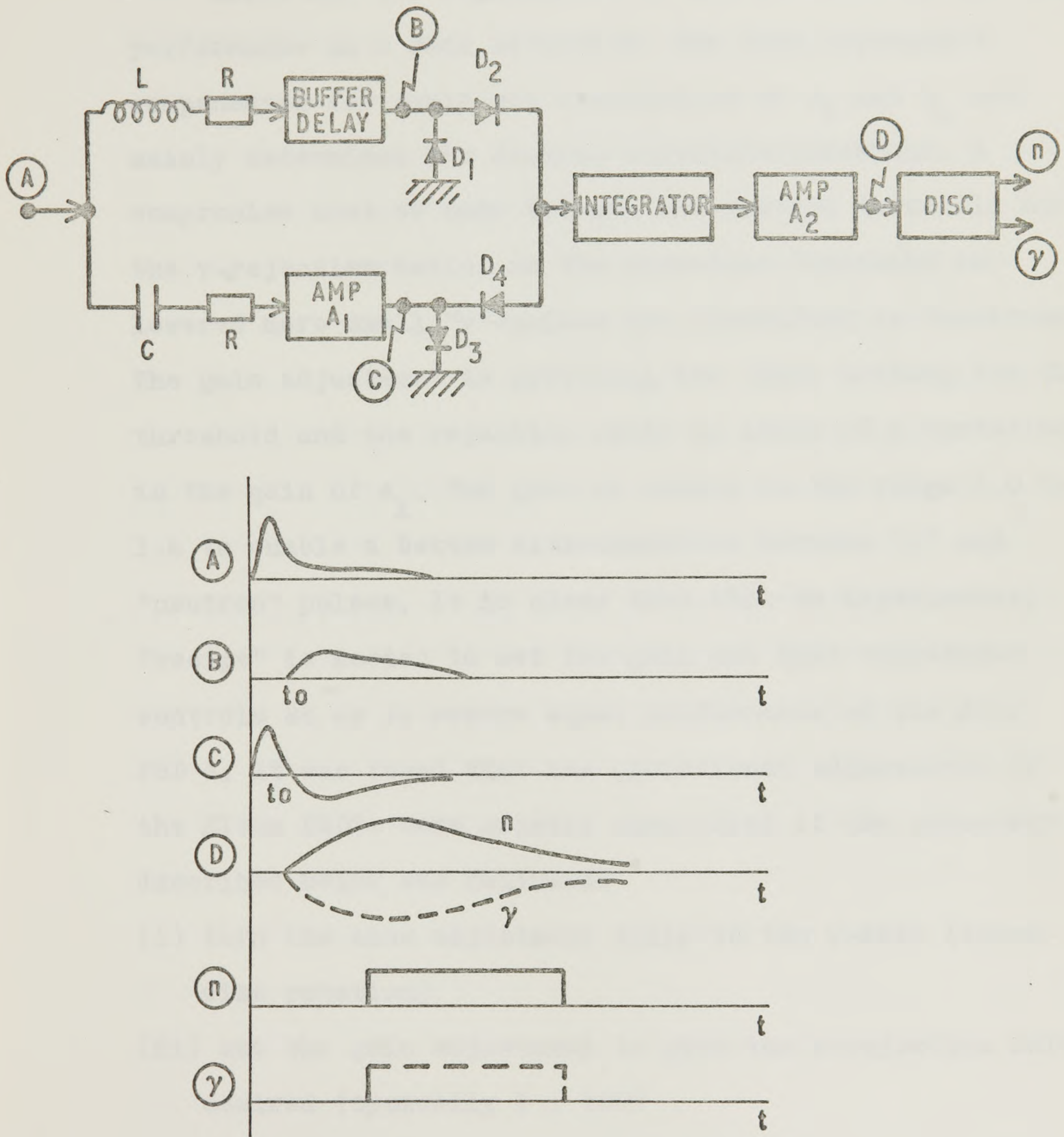


Fig.2.5 - Pulse shape discriminator block diagram and typical waveforms.

discriminator which has outputs for both "neutron" pulses (positive final charge) and "gamma" pulses (negative final charge). The total dead time is 1  $\mu$ s.

There are two adjustments in the PSD unit to optimise performance in a real situation. The bias adjustment compensates for small non linearities of  $D_3$  and  $D_4$  and mainly determines the neutron detection threshold. A compromise must be made between the neutron threshold and the  $\gamma$ -rejection ratio. As the detection threshold is lowered more small " $\gamma$ "-pulses are identified as "neutrons". The gain adjustment is providing the final setting for the threshold and the rejection ratio by means of a variation in the gain of  $A_1$ . The gain is varied in the range 1.0 to 1.4 to enable a better discrimination between " $\gamma$ " and "neutron" pulses. It is clear then that an experimental "recipe" is needed to set the gain and bias adjustment controls so as to assure equal performance of the four PSD's. It was found that the operational adjustments of the Elron PSD's were greatly simplified if the procedure described below was followed:

- (i) turn the bias adjustment fully to the  $\gamma$ -side (clock-wise rotation)
- (ii) set the gain adjustment to give the  $\gamma$ -rejection ratio desired (typically 1 : 100)

With the pulse shape discriminator set in this way to a  $\gamma$ -rejection ratio of 1 : 100 the neutron detection threshold is  $\sim 350$  keV and the neutron PSD efficiency 72%.

To actually measure the threshold and the PSD

efficiency the coincidence-anticoincidence circuit shown in fig.2.6 was used. The  $\gamma$  and neutron logic outputs were fed into a coincidence unit (with on-off switches at the inputs) where they were made to coincide with a logic signal derived by means of a single channel analyser from the added PM anode signals. The coincidence unit (CU) could provide also a signal in anticoincidence with the neutron and  $\gamma$  inputs. The number of pulses from the CU was counted in a scaler and a multichannel analyser (MCA) gated with these pulses accumulated the amplitude spectrum of the added anode pulses coincident with the CU signals.

The neutron threshold was measured from gated neutron spectra accumulated in the MCA using an Am-Be source as a neutron source. The MCA was calibrated using radioactive  $\gamma$ -sources, and the equivalent neutron energy deduced from the curves of the relative response of NE213 for electrons and protons measured by Batchelor et al. (Ba61). The neutron PSD efficiency was measured by counting the number of neutron logic pulses (N), gamma logic pulses (G), total number of anode pulses (T) and total-neutron-gamma pulses ( $T' = T - N - G$ ) for a given time. As the Am-Be source is a mixed source of neutrons and  $\gamma$ -rays, a measurement was also done with a  $^{22}\text{Na}$   $\gamma$ -ray source. Typical results were, for 20s counting time,

$^{22}\text{Na}$  source

$$N = 328$$

$$G = 29.7 \times 10^3$$

$$T' = 6.9 \times 10^3$$

$$T = 36.3 \times 10^3$$

Am-Be source

$$N = 12.0 \times 10^3$$

$$G = 24.2 \times 10^3$$

$$T' = 10.2 \times 10^3$$

$$T = 46.0 \times 10^3$$

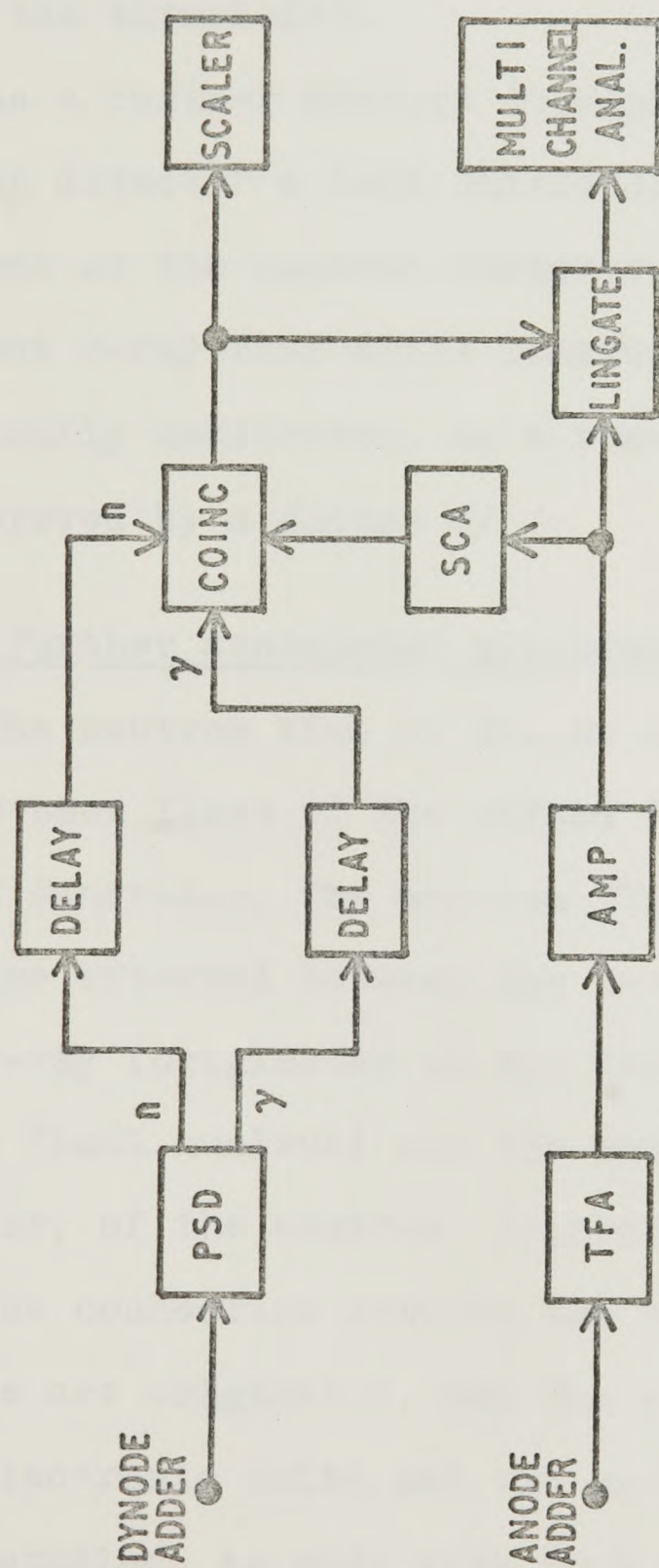


Fig.2.6 - Circuit for measuring the neutron detection threshold and PSD efficiency using radioactive sources.

From the  $^{22}\text{Na}$  source results a  $\gamma$ -rejection ratio of  $\sim 1 : 100$  is extracted. A neutron PSD efficiency of 72% is obtained after correcting the Am-Be source results for its  $\gamma$ -ray emission, making use of the values measured with the  $^{22}\text{Na}$   $\gamma$ -ray source. It is worth noting though that nearly all non PSD-identified events are in the low energy range (near the threshold).

As a further measure to suppress  $\gamma$ -detection in the neutron detector a lead shield of 5 mm thickness is used in front of the neutron detector. This attenuates the incident  $\gamma$ -ray flux while leaving the neutron count rate practically unaffected. As a result, the  $\gamma$ -rejection ratio is improved by a factor of 2.

#### 2.1.5 Further associated electronics

The neutron time of flight detector is set up on one of the beam lines of the Oxford University Tandem van de Graaff Generator. The neutron flight time is measured as the time interval between the detection in a Ge(Li) detector of a  $\gamma$ -ray (originated in the decay of an excited state of the final nucleus) and the detection, in the neutron detector, of the neutron populating that level.

The connection between the target area, where the signals are originated, and the control room, where the main electronic units and the on-line computing facility are installed, is made with 60 m of 100  $\Omega$  cable. Therefore, all the fast electronics treating the neutron detector timing pulses and also the pulse shape discriminators are located in the target room, close to the neutron detector.

This is to avoid any deterioration in the rise time and shape of the neutron signals. On the other hand, the comparatively slower signals originated in the Ge(Li) detector are not substantially affected by the length of cable needed to reach the control room from the target area, and therefore the associated electronics on the  $\gamma$ -side is all situated in the control room. This is shown in fig.2.7. Fig.2.7 depicts the diagram of the electronics used in connection with the decay scheme and angular correlation experiments described in chapters 4 and 5. Only one quadrant of the neutron detector with its associated fast anode and PSD-logic channels has been shown for simplicity.

In the target room, the PM linear dynode outputs are fed (after adding) into Elron PSD units located near the detector. The four neutron logic outputs from these units are mixed in an "OR" gate which provides neutron identifying signals (to a coincidence unit situated in the control room). The outputs from each anode adder are fed into a constant fraction discriminator (CFD)-Ortec model 453. There are four CFD's associated with the anode pulses to avoid the excessive count rates obtainable if the fast signals were mixed before the discriminators. The CFD's are operated in the "constant fraction of pulse height trigger" mode described by Gedcke and McDonald (Ge67) which enables the use of a wide dynamic range at the input, with minimum walk. The fast timing outputs of each CFD are combined in a fast four input "OR" gate (which provides the stop signals to a time to amplitude converter-TAC-

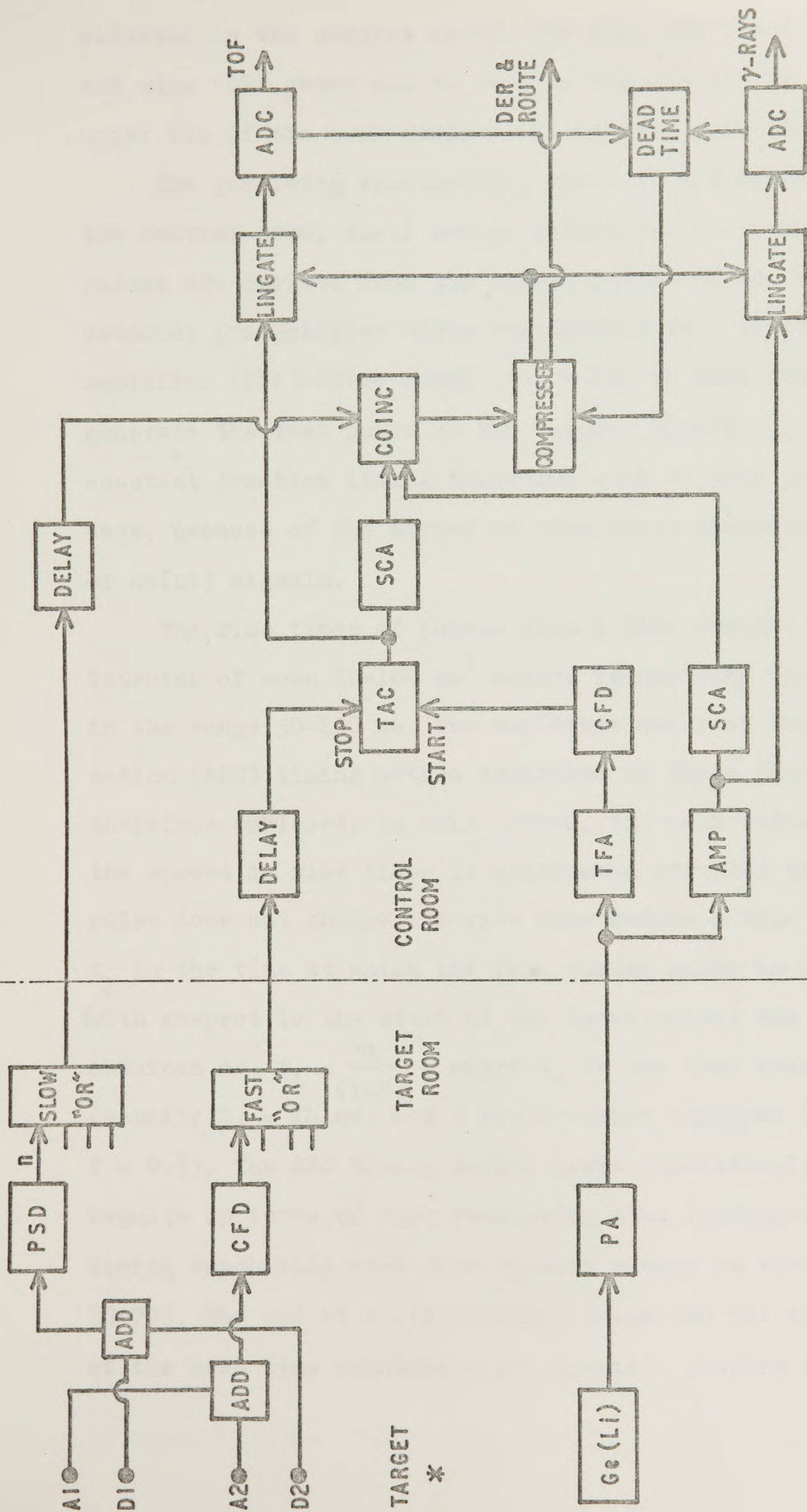


Fig.2.7 - Schematic diagram of the electronics used in the measurements reported in chapters 4 and 5.

situated in the control room). The four CFD's and the fast and slow "OR" gates can be seen in fig.2.4 set up in the upper bin of the rack besides the neutron detector.

The remaining electronics, which is all situated in the control room, shall now be described. The  $\gamma$ -fast timing pulses are derived from the linear output of the Ge(Li) detector preamplifier after amplification in a timing filter amplifier (TFA)-Ortec model 454. A CFD is also used to generate the fast pulse in the  $\gamma$ -side. However, a modified constant fraction timing technique must be used in this case, because of the spread in rise times characteristic of Ge(Li) signals.

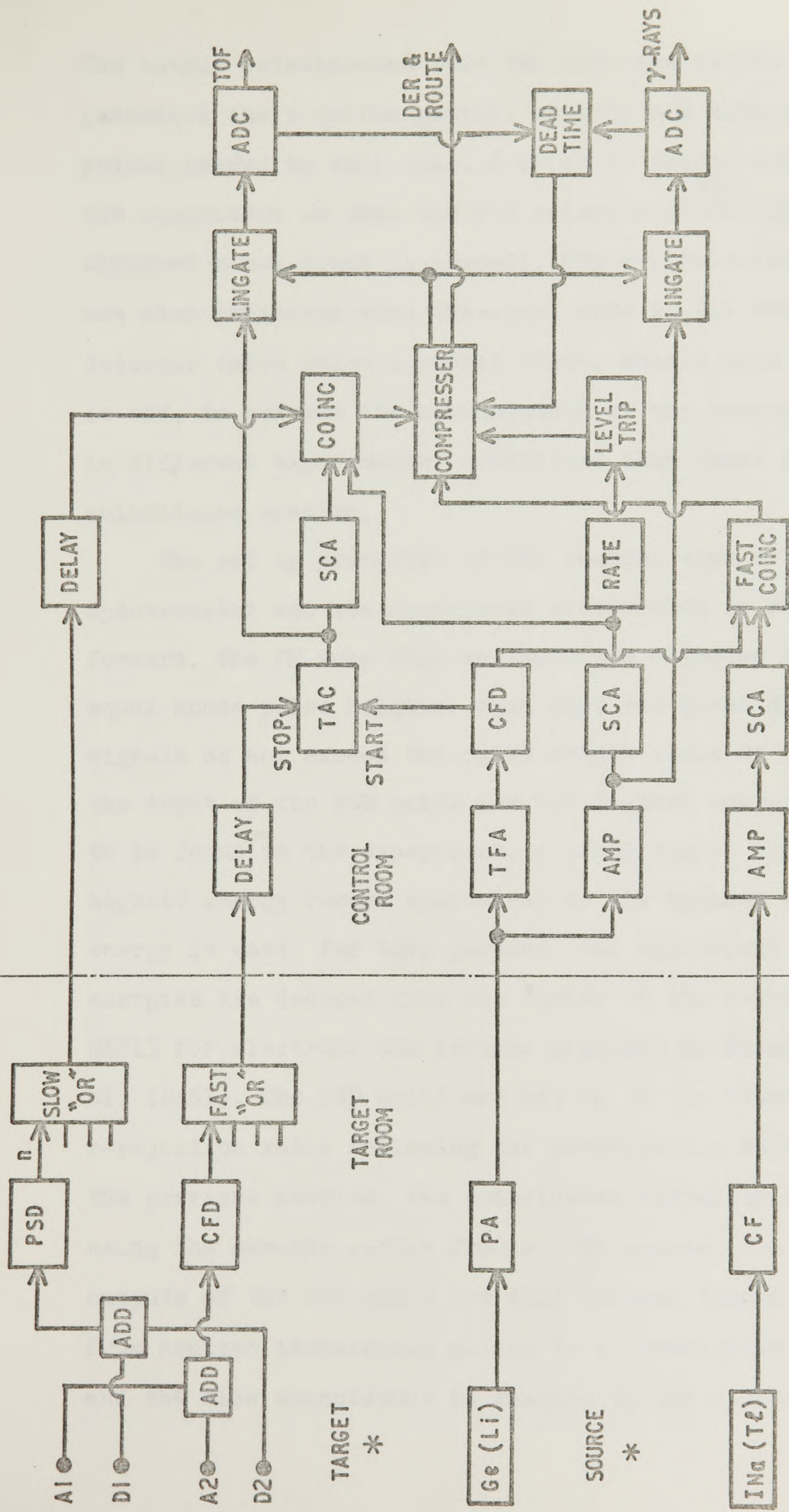
The rise times of pulses from a time coaxial Ge(Li) detector of some 50-100 cm<sup>3</sup> active volume vary typically in the range 50-150 ns. The amplitude and rise time compensation (ARC) timing method described by Chase (Ch68) is therefore employed. In this method, the walk resulting from the spread in rise times is eliminated provided the input pulse does not change its rise time before a time  $t_1$ .  $t_1$  is the time at which the fast timing pulse is derived (with respect to the start of the input pulse) and is obtained as  $t_1 = \frac{t_d}{(1-f)}$ , where  $t_d$  is the time delay selected (usually  $t_d = 14$  ns) and  $f$  the fraction employed (usually  $f = 0.3$ ). The ARC timing method gives consistently better results in terms of time resolution than leading-edge timing especially with wide dynamic ranges at the input (Or70). The use of a wide dynamic range and the attainment of the best time resolution are crucial factors in an

associated  $\gamma$ -ray neutron time of flight spectrometer.

The  $\gamma$ -fast timing pulses are used to start the TAC. Single channel analysers are employed to set upper and lower levels on the time of flight (TOF) and Ge(Li) signals. A slow coincidence (resolving time  $\sim 1 \mu\text{s}$ ) is performed between the neutron, gamma and TOF signals to provide the gating pulses to the linear gates carrying the TOF and the Ge(Li) analogue pulses. The TOF and the Ge(Li) detector signals are fed to two ADC's interfaced to the PDP-7 on-line computer operating in a two parameter mode, so that data can be partially analysed during accumulation. Furthermore, data are also stored on magnetic tape for subsequent analysis. The compressor in fig.2.7 is a unit designed to provide routing and derandomise pulses to the computer.

However, for the lifetime measurement of excited states in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  reported in chapter 6, an improved electronics set up was employed due to the necessity of continuously monitoring the gain of the system. The measuring times, due to the low n- $\gamma$  coincidence/<sup>count-rate</sup>, were of several hours. A source  $\gamma$ -spectrum was then taken during each run to serve as a reference to determine accurately the  $\gamma$ -peak centroid energies.

A NaI(Tl) crystal was placed near to the Ge(Li) detector and an  $^{88}\text{Y}$   $\gamma$ -ray source located between the two crystals. The schematic diagram of the electronics used for the lifetime measurements in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  is shown in fig.2.8. A  $\gamma$ - $\gamma$  fast coincidence (resolving time 50 ns) was performed between the Ge(Li) and the NaI(Tl) signals.



The output coincidences were fed into the compressor which generated the required gating, routing and derandomise pulses needed in this case. A priority scheme operates in the compressor so that the  $\gamma$ - $\gamma$  coincidences<sup>are</sup>/inhibited whenever a n- $\gamma$  count is present. The  $\gamma$ - $\gamma$  coincidences are also inhibited when the count rate in the Ge(Li) detector falls below a preset value, namely when the beam is off, to prevent the accumulation of the source spectra in different experimental conditions than those of the n- $\gamma$  coincidence spectra.

The set up procedure of the neutron time of flight spectrometer and its associated electronics is straightforward. The PM tube high voltages are adjusted to give equal anode pulse heights, such that the added dynode signals do not exceed the pulse height limit of 1 V at the input of the PSD units for the highest energy neutrons to be found in the experiment. A  $\gamma$ -ray source with its highest energy  $\gamma$ -rays equivalent to the highest neutron energy is used for this purpose. The equivalent  $\gamma$ -ray energies are deduced from the curves of the relative response of NE213 for electrons and protons measured by Batchelor et al. (Ba61). The PSD units are set up to the required  $\gamma$ -rejection ratio following the prescription described in the previous section. The coincidence circuitry is set up using the cascade  $\gamma$ -rays from a  $^{60}\text{Co}$  source. The logic outputs of the PSD units are then changed temporarily from neutron identifying pulses to  $\gamma$ -identifying pulses and the slow coincidence is enabled by the  $\gamma$ -pulses detected

in the neutron detector. The zero of the TOF spectrum is determined from the centroid position of the  $\gamma$ - $\gamma$  prompt peak by deducing the time spent by the photons to travel to the neutron detector. The TAC's time calibration is obtained by switching known delays into the stop side of the coincidence system.

### 2.1.6 Performance tests

In order to test the performance of the associate neutron time of flight  $\gamma$ -coincidence detection system under "life" conditions the neutron detection threshold was determined as a function of the  $\gamma$ -rejection ratio using a monoenergetic neutron source. The  ${}^7\text{Li}(p,n){}^7\text{Be}$  reaction ( $Q = -1.644$  MeV) was used to this effect. This reaction is a very good source of neutrons from  $E_p = 1.9$  MeV (the laboratory proton threshold being 1.88 MeV) to  $E_p = 5.5$  MeV (Bo63). Furthermore, if the neutron detector is located at an angle  $\sim 90^\circ$  with respect to the beam axis the neutron yield is approximately independent of proton energy (Bo63 ,Fa64). The neutrons populating the first excited state of  ${}^7\text{Be}$  (which is excited for proton energies  $E_p \geq 2.4$  MeV) correspond only to  $\sim 10\%$  of the total neutron cross section for the useful proton energy range.

The four quadrants were tested separately and found to have very similar characteristics. The results obtained with a  $250 \mu\text{g.cm}^{-2}$   ${}^7\text{Li}$  target on  $100 \text{ mg.cm}^{-2}$  lead backing for quadrant no.4 (the upper right quadrant in fig.2.4) for an integrated beam current of  $3 \mu\text{C}$  are given as an example in the following table:

| $E_p$ (MeV) | $E_n$ (MeV) | $\gamma$ -rej.ratio | n PSD counts<br>( $\times 10^3$ ) |
|-------------|-------------|---------------------|-----------------------------------|
| 5.0         | 2.12        | 1:250               | 1120                              |
| 4.0         | 1.42        | 1:250               | 1055                              |
| 3.0         | 0.72        | 1:250               | 328                               |
| 3.0         | 0.72        | 1:100               | 365                               |
| 3.0         | 0.72        | 1:45                | 425                               |

The typical response curves of the detector as inferred from this table are plotted in fig.2.9. The variation of detection threshold with  $\gamma$ -rejection ratio is clearly observed; also, the neutron count rate is seen to stabilise at  $\sim 1.4$  MeV neutron energy.

The timing performance of the  $\gamma$ -ray associated neutron TOF spectrometer has also been tested and was found very satisfactory. The resolution (FWHM) of the prompt  $\gamma$ - $\gamma$  coincidence peaks obtained using the coincident annihilation  $\gamma$ -rays from a  $^{22}\text{Na}$  source are 2.9 ns, 3.9 ns and 5.5 ns when the start pulses in the TAC are supplied by a 2" x 3" NE102A plastic scintillator - 56AVP PM tube combination, a 2" x 2" NaI(Tl) scintillator - 56AVP PM tube combination and a 32 cm<sup>3</sup> active volume Ge(Li) detector, respectively. All pulse heights above a low level threshold are accepted both in the neutron detector and the  $\gamma$ -detectors. Neutron TOF spectra were obtained using the  $^7\text{Li}(p,n\gamma)^7\text{Be}$  reaction. The neutron group populating the first excited state of  $^7\text{Be}$  is in coincidence with the 431 keV  $\gamma$ -ray resulting from decay of this state. The TOF spectra shown in figs.2.10 and 2.11 were measured with the

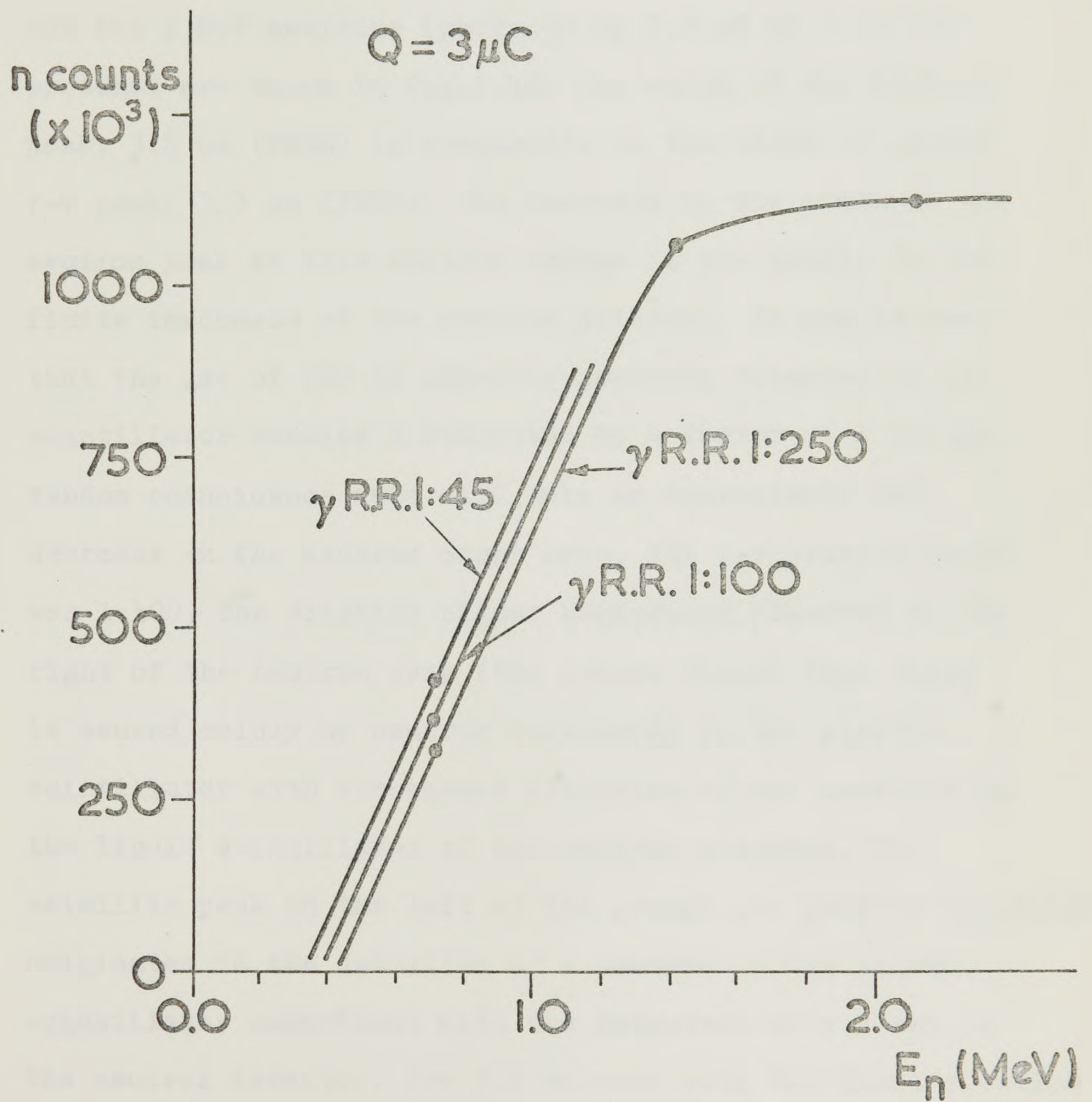


Fig.2.9 - Typical response curves of the neutron detector.

NE102A plastic scintillator placed at  $90^\circ$  and 10 cm from the target and the neutron detector at  $0^\circ$  and 2 m from the target. The target thickness was  $250 \mu\text{g}\cdot\text{cm}^{-2}$  and the beam was stopped on a lead foil placed immediately after the target.

The neutron TOF spectra obtained with and without PSD for 3 MeV neutrons (produced by 7.5  $\mu\text{C}$  of 5.10 MeV protons) are shown in fig.2.10. The width of the neutron peak, 3.8 ns (FWHM) is comparable to the width of prompt  $\gamma$ - $\gamma$  peak, 3.3 ns (FWHM). The increase in the width of the neutron peak at this neutron energy is due mainly to the finite thickness of the neutron detector. It can be seen that the use of PSD to identify neutrons detected in the scintillator enables a reduction by a factor of 6 in the random coincidence rate with only an approximate 40% decrease in the neutron count rate. The  $\gamma$ -rejection ratio was 1:100. The slightly higher background observed to the right of the neutron peak (the longer flight time side) is caused mainly by neutron scattering in the plastic scintillator with subsequent detection of the neutrons in the liquid scintillator of the neutron detector. The satellite peak on the left of the prompt  $\gamma$ - $\gamma$  peak in fig.2.10a originates in the detection of a neutron in the plastic scintillator coincident with the detection of a  $\gamma$ -ray in the neutron detector. The TOF spectra with PSD identification for neutrons of 1, 2 and 3 MeV energy are shown in fig.2.11. The proton bombarding energies are 3.16, 4.14 and 5.10 MeV, respectively and the integrated target current is 7.5  $\mu\text{C}$ . The  $\gamma$ -rejection ratio is 1:100. The width of the

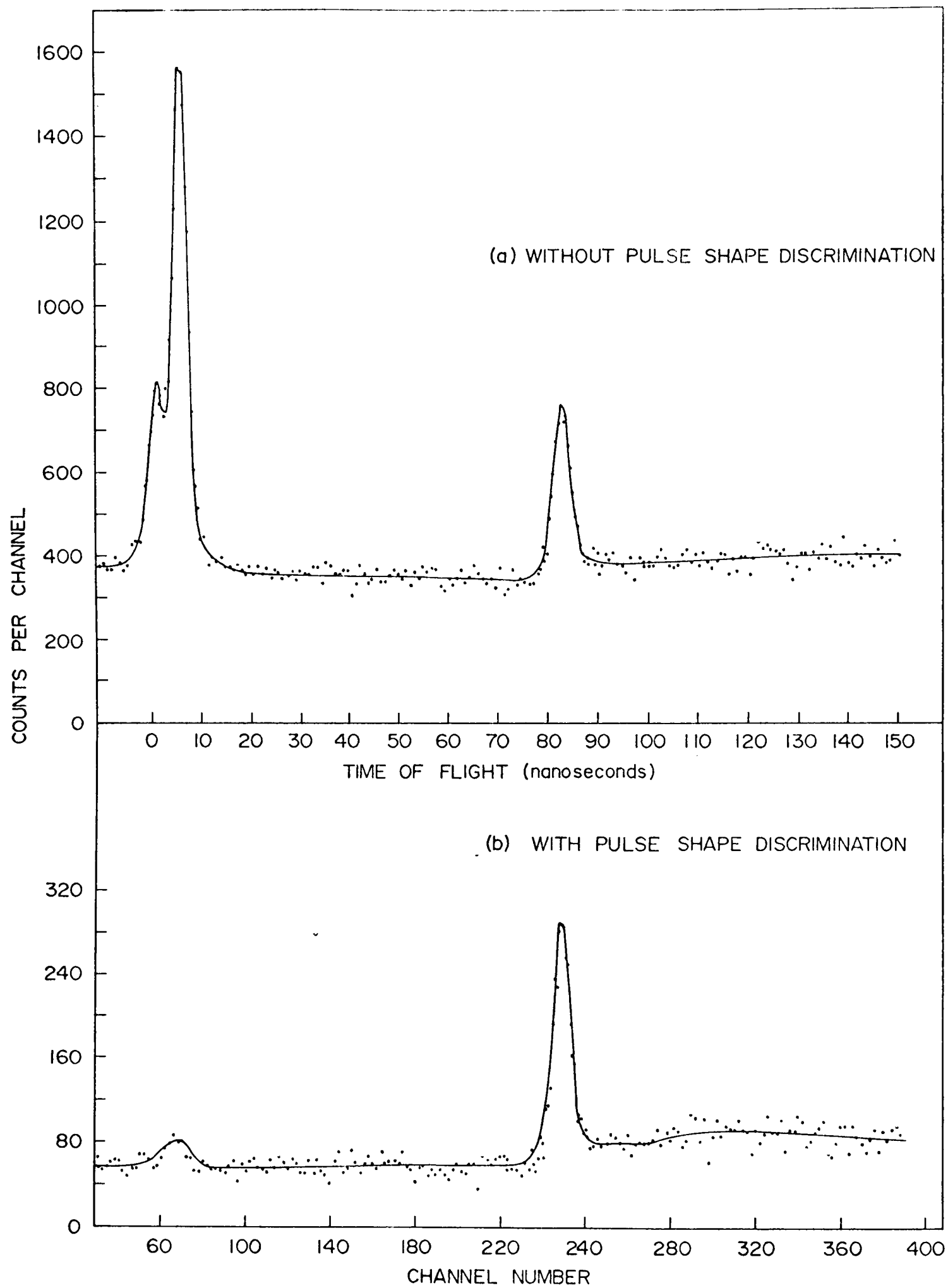


Fig.2.10 - Neutron time of flight spectra with and without pulse shape discrimination.

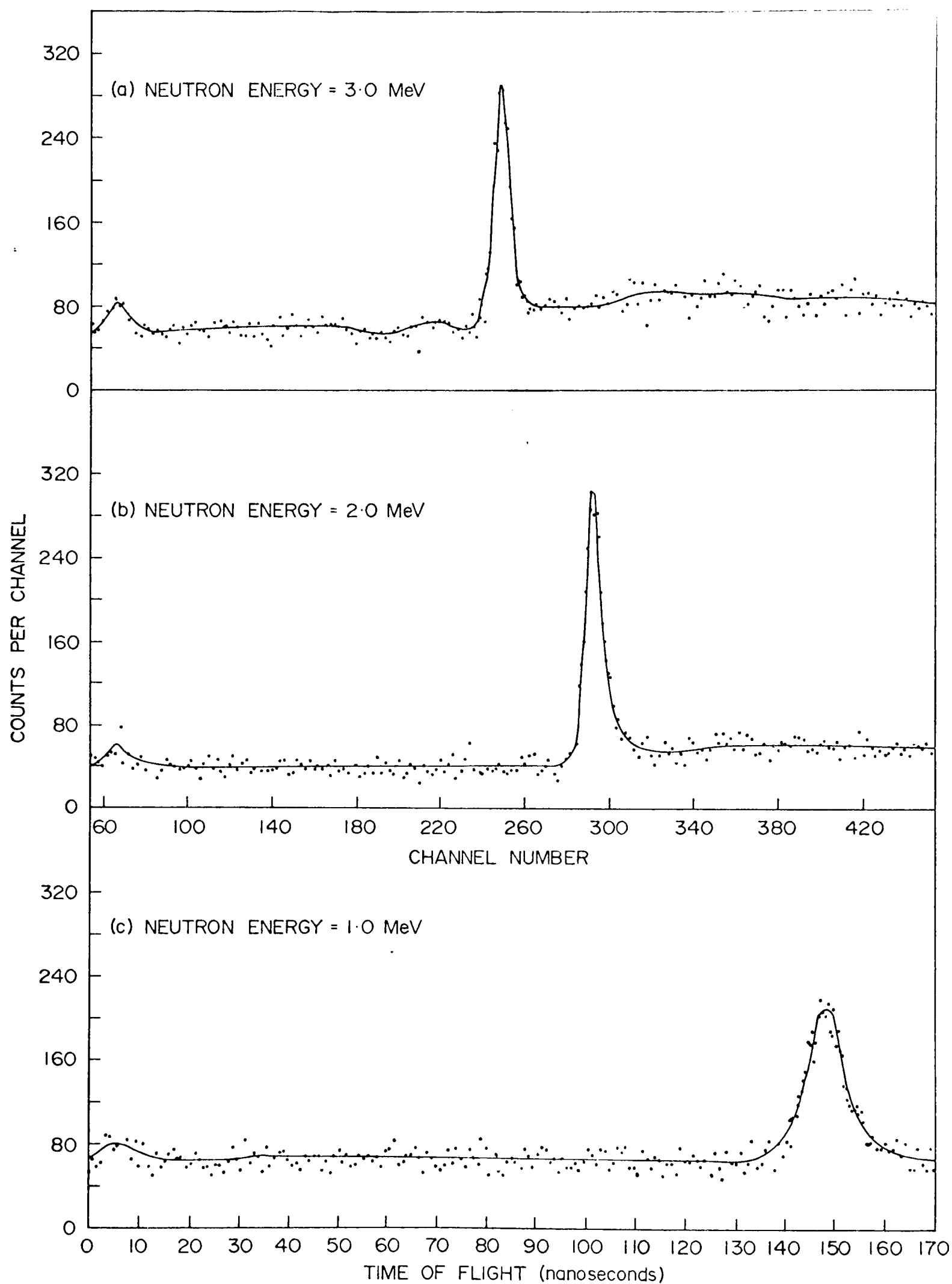


Fig.2.11 - Time of flight spectra for neutrons of energy 1, 2 and 3 MeV.

neutron peaks in the TOF spectra are (FWHM) 7.6, 3.8 and 3.8 ns for 1, 2 and 3 MeV neutron energies respectively. The contributions to the width of the 1 MeV neutron peak are estimated as 2.5 ns (full width) resulting from the target thickness, 3.2 ns (full width) resulting from the neutron detector thickness, 1.0 ns (FWHM) from kinematics as the quadrants were set to minimise geometrical effects only and 3.3 ns (FWHM) resulting from electronics and the statistics of detection. All these contributions decrease with increasing energy except for the electronics and statistical effects.

A first example of the use of the associated  $\gamma$ -ray TOF spectrometer in Nuclear Physics is the measurement of the decay scheme of the low-lying levels of  $^{37}\text{Ar}$ , reported in section 4.2.

## 2.2 The measurement of nuclear lifetimes

### 2.2.1 Introduction

Since Doppler stated in 1842 that the colour of a luminous body depends upon movements of approach or recession (Do42), the observation of these frequency shifts of the spectrum of an emitting source (as caused by its motion relative to the observer) has been a tool of experimental studies in almost all fields of Physics. The usefulness of Doppler's effect in experimental Nuclear Physics stems from the fact that relative energy shifts of  $\gamma$ -rays greater than 0.1% can easily be measured with Ge(Li) detectors. The Doppler shift observed when a  $\gamma$ -ray emitted by a nucleus with velocity  $\underline{v}$  is detected with wave vector  $\underline{k}$  is

$$\Delta E_{\gamma} = \hbar \underline{k} \cdot \underline{v} \quad , \quad \text{if } v \ll c \quad (2.1)$$

where  $c$  is the speed of light. The final nuclei in many nuclear reactions have recoil velocities ranging from 0.2 to a few per cent of the speed of light. Therefore, the characteristic Doppler shift of a 1 MeV  $\gamma$ -ray is of the order of 10 keV ( $\frac{v}{c} \sim 1\%$ ).

A great number of low-lying excited states of light nuclei have lifetimes in the range  $10^{-8} - 10^{-15}$  s. This is expected from the Weisskopf single particle estimates of transition widths (Wi60) and is confirmed by experimental observation (e.g. the compilation of electromagnetic transition rates of (Sk66) ). In order to measure such short lifetimes adequate time references must be chosen. A time

reference that is comparable to decay times of  $10^{-8} - 10^{-12}$  s is the time of flight of the recoiling nuclei over a measurable distance. This gives rise to <sup>the</sup> Doppler shift recoil-distance (plunger) method described in section 2.2.3.

Another characteristic time scale is set by the slowing down time of ions recoiling in solids or gases. The comparison of these slowing down times with the lifetimes of excited states decaying by  $\gamma$ -emission forms the basis of the Doppler shift attenuation method (DSAM).

Characteristic slowing down times range typically from 0.1 to a few picoseconds. Therefore, lifetimes varying between  $10^{-11}$  and  $10^{-14}$  s can be measured in this way. No Doppler shift will be observed when the nuclear lifetime is very long compared with the characteristic slowing down time, as nearly all nuclei will deexcite after stopping; on the other hand a full Doppler shift will be detected when the lifetime is very short, as in this case nearly all deexcitations will come from the first stages in the slowing down process. However, if the two time intervals are of comparable length an attenuated Doppler shift will be measured which depends on the lifetime of the nuclear level. To extract a lifetime from this fractional Doppler shift measurement (F-value) a detailed knowledge of the slowing down mechanism is needed.

### 2.2.2 The Doppler shift attenuation method (DSAM)

From (2.1), the mean Doppler shift measured for a population of excited nuclei recoiling with velocities  $\underline{v}_i$  is  $\langle \hbar \underline{k} \cdot \underline{v}_i \rangle$ . The distribution of the  $\underline{v}_i$  is

symmetric with respect to the beam axis in a typical reaction (unpolarised beam and target). The components of the vectors  $\underline{k}$  and  $\underline{v}_i$  can then be written, assuming the beam direction to be the z-axis for both the Cartesian and the spherical polar coordinate systems depicted in fig.2.12,

$$\underline{k} = k(0, \sin\theta_\gamma, \cos\theta_\gamma) \quad (2.2a)$$

$$\underline{v}_i = v_i(\sin\theta_i \cos\phi_i, \sin\theta_i \sin\phi_i, \cos\theta_i) \quad (2.2b)$$

Hence,

$$\begin{aligned} \langle \hbar \underline{k} \cdot \underline{v}_i \rangle &= \frac{E_\gamma}{c} \langle v_i (\sin\theta_\gamma \sin\theta_i \sin\phi_i + \cos\theta_\gamma \cos\theta_i) \rangle = \\ &= \frac{E_\gamma}{c} \cos\theta_\gamma \langle v_i \cos\theta_i \rangle \end{aligned} \quad (2.3)$$

as, due to the cylindrical symmetry assumed,

$$\langle v_i \sin\theta_i \sin\phi_i \rangle = 0 \quad (2.4)$$

The quantity  $\langle v_i \cos\theta_i \rangle$  is a function of time and contains the information about the slowing down process. Its evaluation, which poses difficult problems, is considered later. The full information contained in the velocity distribution  $v_i \cos\theta_i$  can be used in a line shape analysis once the  $\gamma$ -detector resolution has been incorporated. However, in cases where the Doppler shift is small compared with the detector resolution or when the statistics obtained is not too good (as in coincidence experiments) the first moment of the velocity distribution  $\langle v_i \cos\theta_i \rangle$ , obtained from the measurement of the centroid of the  $\gamma$ -ray peak, yields a better lifetime determination.

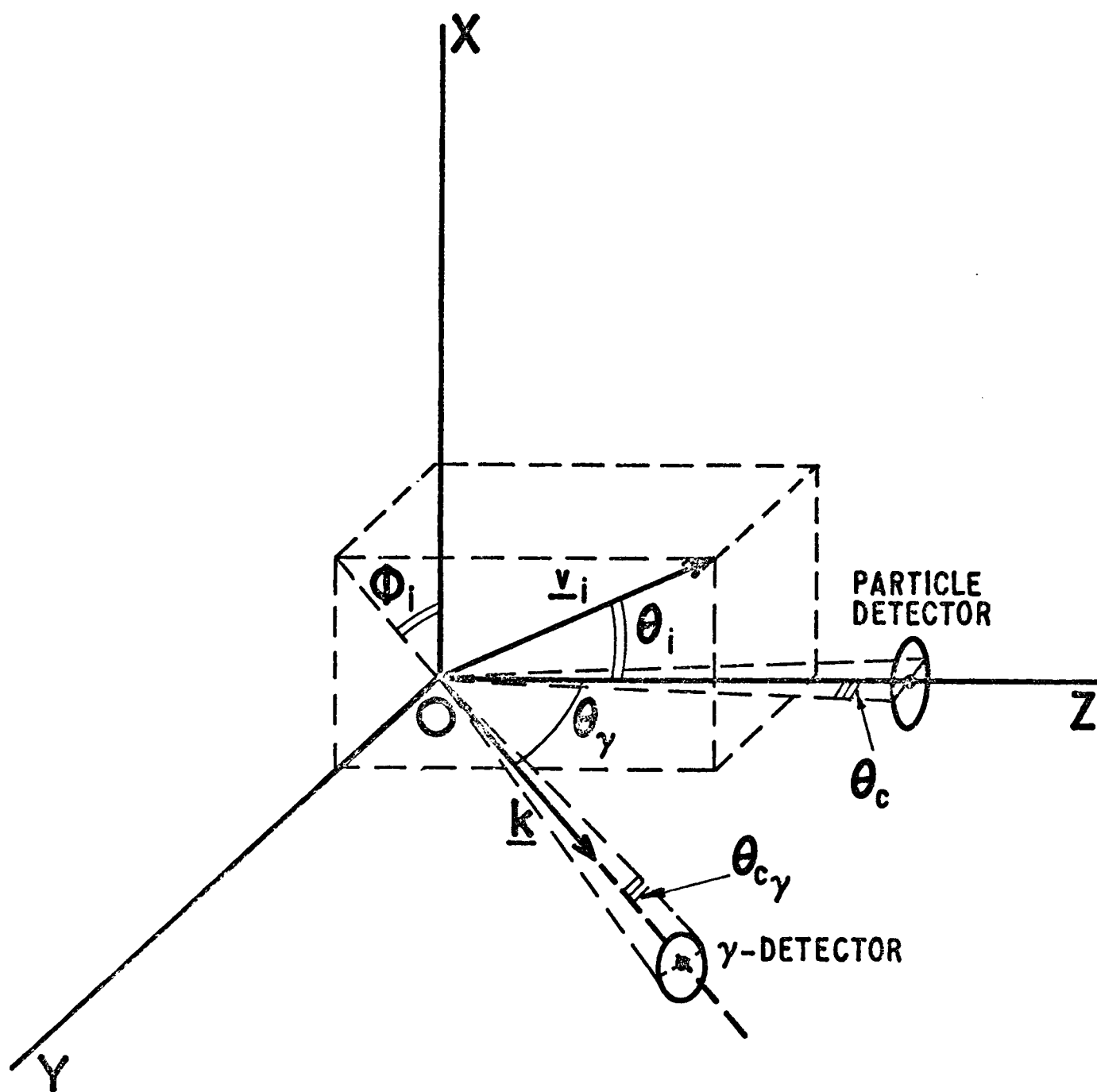


Fig.2.12 - Cartesian and spherical polar coordinate systems.

The attenuated Doppler shift is obtained after defining a full Doppler shift

$$\Delta E_F = \frac{E_\gamma}{c} \cos\theta_\gamma \langle v_o \cos\theta_o \rangle = \frac{E_\gamma}{c} \cos\theta_\gamma V_o \quad (2.5)$$

where  $\langle v_o \cos\theta_o \rangle = V_o$  is the mean recoil velocity at  $t = 0$ . As nuclear states decay exponentially with time the observed shift  $\Delta E$  corresponds to an integration over all decay times. The attenuated shift  $F$  (which is a function of the lifetime  $\tau$  of the excited state under consideration) is the ratio of the observed shift to the full shift,

$$F(\tau) = \frac{\Delta E}{\Delta E_F} = \frac{1}{\langle v_o \cos\theta_o \rangle} \frac{1}{\tau} \int_0^\infty e^{-t/\tau} \langle v_i \cos\theta_i \rangle dt \quad (2.6)$$

The mean recoil velocity at  $t = 0$ ,  $V_o (= \langle v_o \cos\theta_o \rangle)$ , can either be measured experimentally - as described in section 4.3 - or calculated from the reaction kinematics provided the differential cross-sections are known. In this case, expanding the differential cross-section for formation of recoils in the centre of mass (CM) system in a series of Legendre polynomials,

$$\sigma_{CM}(\theta_{o_{CM}}) = \sum_{K \geq 0} a_K P_K(\cos\theta_{o_{CM}}),$$

and transforming to the laboratory frame, we obtain

$$V_o = \langle v_o \cos\theta_o \rangle = V_{CM} + \frac{a_1}{a_o} \frac{v_{o_{CM}}}{3} \quad (2.7)$$

where  $V_{CM}$  is the velocity of the CM,  $v_{oCM}$  is the velocity of the recoiling nuclei in the CM system (which is constant) and  $a_0$  and  $a_1$  are the coefficients in the  $K=0$  and  $K=1$  terms of the Legendre expansion of the angular distribution of recoils in the CM, respectively. Using the  $\gamma^{-1}$  kinematical coefficient one can write

$$v_{oCM} = \gamma^{-1} V_{CM} \quad (2.8a)$$

where

$$\gamma^{-1} = \left\{ \frac{m_2 m_4}{m_1 m_3} \left( 1 + \frac{m_1 + m_2}{m_2} \frac{Q}{E_1} \right) \right\}^{\frac{1}{2}} \quad (2.8b)$$

for a reaction  $m_2(m_1, m_4)m_3^*$ .  $E_1$  is the bombarding energy and  $Q = Q_0 - E_x$  ( $Q_0$  is the ground state  $Q$ -value and  $E_x$  the nuclear level excitation energy). Therefore, inserting (2.8a) in (2.7), we obtain

$$V_o = V_{CM} \left( 1 + \frac{a_1}{a_0} \frac{\gamma^{-1}}{3} \right) \quad (2.9)$$

If however, the outgoing particles are detected so that the  $\gamma$ -decay of a particular state is measured in coincidence with the particle group populating that state, a narrow cone of recoiling nuclei can then be defined (by having a detector with small angular acceptance). The mean initial recoil velocity is therefore uniquely determined

$$V_o = \langle v_o \cos \theta_o \rangle_{\theta_c} \quad (2.10)$$

as for  $\theta_c$  small (the half angle of the cone subtended at the target by the particle detector) the cross section can safely be assumed as isotropic. This procedure was followed in the lifetime measurements reported in chapter 6.

When the full Doppler shift is calculated from kinematics the finite geometry of the  $\gamma$ -detector has to be taken into account; in the case of an isotropic  $\gamma$ -distribution over the face of the counter (or for small  $\theta_{c\gamma}$ ) the correction takes the form of a multiplication by the geometrical  $Q_1$  factor (Gi67).

A much more difficult task is the evaluation of the integral in (2.6), because of the time dependent term  $\langle v_i \cos \theta_i \rangle$ , as a strong correlation exists between  $v_i$  and  $\cos \theta_i$  due to the slowing down mechanisms. The approximation  $\langle v_i \cos \theta_i \rangle = \langle v_i \rangle \langle \cos \theta_i \rangle$  is however usually made in order to simplify the evaluation of (2.6). This approximation is justified below. Blaugrund (Bl66) formulated a method based on multiple scattering theory to evaluate the expectation value of  $\cos \theta_i$ . In this method the quantity  $\langle \cos \theta_i \rangle$  is a function of time, varying smoothly from the value 1 (at  $t = 0$ ) to the value 0, as the recoils slow down in the stopping material. However, an approximation is made in (Bl66) when transforming quantities from the CM frame to the laboratory frame so that  $\langle \cos \theta_i \rangle$  should be accurate only for  $r < 1$  ( $r$  being the ratio of the mass number of the recoiling ion to the one of the slowing down medium); but for  $r \gtrsim 1$  the scattering angles are small and therefore have very little effect on the Doppler shift. Currie (Cu69) tested Blaugrund's method of evaluating  $\langle \cos \theta_i \rangle$  by means of

Monte Carlo calculations of the recoil of  $^{30}\text{Si}$  ions in different materials as a function of energy. The validity of the approximation  $\langle v_i \cos \theta_i \rangle = \langle v_i \rangle \langle \cos \theta_i \rangle$  was also checked using the Monte Carlo approach. It was found that the average quantities calculated using Blaugrund's formulae deviate little from the Monte Carlo ones (in the worst case tested -  $r=2$  - the deviations are  $<15\%$  for recoiling energies  $<100$  keV). Currie (Cu69) therefore concluded that, for lifetime measurement analyses based on centroid shifts, both the assumption  $\langle v_i \cos \theta_i \rangle = \langle v_i \rangle \langle \cos \theta_i \rangle$ , and the treatment of  $\langle \cos \theta_i \rangle$  as prescribed in (Bl66) are valid.

$F(\tau)$  can thus be written

$$\begin{aligned} F(\tau) &= \frac{1}{V_0 \tau} \int_0^\infty e^{-t/\tau} \langle v_i \rangle \langle \cos \theta_i \rangle dt = \\ &= \frac{1}{V_0 \tau} \int_{E_0}^0 e^{-t/\tau} \frac{\langle \cos \theta_i \rangle}{\frac{dE}{dx}} dE \end{aligned} \quad (2.11)$$

where  $\frac{dE}{dx}$  is the stopping power for the recoiling ions in the slowing down material. The integral of (2.11) is thus in a form amenable to computation and the  $F(\tau)$  values calculated in a suitable form to be compared with the experimental one,  $\frac{\Delta E}{\Delta E_F}$ . However, the estimation of  $\frac{dE}{dx}$  is still a very problematic feature of this method.

It is convenient to distinguish two different mechanisms in the stopping of ions in solids, namely a nuclear (or atomic) stopping and an electronic stopping. The first arises from elastic scattering from the atoms of the solid,

the second from the atomic excitation and ionisation caused by the motion of the recoiling ion. Deviations from the initial trajectory are therefore very small in the case of electronic stopping and considerable in the case of nuclear stopping. Nuclear stopping contributes appreciably to the total energy loss at low recoiling velocities -  $v < 0.5\%c$ , which is the range of velocities encountered in the lifetimes measured in this work - whereas for recoils of higher energy electronic stopping is the dominating slowing down mechanism. The stopping cross sections employed in the DSAM analysis are usually taken from the theory of Lindhard, Scharff and Schiøtt (LSS) (Li63) which is based upon the Thomas-Fermi statistical model of the atom. A vast amount of experimentally determined stopping powers are available to test the LSS theory (see (Hv68) and further references therein, and the references quoted in (No70) ). However, no systematic study of experimental stopping cross sections covering the whole range of recoiling ions, stopping materials and recoil velocities which can be encountered in DSAM measurements has yet been completed. From the different electronic stopping power measurements available, those more amenable to a systematic check of the LSS predictions in the case of light recoiling ions are (Or65, Fa66, Hv68). These measurements have been done for ions with atomic number  $Z < 40$  but only in cases where the recoiling material was either boron (for  $V_0/c = 0.22\%$ ), carbon (for  $V_0/c = 0.22\%$ ,  $0.44\%$  and  $0.66\%$ ) or aluminium (for  $V_0/c = 0.22\%$ ). The measured electronic stopping powers show an oscillatory behaviour around the LSS predictions when plotted versus  $Z$ .

The deviations due to these oscillations however, may amount to 50% in the worst cases (for  $v^0/c = 0.22\%$ ). The origin of the fluctuations is not well understood; but as it provides a reasonable mean value to the experimental data, the LSS theory is usually adopted in DSAM determinations.

The procedure followed in DSAM analyses is therefore still to correct in first approximation the stopping powers calculated from the LSS theory by adequate multiplicative factors  $f_e$  and  $f_n$ . These factors whenever possible are extracted from a comparison with experimental stopping power data. However, as no experimental systematic study of stopping powers has yet been made the corrections cannot be applied consistently in most cases. This is at present the main difficulty inherent to the Doppler shift attenuation method.

The adequacy of the LSS theory and the DSAM reliability are further discussed in section 4.4.

### 2.2.3 The Doppler shift recoil-distance (plunger) method

As outlined in section 2.2.1, the measurement of the time of flight of nuclei can serve as a reference to enable the determination of the decay lifetimes of excited nuclear states. The plunger method (Al65, Jo69) to be described in this section is a more direct method. If the velocity distribution of the recoiling nuclei is known or can be calculated it only requires the measurement of the recoil flight path length.

The excited final nuclei are produced by a nuclear

reaction in a thin target, to allow them to recoil into vacuum with velocities as near as possible to the velocity  $v_0$  with which they were formed. A metal stopper placed near to the target stops the recoiling nuclei. The  $\gamma$ -rays emitted during the flight are fully Doppler shifted while those emitted after slowing down in the stopper will be unshifted. The good resolution of a Ge(Li) detector will enable the two resulting peaks due to Doppler effect to be separated. Therefore, the comparison of the intensities of the shifted and unshifted peaks as a function of the target to stopper distance leads to a determination of the lifetime of the excited state. The full Doppler shift obtained is (in the notation of the previous sections)

$$\Delta E_F = \frac{E_\gamma}{c} \cos\theta_\gamma \langle v_0 \cos\theta_0 \rangle = E_\gamma \frac{V_0}{c} \cos\theta_\gamma \quad (2.5)$$

where  $V_0$  is the mean recoil velocity.  $V_0$  can then be derived from a measurement of the full Doppler shift or alternatively calculated from the reaction kinematics. In this case however, the differential cross section for formation of recoils in the centre of mass system must be known. An additional restriction imposed by <sup>a</sup>particle detection can substantially ease this determination (see p.31).

If the stopper is placed at a distance  $D_0 = V_0 t$  from the target the intensity of the resulting shifted and unshifted peaks will be

$$\begin{aligned} n_s &= n [1 - \exp(-D_0/V_0 \tau)] \\ n_0 &= n \exp(-D_0/V_0 \tau) \end{aligned} \quad (2.12)$$

respectively, where  $n$  is the number of excited nuclei produced in the target and  $\tau$  the lifetime of the nuclear level. The ratio  $R$  of unshifted to total number of counts

$$R = \frac{n_o}{n_o + n_s} = \exp(-D_o/v_o \tau) \quad (2.13)$$

measured as a function of  $D_o$  determines the value of  $\tau$ . Great care has to be taken to prevent the stopper being contaminated by the target material. If this is unavoidable a correction must be applied that takes care of the yield increase in the unshifted peak due to this contamination. For example, in the  $^{18}\text{Ne}$  lifetime measurements reported in chapter 5 the reaction used was  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$ . It is difficult to prevent oxygen contamination of the stopper surface and, consequently, this had to be taken into account in the data evaluation of this experiment. This is done in the following way. The intensity of the unshifted peak is now

$$n_o = n_I + n \exp(-D_o/v_o \tau) \quad (2.14)$$

where  $n_I$  is the relative yield from the stopper, and the ratio  $R$  therefore becomes

$$\begin{aligned} R &= \frac{n_o}{n_o + n_s} = \frac{n_I + n \exp(-D_o/v_o \tau)}{n_I + n} = \\ &= \frac{n}{n_I + n} \exp(-D_o/v_o \tau) + \frac{n_I}{n_I + n} \end{aligned} \quad (2.15)$$

The contamination of the stopper is reflected in a constant value of  $R (= \frac{n_I}{n_I+n} \neq 0)$  for large distances. However, the level of contamination must be monitored during the course of the experiment as target evaporation onto the stopper may occur, thus leading to a time dependence of  $n_I$  which has to be corrected for. In the mentioned  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction, the level of contamination was measured from the ratio  $R$  of the  $1887 \rightarrow 0$   $\gamma$ -ray obtained in coincidence with the neutron group populating the first excited state of  $^{18}\text{Ne}$ , as described in p.97. It was found that for lifetime determinations involving small measuring times, such as for the 3376 keV state in  $^{18}\text{Ne}$  (which was studied in singles experiments), the degree of contamination remained approximately constant during the data accumulation process ( $R \simeq 0.25$ , see p.94 ). However, in coincidence measurements, such as the determination of the  $^{18}\text{Ne}$  3576 keV level lifetime, the variation of the contamination level as a function of time had to be taken into account in the extraction of  $D_0/V_0\tau$  from expression (2.15).

The plunger method described above can be used to measure lifetimes in the range  $10^{-8} - 2 \times 10^{-12}$  s. For lifetimes longer than  $\sim 10^{-9}$  s direct timing methods may be employed. The main limitations of the plunger method for short lifetime measurements are due to the finite stopping time of the recoils in the metal stopper and to the possibility of accurate determination of the small separation distances between target and stopper. It results from these two conditions that the lower lifetime limit of

plunger applicability is  $\sim 2$  ps. The characteristic distance involved ( $D = V_0 \tau$ ) in a 2 ps lifetime measurement is of the order of  $6 \mu\text{m}$  ( $\simeq 0.25$  thou.) for  $V_0/c = 1\%$ .

#### 2.2.4 Description of the plunger apparatus

The plunger used in the  $^{18}\text{Ne}$  lifetime measurements described in chapter 5 is shown schematically in fig.2.13. This apparatus was designed by Gill (Gi71) based on the recoil-distance equipment of Jelley, Jones and Weaver (Je72).

The metal stopper used was a disc of optically polished tungsten which was mounted on a water-cooled aluminium block. The targets are evaporated onto  $5 \text{ mg.cm}^{-2}$  gold foils prestretched by means of an O-ring so that they are also optically flat. The target assembly is mounted on a parallel plate system which can be moved by a high precision 50 thou. differential screw micrometer (1 thou. =  $25.4 \mu\text{m}$ ). Each complete turn of the micrometer displaces the plunger by 1.25 thou. allowing therefore great accuracy in the determination of the target position. The design of the apparatus allows thermal expansions under changeable beam regimes to be safely neglected, as the water cooling is used to dissipate the heat produced by the beam in the tungsten disc (which also serves as the beam stop). Investigations were made on possible thermal expansions. Using the  $\gamma$ -rays corresponding to the transitions  $891 \rightarrow 0$ ,  $1528 \rightarrow 0$  and  $2210 \rightarrow 657$  in  $^{22}\text{Na}$  and  $1275 \rightarrow 0$  in  $^{22}\text{Ne}$ , populated with the  $^{19}\text{F}(\alpha, n)$  and  $^{19}\text{F}(\alpha, p)$  reactions, respectively several runs at the same target positions were made. Different beam currents (in the range 50-400 nA)

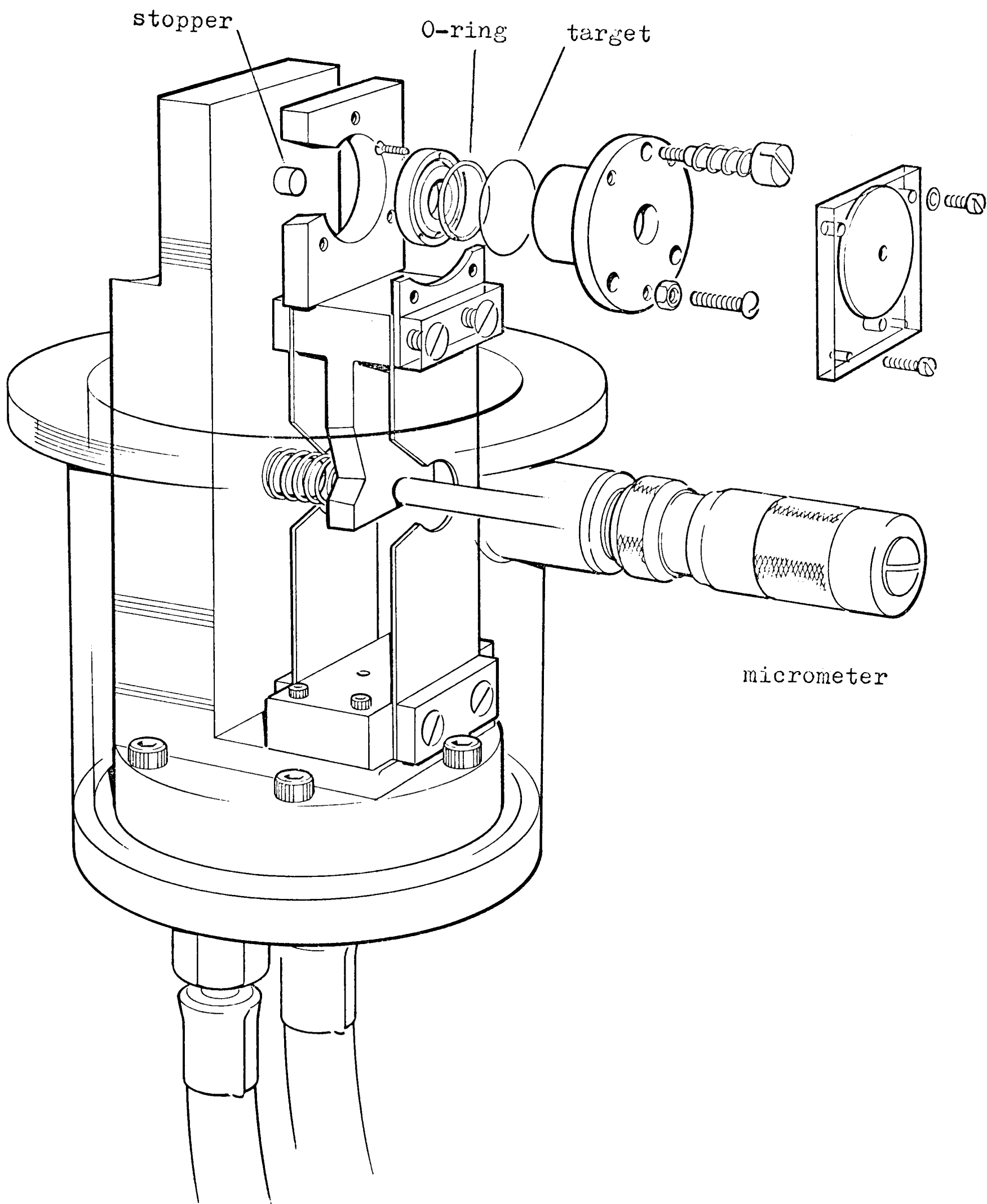


Fig.2.13 - Schematic diagram of the plunger apparatus.

for each target position were employed in order to measure possible variations in the ratio  $R$ . As a result, we observed that the experimental ratios remained remarkably constant within errors, thus leading to the conclusion that very stable experimental conditions are obtained with the plunger apparatus.

The whole apparatus could be mounted on an optical bench so that both the zero of the micrometer and the parallelism of target and plunger could be established by means of a Michelson interferometer. The mirror along one of the arms was either the tungsten stopper or the back of the gold foil, whereas the mirror along the other arm could be adjusted with a calibrated screw drive. The fringes produced by the light of a mercury arc source enabled the inspection of the flatness of the foil (which was found to be of the order of  $1\text{ }\mu\text{m}$ ) and the alignment of the target parallel to the stopper. The use of white light fringes allowed both a check of the linearity of the micrometer screw (in the range 0-40 thou.) and the determination of the zero of the micrometer (after correcting the target-stopper distance for the thickness of the gold foil) to be made. The minimum separation possible between the target and stopper (due to dust grains on the target) was found to be  $\sim 0.5$  thou.

The reactions  $^{19}\text{F}(\alpha, n)^{22}\text{Na}$  ( $Q = -1.951\text{ MeV}$ ) and  $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$  ( $Q = 1.675\text{ MeV}$ ) at 7 MeV  $\alpha$  bombarding energy were used to check the consistency of the results obtained with the plunger apparatus as a comparison could be made with the measurements of Jones et al. (Jo69) published

in the literature. A  $\text{CaF}_2$  target  $50 \mu\text{g}\cdot\text{cm}^{-2}$  thick evaporated onto a gold foil of thickness  $5 \text{ mg}\cdot\text{cm}^{-2}$  was used. The beam energy loss in the foil was  $\sim 700 \text{ keV}$  so that the mean energy at the target was  $\sim 6.3 \text{ MeV}$ . The  $\gamma$ -rays were detected in a  $36 \text{ cm}^3$  active volume  $\text{Ge(Li)}$  detector with  $2.3 \text{ keV}$  resolution measured for the  $1332 \text{ keV}$   $^{60}\text{Co}$  line. The  $\gamma$ -counter was placed at  $0^\circ$  with respect to the beam axis and at  $6.8 \text{ cm}$  distance from the target. Spectra taken at target-stopper distances  $D_0 = 1, 3$  and  $5$  thou. for an integrated charge of  $\sim 400 \mu\text{C}$  are plotted in fig.2.14. The  $\gamma$ -rays shown correspond to the  $891 \rightarrow 0$ ,  $1528 \rightarrow 0$  and  $2210 \rightarrow 657$  transitions in  $^{22}\text{Na}$  and to the  $1275 \rightarrow 0$  transition in  $^{22}\text{Ne}$  (the energies indicated are in keV).  $V_0$  was extracted in each case from the measured full Doppler shift. The results of the analysis of spectra similar to those of fig.2.14 for target-stopper distances ranging from  $0.8$  to  $7$  thou. are presented in the table 2.1 below, where the measurements of Jones et al. (Jo69) are also shown for comparison.

| <u>Table 2.1</u> |         |                        |                                |                       |
|------------------|---------|------------------------|--------------------------------|-----------------------|
| Nucleus          | E (keV) | Transition             | Our measurement<br>$\tau$ (ps) | (Jo69)<br>$\tau$ (ps) |
| $^{22}\text{Na}$ | 891     | $891 \rightarrow 0$    | $13.3 \pm 1.9$                 | $14.1 \pm 0.7$        |
| $^{22}\text{Ne}$ | 1275    | $1275 \rightarrow 0$   | $3.9 \pm 0.9$                  | $4.6 \pm 0.5$         |
| $^{22}\text{Na}$ | 1528    | $1528 \rightarrow 0$   | $4.8 \pm 1.0$                  | $5.0 \pm 0.7$         |
| $^{22}\text{Na}$ | 2210    | $2210 \rightarrow 657$ | $16.9 \pm 2.4$                 | $20.8 \pm 1.0$        |

It can be seen that good agreement exists between the results of (Jo69) and ours.

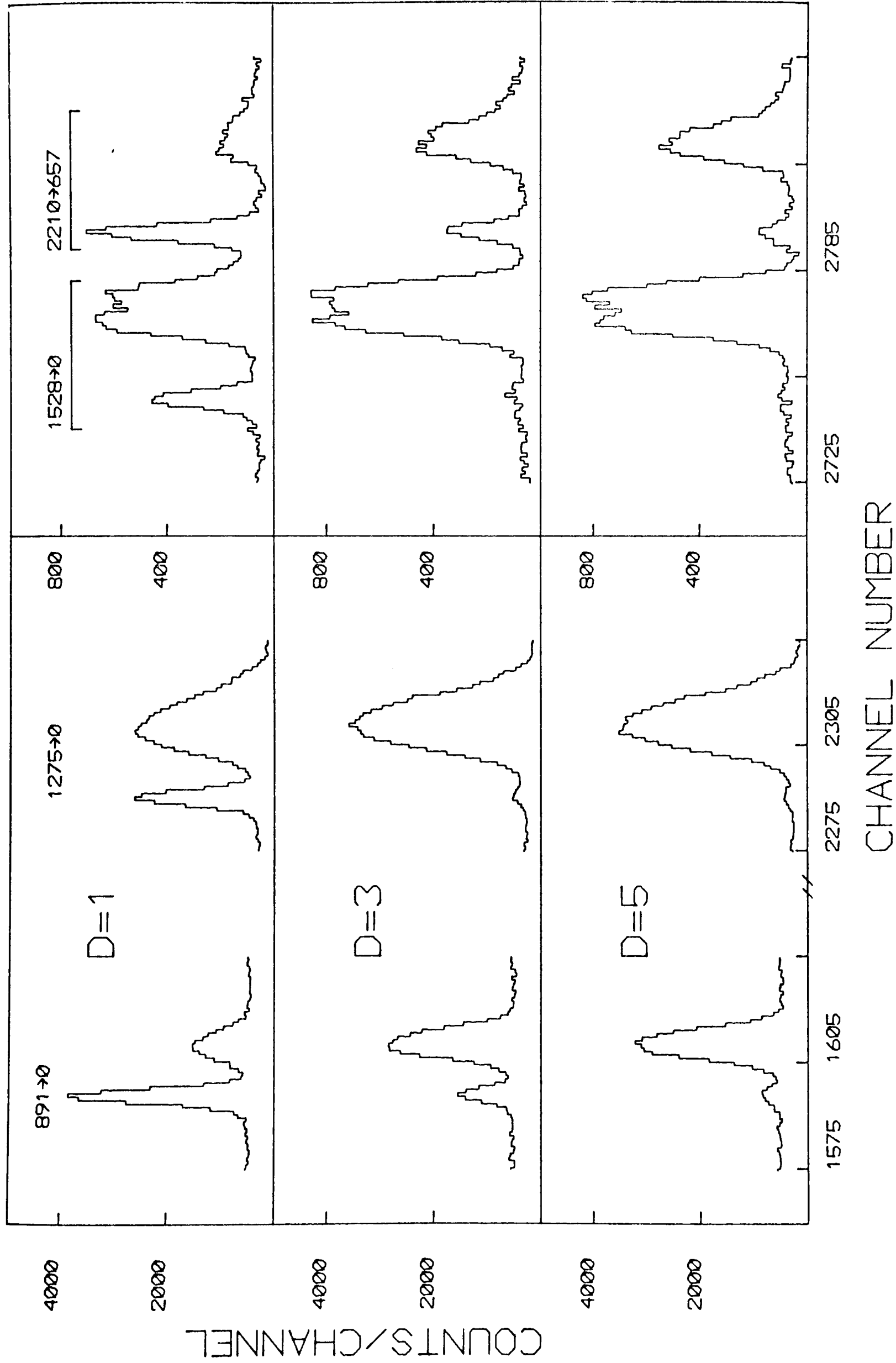


Fig.2.14 - Relevant parts of  $\gamma$ -spectra taken at distances  $D_0=1, 3$  and  $5$  thou.

### 3. Electromagnetic Deexcitation Theory and Data Analysis

#### 3.1 Angular correlation theory

Electromagnetic transitions in nuclei are a useful source of information about nuclear configurations and provide much more severe tests to wave functions than the simple sequence of nuclear levels, spins and parities. This is because the electromagnetic interaction is well known and consequently there are no uncertainties in the calculation of matrix elements other than from the wave functions themselves. The technique of measuring angular distributions of  $\gamma$ -rays emitted during a nuclear reaction is widely used for determining the mixing ratios of different multipoles and spins of excited states. Mixing ratios, spins and population parameters of the initial state excited by the reaction thus are free parameters to be determined from an experiment. It is obvious that the geometry in which the angular distribution measurement is made will put restrictions onto the number of these free parameters. In the "method II" of Litherland and Ferguson (Li61) employed in the angular correlations measured in this work the particles populating the nuclear level studied are detected on the beam axis and the  $\gamma$ -rays arising from the decay are measured in coincidence with the particle group. The system has cylindrical symmetry about the beam direction which is taken as quantization axis. Therefore, the population of magnetic substates of the excited state concerned is restricted to those with magnetic quantum numbers not higher than the algebraic sum of the spins of the incident particle, target nucleus and outgoing particle

(see page 49 ). Further, the analysis of the particle gamma correlations is simplified. Because of the axial symmetry, it depends on only one angle ( $\theta$ ), between the  $\gamma$ -detector and the direction defined by the beam.

As the electromagnetic interactions are believed to be time reversal invariant (as well as the nuclear structure equations) one can, using a time reversal transformation (as opposed to the use of the theorem of "detailed balance"), relate in a general way an emission to an absorption process and thus treat the emission process semiclassically, rather than using quantum field theory. In the phase consistent Rose and Brink treatment (Ro67) - which is followed below - the angular distribution formulae are expressed in terms of phase defined reduced matrix elements and in terms of population parameters. The latter set of parameters describes the alignment of the magnetic substates of the excited state studied.

If the nuclear forces are local the interaction Hamiltonian for a nucleus in the presence of a classical electromagnetic field is

$$H_{\text{int}} = \frac{-e\hbar}{2mc} \sum_{k=1}^A [2g_{\ell_k} \underline{p}_k \cdot \underline{A}(\underline{r}_k) + g_{s_k} \underline{s}_k \cdot \underline{H}(\underline{r}_k)] \quad (3.1)$$

where  $\underline{H} = \text{curl } \underline{A}$ ,  $\underline{p}_k = -i\nabla_k$ ,  $\underline{s}_k = \frac{1}{2} \underline{\sigma}_k$  and  $g_{\ell_k}$  and  $g_{s_k}$  are the orbital and spin g factors for the kth nucleon, respectively. If the subscripts p are applied to protons and n to neutrons then

$$\begin{aligned} g_{\ell_p} &= 1 & g_{s_p} &= 5.585 \\ g_{\ell_n} &= 0 & g_{s_n} &= -3.826 \end{aligned} \quad (3.2)$$

As the initial and final states in the  $\gamma$ -decay of the nucleus are quantum mechanical states, specified by quantum numbers  $\alpha_1 J_1 M_1$  ( $|\alpha_1 J_1 M_1\rangle$  for the initial and  $|\alpha_2 J_2 M_2\rangle$  for the final states) a spherical representation for the vector potential  $\underline{A}$  is needed. A phase consistent expansion of  $\underline{A}$  (which is chosen to be a plane circularly polarised wave) is made in terms of spherical multipoles using the long wavelength approximation. The interaction Hamiltonian can then be expanded in terms of well defined interaction multipole operators with definite hermitian and time reversal properties. The angular distribution formulae are thus derived in a phase consistent way and can be related unambiguously to the calculations of nuclear structure models.

The initial state in the  $\gamma$ -decay can be described as a statistical superposition of pure angular momentum states  $\sum_{M_1} w(M_1) |J_1 M_1\rangle$  in the case of cylindrical symmetry. Then, the radiative probability for photons with wave vector  $\underline{k}$  and polarisation  $q$ , corresponding to the transition

$J_1 \rightarrow J_2$  (if the orientation of  $J_2$  is not observed) is (Ro67)

$$\begin{aligned}
 P^q(\underline{k}) = & \frac{k}{2\pi\hbar} \sum_{KLL'\pi\pi'} B_K(J_1) P_K(\cos\theta) (-)^{q+J_1-J_2+L'-L-K} (2J_1+1)^{\frac{1}{2}} \times \\
 & \times (LL'q-q|KO) W(J_1 J_1 LL'; KJ_2) q^{\pi+\pi'} \times \\
 & \times \langle J_1 \| T_L^{\langle\pi\rangle} \| J_2 \rangle \langle J_1 \| T_{L'}^{\langle\pi'\rangle} \| J_2 \rangle^* \quad (3.3)
 \end{aligned}$$

where  $\langle J_1 \| T_L^{\langle\pi\rangle} \| J_2 \rangle$  are the reduced matrix elements

corresponding to the interaction multipole operators  $T_{LM}^{<\pi>}$ ,  $L, L'$  are the transition multipolarities and the values of  $\pi, \pi'$  are 0 for electric and 1 for magnetic transitions ( $<\pi>$  serving as a label for electric or magnetic),

$$B_K(J_1) = \sum_{M_1} w(M_1) (-)^{J_1-M_1} (2J_1+1)^{\frac{1}{2}} (J_1 J_1 M_1 -M_1 | K0) \quad (3.4)$$

with  $B_0(J_1) = 1$  and  $\sum_{M_1} w(M_1) = 1$

The operators  $T_{LM}^{<\pi>}$  are defined as

$$T_{LM}^{<\pi>} = \alpha_L^{<\pi>} G_{LM}^{<\pi>} \quad (3.5a)$$

$$\text{where } \alpha_L^e = i\alpha_L^m = [(ik)^L / (2L-1)!!] [(L+1)/2L]^{\frac{1}{2}} \quad (3.5b)$$

and the  $G_{LM}^{<\pi>}$  are the multipole operators

$$G_{LM}^e = Q_{LM} + Q'_{LM}, \quad G_{LM}^m = M_{LM} + M'_{LM} \quad (3.5c)$$

with  $Q_{LM} = 2g_\ell (m\beta/\hbar^2 k) [H, r^L C_{LM}]$

$$Q'_{LM} = -g_s \beta [k/(L+1)] \underline{L}(r^L C_{LM}) \cdot \underline{s} \quad (3.5d)$$

$$M_{LM} = 2g_\ell \beta (L+1)^{-1} \underline{\nabla}(r^L C_{LM}) \cdot \underline{\ell}$$

$$M'_{LM} = g_s \beta \underline{\nabla}(r^L C_{LM}) \cdot \underline{s}$$

where  $\beta$  is the nuclear magneton ( $= \frac{e\hbar}{2mc}$ ) and  $H$  is the total Hamiltonian of the nuclear system. The operators in equations

(3.5a, c and d) are single particle operators. Of course, when inserted in matrix elements involving many particle states they are always understood <sup>as</sup> a sum over all particles.

In the angular correlations studied in this work both the beam and the target were unpolarised. Then, as parity is conserved, the magnetic substates of the initial spin  $J_1$  with the same value of  $|M_1|$  are equally populated, i.e.

$$w(+M_1) = w(-M_1) \quad (3.6)$$

and the initial state is said to be aligned.  $B_K(J_1)$  can thus be written

$$B_K(J_1) = \sum_{M_1=0 \text{ or } 1/2}^{J_1} w(M_1) \rho_K(J_1 M_1) \quad (3.7)$$

$$\text{with } \rho_K(J_1 M_1) = (2 - \delta_{0, M_1}) (-)^{J_1 - M_1} (2J_1 + 1)^{\frac{1}{2}} (J_1 J_1 M_1 -M_1 | K 0)$$

The measurement of angular distributions provides information about the relative magnitudes and signs of the reduced matrix elements (which are real). It is then usual to define the multipole mixing ratios as

$$\delta_L^{\langle \pi \rangle} = \frac{\langle J_1 \| T_L^{\langle \pi \rangle} \| J_2 \rangle / (2L+1)^{\frac{1}{2}}}{\langle J_1 \| T_{\bar{L}}^{\langle \bar{\pi} \rangle} \| J_2 \rangle / (2\bar{L}+1)^{\frac{1}{2}}} \quad (3.8)$$

where  $\bar{L}$ ,  $\bar{\pi}$  correspond to the lowest multipole present in the

decay. The sum of the square moduli of the reduced matrix elements can be extracted from the measurement of the lifetime of the initial state  $J_1$  (or from an absolute yield measurement in the case of a capture reaction). The lifetime of the transition  $J_1 \rightarrow J_2$  is obtained from (3.3) by summing over the polarisations  $q$  and integrating over all  $\underline{k}$ ,

$$\tau^{-1} = \frac{\Gamma}{\hbar} = \sum_q P^q(\underline{k}) d\Omega = \frac{4k}{\hbar} \sum_{L\pi} \frac{|\langle J_1 || T_L^{(\pi)} || J_2 \rangle|^2}{2L+1} \quad (3.9)$$

where  $\Gamma$  is the transition width.

For the typical sizes of nuclei and energies of  $\gamma$ -rays encountered the product  $kR$  (where  $R$  is the radius of the nucleus) is of the order of 0.1, which thus justifies the long wavelength approximation made earlier. Also, it implies that in general only the lowest multipoles will contribute to the transition. In this case, and if the initial and final states have definite parity and  $\gamma$ -polarisation is not measured, the angular distribution/<sup>formula</sup>for the electromagnetic transition  $J_1 \rightarrow J_2$  can then be written

$$W(\theta) = \sum_{K \text{ even}} B_K(J_1) R_K(J_1 J_2) P_K(\cos\theta) \quad (3.10)$$

where

$$R_K(J_1 J_2) = \frac{R_K(\bar{L} \bar{L} J_1 J_2) + 2\delta R_K(\bar{L} \bar{L}' J_1 J_2) + \delta^2 R_K(L' L' J_1 J_2)}{1 + \delta^2} \quad (3.11)$$

and

$$R_K(\bar{L} \bar{L}' J_1 J_2) = (-)^{1+J_1-J_2+L'-\bar{L}-K} [(2J_1+1)(2\bar{L}+1)(2L'+1)]^{\frac{1}{2}} \times \\ \times (\bar{L} \bar{L}' 1 - 1 | K 0) W(J_1 J_1 \bar{L} \bar{L}'; K J_2) \quad (3.12)$$

with  $B_K(J_1)$  defined in (3.7). Only one mixing ratio ( $\delta$ ) is sufficient in this case to describe the decay, and from (3.8)

$$\delta = \frac{\langle J_1 \| T_{L'}^{<\pi'>} \| J_2 \rangle / (2L'+1)^{\frac{1}{2}}}{\langle J_1 \| T_{\bar{L}}^{<\bar{\pi}>} \| J_2 \rangle / (2\bar{L}+1)^{\frac{1}{2}}} \quad (3.13)$$

with  $L' = \bar{L}+1$ . The triangular conditions

$$0 \leq K \leq 2J_1, \quad |J_1 - J_2| \leq L \leq J_1 + J_2 \quad (3.14)$$

governing the decay, arise from the coefficients in (3.7) and (3.12). The nuclear alignment is described by  $B_K(J_1)$  and the nuclear structure information about the transition is contained in  $R_K(J_1 J_2)$  of formula (3.10). This expression is thus in a suitable form to be compared with experimental angular distributions, i.e. the theoretical distribution will be of the form

$$W_{th}(\theta) = \sum_{K \text{ even}} A_K P_K(\cos\theta) \quad (3.15)$$

Corrections due to the finite size of the  $\gamma$ -detector will be discussed in the following section.

In the case where the initial nuclear state decays through a cascade of  $\gamma$ -rays and only the  $n^{\text{th}}$   $\gamma$ -ray belonging to the decay is observed, the nuclear alignment parameter  $B_K(J_1)$  is to be replaced by

$$B_K^{(n)}(J_1) = B_K(J_1) \prod_{i=1}^{n-1} U_K(J_i J_{i+1}) \quad (3.16)$$

with

$$U_K(J_1 J_2) = \frac{U_K(\bar{L}_{12} J_1 J_2) + \delta_{L_{12}}^2 U_K(L'_{12} J_1 J_2)}{1 + \delta_{L_{12}}^2} \quad (3.17)$$

and

$$U_K(L_{12} J_1 J_2) = (-)^K \frac{W(J_1 J_1 J_2 J_2; KL_{12})}{W(J_1 J_1 J_2 J_2; OL_{12})} \quad (3.18)$$

where  $\bar{L}_{12}$  is the lowest multipolarity in the (unobserved)

$J_1 \rightarrow J_2$  decay,  $\delta_{L_{12}}$  is its mixing ratio and  $L'_{12} = \bar{L}_{12} + 1$ .

In the measurement of the  $\gamma$ -decay of the 3616 keV state in  $^{18}\text{Ne}$  described in chapter 5, both the (3.10) and (3.10 $\otimes$ 3.16) formulae were applied as the initial level decays to both the 1887 keV and the ground state, thus giving rise to 3  $\gamma$ -rays ( $3616 \rightarrow 0$ ,  $3616 \rightarrow 1887$  and  $1887 \rightarrow 0$ ).

## 3.2 Geometry corrections and data analysis

### 3.2.1 Corrections due to finite size of detectors

In the cases of cylindrical symmetry, e.g. when the emergent particles from the target are detected on the beam axis (which is then taken as an axis of quantization) the projections on this axis of the orbital angular momenta of the incident and outgoing particles are identically zero. Therefore, the magnetic substates ( $M_1$ ) of the initial state  $J_1$  are populated only if

$$|M_1| \leq M_{1\text{Max}} = J_T + s_i + s_o \quad (3.19)$$

where  $J_T$ ,  $s_i$  and  $s_o$  are the spins of the target, incident

and outgoing particles, respectively. The alignment condition (3.6) is in this case also fulfilled.

For example, in the  $^{16}_0(^3\text{He},n)^{18}\text{Ne}$  reaction (see chapter 5) the only substates in  $^{18}\text{Ne}$  populated are  $M_1 = 0$  and  $M_1 = \pm 1$ . Due to the alignment of the initial state and to the normalisation condition  $\sum_{M_1} w(M_1) = 1$  of (3.4) only one free population parameter is allowed which has to be determined from experiment.

However, as the particle detector has a finite size, even in a cylindrical symmetric geometry substates with  $|M_1|$  higher than the value allowed by (3.19) will be populated, and their contribution to the  $\gamma$ -decay has to be estimated. Of these, the most important substates have  $|M_1| = M_{1\text{Max}} + 1$  and the corresponding population parameters are proportional to  $\theta_{\text{cCM}}^2$

$$w(M_{1\text{Max}} + 1) = w(-M_{1\text{Max}} - 1) \propto \theta_{\text{cCM}}^2 \quad (3.20)$$

for small  $\theta_{\text{cCM}}$  (Ha66).  $\theta_{\text{cCM}}$  is the half angle of the cone in which the detector is seen in the centre of mass frame. The effect caused by the population of these substates can be readily checked by measuring angular correlations at different detector distances (different  $\theta_{\text{cCM}}$ ) or by including a population of a few per cent due to substates with  $|M_1| = M_{1\text{Max}} + 1$  in the analysis. It was found that for  $\theta_{\text{cCM}} \ll 10^\circ$  the population of these substates was too small to affect the  $\gamma$ -distribution (Ha66). Particularly in the case of the  $^{16}_0(^3\text{He},n)^{18}\text{Ne}$  reaction under consideration, Bell (Be69) (using a bombarding energy of 12 MeV and a

similar value of  $\theta_{c_{CM}}$  found that even a 5% population of the  $|M_1| = 2$  substates had no significant effect on the results.

As to the finite acceptance angle of the  $\gamma$ -detector employed to measure the angular distributions, its effect will be to attenuate (3.15). The measured distribution using a cylindrical  $\gamma$ -counter can then be described by

$$W_{\text{exp}}(\theta) = \sum_K A_K Q_K P_K(\cos\theta) = \sum_K a_K P_K(\cos\theta) \quad (3.21)$$

where  $Q_K$  are the geometrical attenuation factors (Ro53).

These factors are defined by

$$Q_K = \frac{J_K}{J_0}, \quad J_K = \int_0^\pi P_K(\cos\xi) E(\xi) \sin\xi \, d\xi \quad (3.22)$$

where  $E(\xi)$  is the detector efficiency for  $\gamma$ -rays travelling at an angle  $\xi$  with respect to the axis of the  $\gamma$ -detector.

The  $Q_K$  coefficients used in chapter 5 were calculated by Griffiths (Gr71) for the Ge(Li) detector employed in the n- $\gamma$  angular correlation experiments.

### 3.2.2 Data analysis; spin and mixing ratio determination

The result of an angular distribution measurement of the type discussed above is a set of  $N$   $\gamma$ -ray yields  $Y_i$  each with an associated error  $\xi_i$  obtained at angles  $\theta_i$ . In the cases where Ge(Li) detectors with high resolution and high peak to background ratio are used, the errors associated with the determination of the experimental yields  $Y_i$  will be statistical in nature (assuming of course that systematic

errors such as absorptions and charge normalisations have been properly corrected for).

The measured angular distribution  $W(\underline{a}, \theta)$  is fitted to a series of Legendre polynomials of the type (3.21) so as to minimise the quantity

$$\frac{S(\underline{a})}{f} = \frac{1}{f} \sum_{i=1}^N \left[ \frac{Y_i - A_0 \sum_K a_K P_K(\cos \theta_i)}{\epsilon_i} \right]^2 \quad (3.23)$$

where  $A_0$  is a normalisation constant and  $f$  the number of degrees of freedom; if  $p$  is the number of free parameters allowed in the fit, then  $f = N - p$ . The  $a_K$  are the product of  $Q_K$ ,  $B_K(J_1)$  and  $R_K(J_1 J_2)$  defined before. The free parameters  $p$  are in a typical case normalisation constants, population parameters and mixing ratios. This set of parameters in a particular measurement is represented by  $\underline{a} = (a_1, a_2, \dots, a_p)$ . In the case of a simultaneous fit to two or more  $\gamma$ -rays originating from the initial level and subsequent cascades (see chapter 5)  $S(\underline{a})$  will be the sum of the partial  $S(\underline{a})$ 's for each transition.

In order to determine the minimum (or minima) of  $S(\underline{a})/f$  and therefore obtain values for the set of free parameters allowed in the fit, the following procedure is used. As  $S(\underline{a})$  is a quadratic function of the normalisation constants the minimisation is carried out analytically by requiring

$$\frac{\partial S(\underline{a})}{\partial A_0} = 0, \text{ etc.} \quad (3.24)$$

However, due to the non-linear dependence of  $W(\underline{a}, \theta)$  on spins

and mixing ratios,  $S(\underline{a})$  is a much more complex function of these variables. The adopted procedure is then to map  $\frac{S(\underline{a})}{f}$  for several values of the mixing ratios (adequately stepped) and for all spin values which can be expected.  $S(\underline{a})/f$  is also usually mapped as a function of the population parameters in spite of the  $a_K$  being linear functions of  $w(M_1)$ .

If we assume the experimental yields  $Y_i$  to be normally distributed, the most probable values measured for the parameters are those which minimise  $S(\underline{a})$  as mentioned earlier. This minimum,  $S(\underline{a}^*)$ , follows a  $\chi^2$  distribution with  $f = N-p$  degrees of freedom (Br70).  $S(\underline{a})$  is a measure of "goodness of fit", and the expectation value of  $S(\underline{a}^*)$  for the "true" values of the parameters is  $f(=N-p)$ . However, one, two or more minima can be the result of the minimisation procedure described above. The confidence level associated with each minimum  $S(\underline{a}^*)$  can be determined using a  $\chi^2$  tabulation (e.g. (Wa59)). The usual adopted procedure whether to accept or reject a spin assignment is based on the consideration of established confidence limits of the  $\chi^2$  distribution (usually the 1% or the 0.1% confidence levels). The only spin assumptions retained are those which have lead to minima below those limits. However, this procedure is somewhat arbitrary as smaller  $S(\underline{a}^*)$  values can be obtained by simply increasing the errors  $\epsilon_i$ , so that ultimately a physicist's judgement, on how sharp and well defined a minimum in the  $S(\underline{a})$  distribution occurs, is required.

When a minimum is obtained which is accepted, the parameters  $\underline{a}^*$  (which minimise  $S(\underline{a})$ ) constitute the results

of the experiment (or just one of the possible results in the case of two or more accepted minima). Thus, the standard deviations from the expectation values  $\underline{a}^*$ , which are by definition the errors associated with the measured values, must be determined accordingly. This can be done in a rather direct manner for those parameters in which  $W(\underline{a}, \theta)$  is linear, e.g. normalisation constants, as the error matrix is then known - cf. (Ha66), formula (42). However, the situation is not so straightforward for non-linear parameters (such as mixing ratios). The method which has to be used then is described below.

In the estimation of errors associated with non-linear parameters, an exact method can be employed provided  $W(\underline{a}, \theta)$  is approximately linear in  $\underline{a}$  around the measured  $\underline{a}^*$ , i.e.

$$W(\underline{a}, \theta) = W(\underline{a}^*, \theta) + \sum_i \left[ \frac{\partial W(\underline{a}, \theta)}{\partial a_i} \right]_{\underline{a}^*} \Delta a_i + 0 \quad (3.25)$$

If no systematic errors are involved in the experiment the measured yields will be normally distributed; also, the linearity condition (3.25) will be satisfied in the cases where  $S(\underline{a})$  is sharply varying in the region of  $\underline{a}^*$  (particularly when mixing ratios are close to zero). The method followed here is based on the one described by Cline and Lesser (Cl70), the difference being in the treatment of standard deviations in the general case of  $p$  parameters, which is done incorrectly in (Cl70). Our method, which is equivalent to Davies' (Da71) agrees only with (Cl70) in the one parameter case.

The correct way to use the statistic given by  $S(\underline{a})$  to determine the standard deviation of any parameter  $\alpha_i$  (e.g. the E2/M1 mixing ratio  $\delta$  of the  $3616 \rightarrow 1887$  transition in the nucleus  $^{18}\text{Ne}$ , in chapter 5) is to vary  $S(\underline{a})$  (around  $S(\underline{a}^*)$ ) as a function of one parameter, say  $\alpha_i$ , adjusting all the other parameters  $\alpha_{j \neq i}$  to a local minimum (Li61a, Ar66). Then, if the linearity condition (3.25) is satisfied in the region of  $S(\underline{a}^*)$ , the resulting curve  $S(\underline{a})_{\alpha_i}$  is locally parabolic in shape (Ar66) and the difference  $S(\underline{a})_{\alpha_i} - S(\underline{a}^*)$  is distributed independently of  $S(\underline{a}^*)$  (Li61a). The difference  $S(\underline{a})_{\alpha_i} - S(\underline{a}^*)$  follows therefore a  $\chi^2$  distribution with one degree of freedom. Thus, the statistical F-distribution (e.g. tabulated by Abramowitz (Ab65)) can be used to estimate the value of  $S(\underline{a})_{\alpha_i}$  which corresponds to a standard deviation of  $\alpha_i$  from its expectation value  $\alpha_i^*$ . Thus, as the  $Y_i$  are normally distributed and (3.25) holds, we have by definition

$$F(1, N-p, 1-\beta) = \frac{[S(\underline{a})_{\alpha_i} - S(\underline{a}^*)]/1}{S(\underline{a}^*)/(N-p)} \quad (3.26)$$

where  $\beta$  is a confidence level (Br70).  $\beta = 0.317$  corresponds to the one standard deviation limit. Hence, from (3.26)

$$\frac{S(\underline{a})_{\alpha_i}}{S(\underline{a}^*)} = 1 + \frac{F(1, N-p, 1-\beta)}{N-p} \quad (3.27)$$

The values of  $\alpha_i$  that cause  $S(\underline{a})_{\alpha_i}$  to satisfy (3.27) are the limits of the  $1-\beta$  confidence region. Therefore, the standard

deviation of the parameter  $\alpha_i$  will be determined by

$$S(\underline{\alpha})_{\alpha_i \pm \sigma_{\alpha_i}} = S(\underline{\alpha}^*) \left[ 1 + \frac{F(1, N-p, 0.683)}{N-p} \right] \quad (3.28)$$

Summarising, the determination of the free parameters in an angular distribution measurement is made by means of a minimisation of  $S(\underline{\alpha})/f$ . Computer programmes are employed which optimise the normalisation constants using (3.24). Then, the programme computes  $S(\underline{\alpha})/f$  as a function of the other parameters (for reasonable sets of values of these parameters). From this mapping of  $S(\underline{\alpha})/f$ , minima are obtained and functions  $S(\underline{\alpha})_{\alpha_i}$  are extracted. The errors in the parameters, e.g. mixing ratios, are determined from these curves using (3.28). A table of  $F(1, N-p, 0.683)$  for  $N-p$  ranging from 1 to 16 is presented below.

Table 3.1

| <u>N-p</u> | <u>F(1, N-p, 0.683)</u> | <u>N-p</u> | <u>F(1, N-p, 0.683)</u> |
|------------|-------------------------|------------|-------------------------|
| 1          | 3.38                    | 9          | 1.12                    |
| 2          | 1.75                    | 10         | 1.11                    |
| 3          | 1.43                    | 11         | 1.10                    |
| 4          | 1.30                    | 12         | 1.09                    |
| 5          | 1.23                    | 13         | 1.09                    |
| 6          | 1.19                    | 14         | 1.08                    |
| 7          | 1.16                    | 15         | 1.08                    |
| 8          | 1.14                    | 16         | 1.07                    |

These values were obtained by interpolation of the tables given by (Ab65).

The main advantage of this method is that errors on mixing ratios are consistently estimated in a way which depends solely on the shape of the curve  $S(\underline{a})_{a_i}$ . The standard deviations determined are exact, provided that the covariance terms between  $a_i$  and  $a_{j \neq i}$  are zero, which is true if condition (3.25) is satisfied at the local minimum  $S(\underline{a}^*)$ . This was the case encountered in the experiments described in this thesis. However, if the linearity condition is not satisfied, and therefore  $S(\underline{a})_{a_i}$  cannot be approximated by a parabola, the error estimated is only a lower limit of the standard deviation (which in many cases differs only by a few per cent from the correct value (Da71)). But, if  $S(\underline{a})_{a_i}$  is pronouncedly non-parabolic or asymmetric no significance can be attached to the error determination, and the whole  $S(\underline{a})_{a_i}$  curve should then be displayed.

### 3.3 Gamma transition widths in isospin multiplets

The interaction Hamiltonian  $H_{int}$  defined in (3.1) can be expressed as a sum of operators with definite transformation properties both under rotations in space and in isospin space. Therefore, if isospin is assumed to be a good quantum number, it is convenient to express the matrix elements of electromagnetic transitions also in terms of this quantum number, so that their isospin dependence and the associated rules governing the decay can be obtained.

The interaction multipole operators  $T_{LM}^{<\pi>}$  (3.5) may be rewritten using isospin formalism in the way described below (which is based on the treatment of Towner and Davies

(To69) ). We can express  $T_{LM}^{<\pi>}$  as

$$T_{LM}^{<\pi>} = \sum_{i=1}^n \left\{ g_{\ell_i}^{<\pi>} P_{LM}^{<\pi>}(i) + g_{s_i}^{<\pi>} P'_{LM}^{<\pi>}(i) \right\} \quad (3.29)$$

where  $P_{LM}^{<\pi>}(i)$  and  $P'_{LM}^{<\pi>}(i)$  only operate in angular momentum space ( $P_{LM}^{<\pi>}(i)$  and  $P'_{LM}^{<\pi>}(i)$  correspond to the space and spin parts, respectively of the interaction multipole operators, as defined in (3.5c and d) ) and  $n$  is the number of (active) valence nucleons outside a chosen inert core. The factors  $g_{\ell_i}^{<\pi>}$  and  $g_{s_i}^{<\pi>}$  are defined below. In electric multipole transitions the spin part contribution can be neglected, as the ratio of the single particle reduced matrix elements of  $Q'_{LM}$  and  $Q_{LM}$  is typically of the order  $10^{-3}$  or less, and thus  $T_{LM}^e \simeq a_L^e Q_{LM}^e$ . Further, in this case the reduced matrix elements of  $T_{LM}^e$  are calculated using the operator  $(Q_{LM})_{\text{eff}}$  (Ro67), which is given by

$$(Q_{LM})_{\text{eff}} = e g_i r^L C_{LM} \quad (3.30)$$

Here  $C_{LM}$  is a modified spherical harmonic and  $g_i$  (the index  $i$  refers to the nucleon concerned being either a proton or a neutron) is usually defined as

$$\begin{aligned} g_p &= g_{\ell_p} + g_{\text{eff}_p} \\ g_n &= g_{\text{eff}_n} \end{aligned} \quad (3.31)$$

in the case of protons and neutrons, respectively.  $g_{\ell_p}$  is the proton  $g$  factor defined in (3.2), i.e.  $g_{\ell_p} = 1$ , ( $g_{\ell_n} = 0$ ) and  $g_{\text{eff}_i}$  are effective  $g$  factors. Resulting

from these considerations, we can define the  $g_{\ell_i}^e$  and  $g_{s_i}^e$  factors of (3.29) as

$$\begin{aligned} g_{\ell_p}^e &= g_{\ell_p} + g_{\text{eff}_p} = g_p & g_{s_p}^e &= 0 \\ g_{\ell_n}^e &= g_{\text{eff}_n} = g_n & g_{s_n}^e &= 0 \end{aligned} \quad (3.32a)$$

for the electric case. In the case of magnetic multipole transitions however, both space and spin contributions will usually be of comparable magnitude. We define then

$$\begin{aligned} g_{\ell_p}^m &= g_{\ell_p} & g_{s_p}^m &= g_{s_p} \\ g_{\ell_n}^m &= g_{\ell_n} = 0 & g_{s_n}^m &= g_{s_n} \end{aligned} \quad (3.32b)$$

for the magnetic case, with the proton and neutron  $g$  factors given by (3.2).

We can therefore express  $T_{LM}^e$  as

$$T_{LM}^e = \sum_{i=1}^n g_i P_{LM}^e(i) \quad (3.33)$$

whereas  $T_{LM}^m$  will be given by

$$T_{LM}^m = \sum_{i=1}^n \{ g_{\ell_i}^m P_{LM}^m(i) + g_{s_i}^m P_{LM}^m(i) \} \quad (3.34)$$

In the following derivations we only treat the case of electric multipole transitions, which concerns the studies reported in this thesis (see chapter 6). Formulae for magnetic multipole transitions can easily be derived from

the ones presented. The difference in the magnetic case is the presence of an additional term (arising from the spin part) and the use of two more  $g$  factors, as inferred from (3.33) and (3.34).

If we now introduce an isospin operator  $\tau_3(i)$ , with eigenvalues  $+1$  for a neutron and  $-1$  for a proton, the operator  $T_{LM}^e$  can be written

$$\begin{aligned} T_{LM}^e &= \sum_{i=1}^n \left\{ \frac{1}{2} [1 - \tau_3(i)] g_p P_{LM}^e(i) \right\} + \sum_{i=1}^n \left\{ \frac{1}{2} [1 + \tau_3(i)] g_n P_{LM}^e(i) \right\} = \\ &= \frac{g_p + g_n}{2} \sum_{i=1}^n P_{LM}^e(i) + \frac{g_n - g_p}{2} \sum_{i=1}^n \tau_3(i) P_{LM}^e(i) \end{aligned} \quad (3.35)$$

where the first term is independent of  $\tau_3$  and therefore is a scalar in isospin space, and the second term depends linearly on the isospin operator being thus an isovector.

The initial and final states of a  $\gamma$ -transition will now be specified by the quantum numbers  $|T_1 T_{31}; J_1 M_1\rangle$  and  $|T_2 T_{32}; J_2 M_2\rangle$ , respectively (all further quantum numbers which may be needed to specify these states uniquely have been suppressed). The transition matrix element between these two states can also be separated into two terms. By application of the Wigner-Eckart theorem in isospin space, we obtain

$$\begin{aligned} \langle T_1 T_{31}; J_1 M_1 | T_{LM}^e | T_2 T_{32}; J_2 M_2 \rangle &= \\ &= \delta_{T_1 T_2} \delta_{T_{31} T_{32}} \left[ \frac{g_p + g_n}{2} \langle T_1; J_1 M_1 \| \sum_i P_{LM}^e(i) \| T_2; J_2 M_2 \rangle \right] + \\ &+ (T_2 T_{32}^0 | T_1 T_{31}) \left[ \frac{g_n - g_p}{2} \langle T_1; J_1 M_1 \| \sum_i P_{LM}^e(i) \tau_3(i) \| T_2; J_2 M_2 \rangle \right] \end{aligned} \quad (3.36)$$

taking into account the isoscalar nature of the first term and that  $(T_2 0 T_3 0 | T_1 T_3)_1 = \delta_{T_1 T_2} \delta_{T_3 T_3}$ . The matrix elements on the right hand side of (3.36) are reduced with respect to  $T$  but not with respect to  $J$ . Also from expression (3.36) the basic isospin selection rules  $\Delta T = 0, \pm 1$  and  $\Delta T_3 = 0$  can be inferred.

It is interesting to test the isospin dependence of the transition matrix elements as expressed in (3.36) through the comparison of analogue decays in isospin multiplets. Particularly useful for this purpose are E2 transitions such as the lowest E2  $\gamma$ -decays in the mass 30 and mass 34 isospin triplets ( $T = 1$ ). Lifetimes of the low-lying  $2^+$  states in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  were measured in this work (see chapter 6). These measurements complete the experimental information needed to test the isospin dependence as described above.

The  $T = 1$  energy level spectra in mass 30 and mass 34 have a "ground" state with spin  $0^+$ , the first excited state occurring approximately at 2.1 MeV excitation energy and with spin  $2^+$ . The  $\gamma$ -transitions between these two sets of states are then pure E2.

The transition matrix element (3.36) can be written in this case

$$\begin{aligned}
 \langle 1T_3; J_1 M_1 | T_{LM}^e | 1T_3; J_2 M_2 \rangle = & \\
 = \left[ \frac{g_p + g_n}{2} \langle 1; J_1 M_1 | \sum_i P_{LM}^e(i) | 1; J_2 M_2 \rangle \right] + & \\
 + (11T_3 0 | 1T_3) \left[ \frac{g_n - g_p}{2} \langle 1; J_1 M_1 | \sum_i P_{LM}^e(i) \zeta(i) | 1; J_2 M_2 \rangle \right] & \quad (3.37)
 \end{aligned}$$

The Clebsch-Gordan coefficient  $(11T_3 0 | 1T_3)$  has the values 0 or  $\pm 1/\sqrt{2}$  for  $T_3 = 0$  or  $\pm 1$ , respectively. Hence, the left hand side of (3.37) is a linear function of  $T_3$  of the form

$$\langle 1T_3; J_1 M_1 | T_{LM}^e | 1T_3; J_2 M_2 \rangle = a + b \frac{1}{\sqrt{2}} T_3 \quad (3.37a)$$

Consequently the matrix element describing the three analogue decays in a triplet is a function of two parameters only, namely  $a$  and  $b$ .

An important experimental quantity to be extracted from the results is the ratio of the isovector part to the isoscalar part in the transition matrix element. This ratio,  $a$ , can be calculated in the following way. Applying the Wigner-Eckart theorem in angular momentum space, the transition matrix element (3.37) can be written

$$\begin{aligned} \langle 1T_3; J_1 M_1 | T_{LM}^e | 1T_3; J_2 M_2 \rangle &= \\ &= (J_2 M_2 | J_1 M_1) \left[ \frac{g_p + g_n}{2} \langle 1; J_1 \| \sum_i P_L^e(i) \| 1; J_2 \rangle + \right. \\ &+ \left. \frac{g_n - g_p}{2} (11T_3 0 | 1T_3) \langle 1; J_1 \| \sum_i P_L^e(i) \underline{z}(i) \| 1; J_2 \rangle \right] = \\ &= (J_2 M_2 | J_1 M_1) \left[ \langle 1; J_1 \| \sum_i P_L^e(i) S^{(0)}(i) \| 1; J_2 \rangle + \right. \\ &+ \left. \langle 1; J_1 \| \sum_i P_L^e(i) S^{(1)}(i) \| 1; J_2 \rangle \right] \quad (3.38) \end{aligned}$$

where  $S^{(0)}$  and  $S^{(1)}$  are defined as the scalar and the vector tensor operators in isospin space, respectively. For convenience, the Clebsch-Gordan coefficient  $(11T_3 0 | 1T_3)$  has been included in the definition of  $S^{(1)}$ . Hence,

$$S^{(0)} = \frac{g_p + g_n}{2} \cdot 1$$

$$S^{(1)} = \frac{g_n - g_p}{2} (11T_3 0 | 1T_3) \cdot \sqrt{3} \quad (3.39)$$

and their single particle reduced matrix elements are therefore

$$\begin{aligned} \langle \frac{1}{2} || S^{(0)} || \frac{1}{2} \rangle &= \frac{g_p + g_n}{2} \\ \langle \frac{1}{2} || S^{(1)} || \frac{1}{2} \rangle &= \frac{g_n - g_p}{2} (11T_3 0 | 1T_3) \sqrt{3} \end{aligned} \quad (3.40)$$

The single particle reduced matrix elements of the operators  $P_{LM}^e(i)$  can be calculated using the operator  $(Q_{LM})_{eff}$  (3.30) as mentioned earlier. The product  $eg_i = \tilde{e}_i$  occurring in (3.30) is called the total (effective) charge. We have

$$\begin{aligned} \tilde{e}_p &= eg_p = e(g_{lp} + g_{eff_p}) = e + e_{eff_p} \\ \tilde{e}_n &= eg_n = e(g_{eff_n}) = e_{eff_n} \end{aligned} \quad (3.41)$$

for protons and neutrons, respectively. The isoscalar term of the transition matrix element (3.38) will then be proportional to  $\tilde{e}_p + \tilde{e}_n$ , the isovector part being proportional to  $\tilde{e}_n - \tilde{e}_p$ . The ratio of the isovector to the isoscalar parts of the transition matrix element (3.38) will be given by the ratio of the isovector to the isoscalar reduced matrix elements of (3.40). Therefore, recalling the values of the Clebsch-Gordan coefficient in the particular case considered, this ratio can be written

$$\eta = \sqrt{\frac{3}{2}} \frac{\tilde{e}_n - \tilde{e}_p}{\tilde{e}_p + \tilde{e}_n} \quad (3.42)$$

However, as  $\tilde{e}_p$  is usually larger than  $\tilde{e}_n$ , it is convenient to define  $\alpha = -\eta$  which we then call the "ratio of the isovector to the isoscalar parts of the E2 transition matrix elements in isospin triplets". Hence, we have

$$\alpha = \sqrt{\frac{3}{2}} \frac{\tilde{e}_p - \tilde{e}_n}{\tilde{e}_p + \tilde{e}_n} \quad (3.43)$$

and from here  $\tilde{e}_p - \tilde{e}_n$  is called the total isovector charge and  $\tilde{e}_p + \tilde{e}_n$  the total isoscalar charge. It is this definition of  $\alpha$  which is used in the discussion of the mass 30 and mass 34 results in chapter 6. In order to extract  $\alpha$  from the experimental data, a least squares fit of these data to the formula (3.37a) is made. In principle both  $a$  and  $b$  can be extracted from this fit as separate quantities. However, in order to determine  $\alpha$  it is sufficient to only extract the slope of the linear function. The relationship between  $a$ ,  $b$  and  $\alpha$  is

$$\alpha = -\frac{1}{\sqrt{2}} \frac{b}{a} \quad (3.44)$$

## 4. The Decay Scheme and Lifetime Measurements in $^{37}\text{Ar}$

### 4.1 Introduction

As mentioned in chapter 2, the purposes of studying the nucleus  $^{37}\text{Ar}$  were twofold: (i) to investigate its  $\gamma$ -decay properties in order to provide more experimental information on electromagnetic transitions in the upper end of the sd shell, and (ii) to test the performance and reliability of the n- $\gamma$  coincidence technique in a real experimental situation.

From the nuclear structure point of view,  $^{37}\text{Ar}$  ( $Z = 18$ ,  $A = 37$ ) can be envisaged in terms of one-neutron-two-proton holes in the doubly closed shell nucleus  $^{40}\text{Ca}$ . Shell model calculations of excitation energies and wave functions for low-lying positive parity states have been performed (Gl64, Di69). Recently, electromagnetic transition strengths have also been calculated with the shell-model by Wildenthal et al. (Wi71a). The experimental information available on  $^{37}\text{Ar}$  as at the beginning of the present work is summarised in the following paragraph.

Level excitation energies have been determined and spin assignments were made mainly using the stripping  $^{36}\text{Ar}(d,p)^{37}\text{Ar}$ , the  $^{39}\text{K}(d,\alpha)^{37}\text{Ar}$  and the  $^{35}\text{Cl}(^3\text{He},p)^{37}\text{Ar}$  reactions (Ro65, Ho66 and Mc66). The levels at 1.41, 1.61, 2.49 and 3.52 MeV were assigned spins of  $1/2^+$ ,  $7/2^-$ ,  $3/2^-$  and  $3/2^-$ , respectively based on proton angular distributions from the stripping reaction (Ro65). The spin of the 2.22 MeV level was assigned ( $5/2$ ,  $7/2$ ) from Hauser-Feshbach

type of arguments (Na68). The  $\gamma$ -decay properties had been scarcely studied, however. The angular distribution of the  $\gamma$ -ray originating in the decay of the 1.41 MeV state was measured to be isotropic (Iy66). From the  $\beta^+$  decay of the mirror nucleus  $^{37}\text{K}$  a spin assignment of  $5/2^+$  to the 2.80 MeV state was made (En67). Particle- $\gamma$  angular correlations following the  $^{36}\text{Ar}(d,p)^{37}\text{Ar}$  reaction enabled the assignment of spins ( $3/2, 5/2$ ), ( $3/2, 5/2$ ),  $7/2$  and ( $3/2, 5/2$ ) to the 3.17, 3.27, 3.54 and 3.60 MeV levels, respectively (Ho67). In addition, the lifetime of the 1.61 MeV state was measured by the Doppler shift recoil-distance method (Go67).

However, since the completion of the present work and submission for publication, a number of papers dealing with electromagnetic properties of the low-lying states in  $^{37}\text{Ar}$  have also appeared in the literature. Gamma decay modes and lifetimes of excited states have been measured (Iv71, Ra71, Ra71a and Lu72), together with proton- $\gamma$  angular correlations following the  $^{36}\text{Ar}(d,p)^{37}\text{Ar}$  reaction (Ch71). The measurement of the linear polarisation of the  $\gamma$ -rays originated in the decay of the 1.41 and 1.61 MeV levels has also been reported (Ta71).

The level scheme and decay modes of  $^{37}\text{Ar}$  observed in this work are summarised in fig.4.1. Spin assignments are from (En67), (Iv71) and (Ch71).

#### 4.2 Energy determinations and decay scheme

The neutron emitting reaction chosen to populate the  $^{37}\text{Ar}$  levels studied was the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction

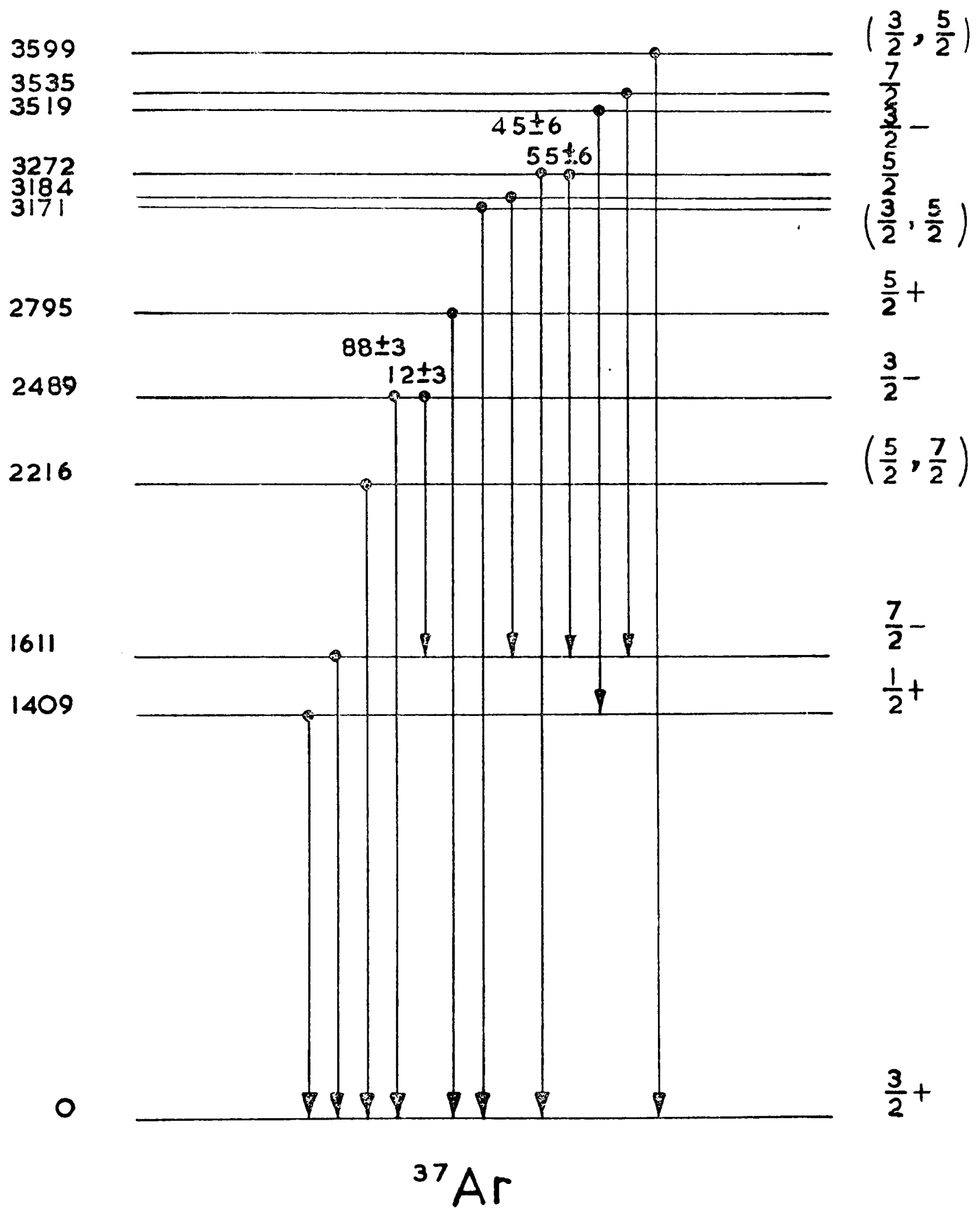
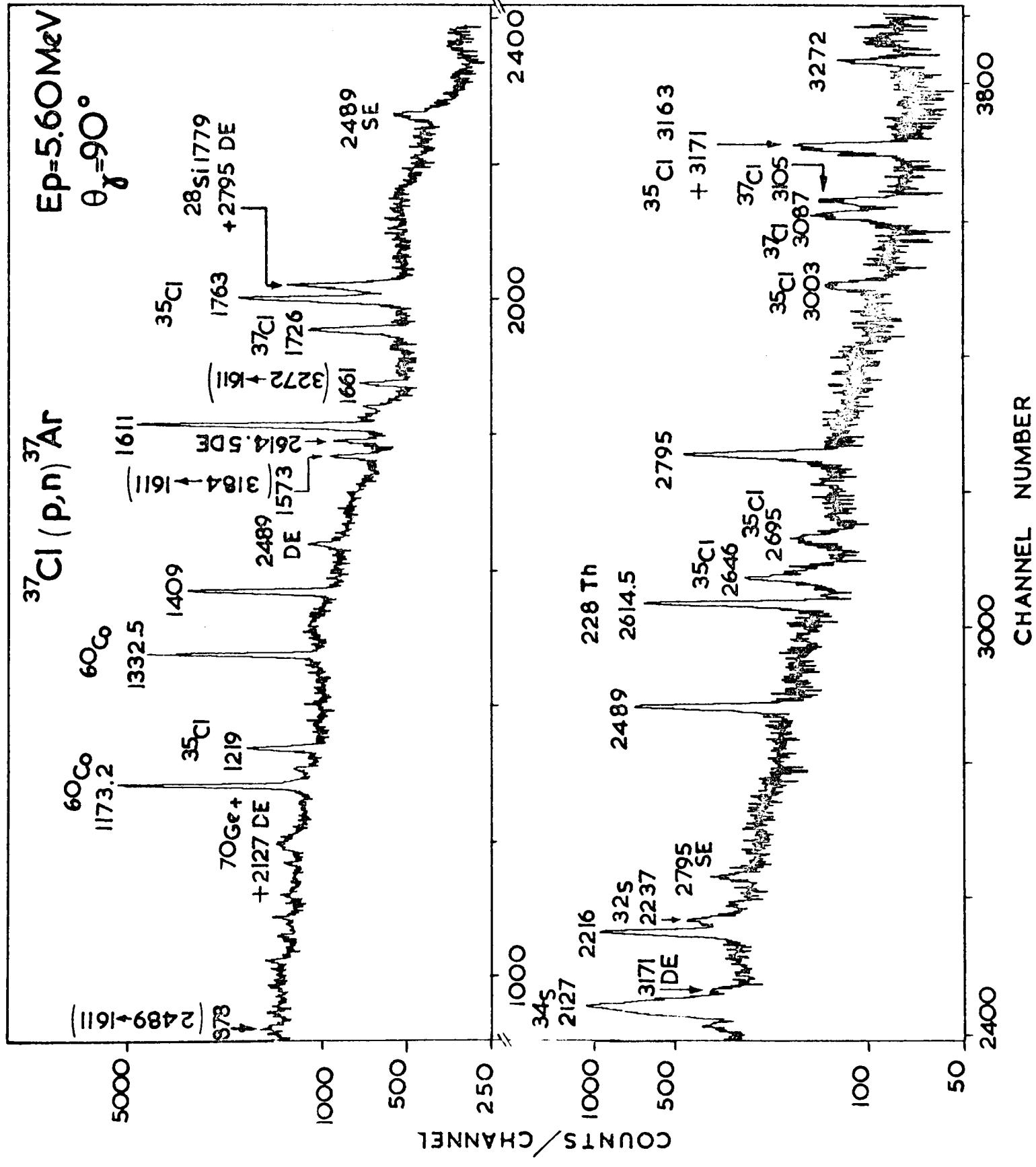


Fig.4.1 - Level scheme  
and decay modes of  $^{37}\text{Ar}$ .

( $Q = -1.5963$  MeV). A negative  $Q$ -value is convenient from the point of view of the time of flight techniques, because it allows the energy of the bombarding beam to be adjusted so that the neutron groups of interest are in the energy range 1-4 MeV (see chapter 2). The proton beams were obtained from the Oxford Tandem Van de Graaff Generator and measurements done at 4.15, 5.15, 5.60 and 6.15 MeV proton energies. The beams were collimated by a series of tantalum annuli before reaching the target chamber.

Accurate excitation energies for the excited states in  $^{37}\text{Ar}$  lying below 3 MeV were measured from  $\gamma$ -singles spectra. The spectra were accumulated with the  $\gamma$ -detector at  $90^\circ$  with respect to the beam axis and at 6 cm from the target. The target used in these measurements was an enriched  $\text{BaCl}_2$  ( $^{37}\text{Cl} = 78.2\%$ )  $400 \mu\text{g}\cdot\text{cm}^{-2}$  thick target on  $10 \text{ mg}\cdot\text{cm}^{-2}$  lead backing and the proton bombarding energy chosen was 5.6 MeV.  $^{60}\text{Co}$  and  $^{228}\text{Th}$  sources were placed near the  $\gamma$ -detector to give adequate reference peaks at a beam intensity of approximately 150 nA (see fig.4.2). The linearity of the  $\gamma$ -ADC was checked beforehand. The  $\gamma$ -rays were detected in a  $32 \text{ cm}^3$  active volume  $\text{Ge}(\text{Li})$  detector with 3.4 keV resolution for the 1332 keV  $^{60}\text{Co}$  line. The  $\gamma$ -ray singles spectrum accumulated at 5.60 MeV bombarding energy is shown in fig.4.2. Excitation energies for the  $^{37}\text{Ar}$  states between 3 MeV and 3.6 MeV were measured from the n- $\gamma$  coincident spectra obtained with time of flight techniques.

The energies of the first eleven states excited with



the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction are listed in table 4.1. Also listed in this table are the energies measured by (Iv71, Ch71, En67 and Go67). There is good agreement particularly with the more accurate results of (Iv71 and Ch71).

The decay modes of the low-lying levels were observed in coincidence with the neutrons emitted in the (p,n) reaction. The neutron time of flight (TOF) spectrometer was set up as described in chapter 2. The flight path chosen was 2 m and the detector was at  $0^\circ$  with respect to the beam axis. The quadrants were pivoted by an angle of  $6.5^\circ$  to compensate for different geometrical path lengths and the neutron detection threshold was approximately 500 keV for a  $\gamma$ -rejection ratio of 1 : 80. The electronics employed is also described in chapter 2; the time resolution of the system was  $\sim 6$  ns.

Natural  $\text{BaCl}_2$  targets  $\frac{500}{\mu\text{g.cm}^{-2}}$  thick evaporated onto  $10 \text{ mg.cm}^{-2}$  lead backings were bombarded by proton beams of energies 4.15, 5.15, 5.60 and 6.15 MeV. These different proton energies were chosen to allow good separation between the neutron peaks - in the TOF spectrum - corresponding to the various  $^{37}\text{Ar}$  states populated. The  $\gamma$ -decay spectrum of each level could then be studied separately and with no contamination from adjacent neutron groups. For example, at 4.15 MeV proton energy the neutron peaks corresponding to the 1409 and 1611 keV levels were completely separated (their centroids being 16 ns apart), a similar situation arising at 5.15 MeV bombarding energy for the 2216, 2489 and 2795 keV state neutron groups. The time of flight spectrum corresponding to an integrated target current of

Table 4.1

Excitation energies and  $\gamma$ -rays in the decay of the  $^{37}\text{Ar}$  states excited by means of the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction

| $E_x(\text{keV})$<br>this work | $E_\gamma(\text{keV})$ | $E_x(\text{keV})$<br>(Iv71) | $E_x(\text{keV})$<br>(Ch71) | $E_x(\text{keV})$<br>(En67,Go67) |
|--------------------------------|------------------------|-----------------------------|-----------------------------|----------------------------------|
| 1409.0 $\pm$ 0.6               | 1409.0 $\pm$ 0.6       | 1408.9 $\pm$ 1.3            | 1409 $\pm$ 1.5              | 1414 $\pm$ 8                     |
| 1610.7 $\pm$ 1.0               | 1610.7 $\pm$ 1.0       | 1611.3 $\pm$ 1.2            | 1611 $\pm$ 0.8              | 1611 $\pm$ 1                     |
| 2216.4 $\pm$ 1.5               | 2216.4 $\pm$ 1.5       | 2219.8 $\pm$ 1.5            | 2218 $\pm$ 1.5              | 2217 $\pm$ 16                    |
| 2489.0 $\pm$ 1.0               | 2489.0 $\pm$ 1.0       | 2491.2 $\pm$ 1.5            | 2491 $\pm$ 1.3              | 2489 $\pm$ 4                     |
|                                | 878.3 $\pm$ 1.0        |                             |                             |                                  |
| 2795.1 $\pm$ 1.3               | 2795.1 $\pm$ 1.3       | 2798 $\pm$ 2                | 2796 $\pm$ 1.8              | 2802 $\pm$ 8                     |
| 3171 $\pm$ 3                   | 3171 $\pm$ 3           | 3168 $\pm$ 2                | 3171 $\pm$ 1.7              | 3173 $\pm$ 16                    |
| 3184 $\pm$ 3                   | 1573 $\pm$ 3           | 3189 $\pm$ 2                | 3186 $\pm$ 1.7              |                                  |
| 3272 $\pm$ 3                   | 3272 $\pm$ 3           | 3270 $\pm$ 3                | 3273 $\pm$ 1.6              | 3273 $\pm$ 16                    |
|                                | 1661 $\pm$ 3           |                             |                             |                                  |
| 3519 $\pm$ 6                   | 2110 $\pm$ 6           | 3517 $\pm$ 3                | 3516 $\pm$ 1.8              | 3515 $\pm$ 5                     |
| 3535 $\pm$ 6                   | 1924 $\pm$ 6           |                             | 3526 $\pm$ 2.1              |                                  |
| 3599 $\pm$ 10                  | 3599 $\pm$ 10          | 3609 $\pm$ 2                | 3608 $\pm$ 2.9              | 3614 $\pm$ 16                    |

7 mC and 6.15 MeV proton bombarding energy is shown in fig.4.3. The neutron groups populating the  $^{37}\text{Ar}$  states excited are clearly seen. It can also be seen in fig.4.3 that the width of the peaks corresponding to single neutron groups is smaller than that of the prompt  $\gamma$ - $\gamma$  peak. The better timing evident in those peaks is due to the higher energy of the  $\gamma$ -rays involved, as most of the contributions to the prompt peak are due to low energy  $\gamma$ -rays.

In fig.4.4 the  $\gamma$ -decays of the states excited in the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction are shown. The spectra were obtained by sorting the multiparameter data into slices which were determined by a selection of digital windows (A, B, C and D) as is indicated in fig.4.3. Random coincidences have been subtracted from the spectra by choosing a TOF digital window in the region free of peaks.

From the spectra of fig.4.4 the ground state decays of the 1409, 1611, 2216, 2489, 2795, 3171, 3272 and 3599 keV levels are clearly established as well as the 1611 keV branches of the 2489 and 3272 keV states. The  $1573 \pm 3$  keV  $\gamma$ -ray of fig.4.4C cannot be assigned <sup>to</sup> a decay branch of the 3171 keV state through the 1611 keV one (this branch would correspond to a 1560 keV  $\gamma$ -ray). A discrepancy of 13 keV exists and calibration errors cannot account for more than 3 keV. Therefore, a new level was proposed at  $3184 \pm 3$  keV excitation energy. The existence of this level was also confirmed by (Iv71 and Ch71) (see table 4.1). The decay of the doublet at 3519 and 3535 keV is well observed in fig.4.4D. The level located by (Ho67) at

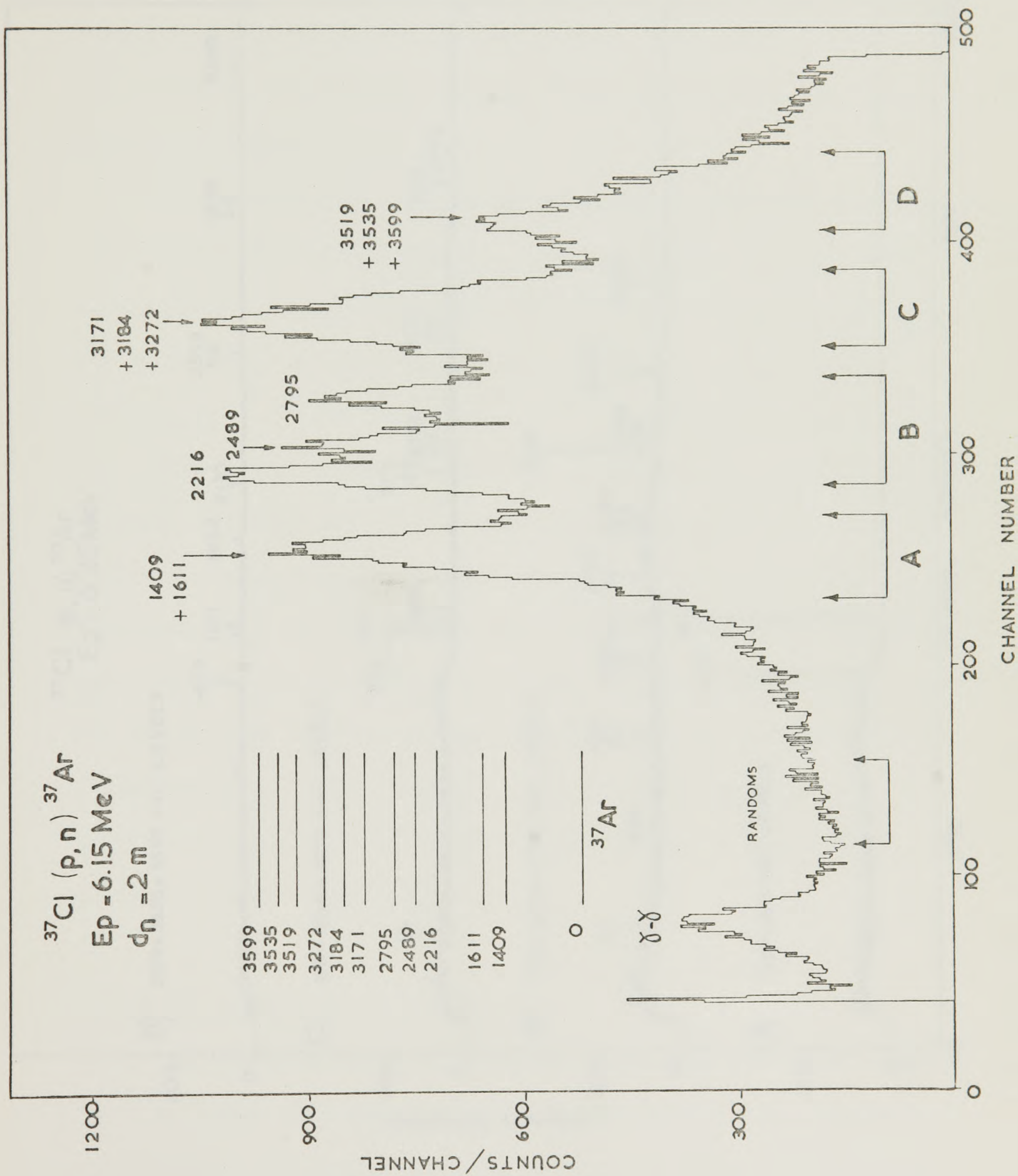


Fig.4.3 - Neutron time of flight spectrum at  $E_p = 6.15 \text{ MeV}$ .

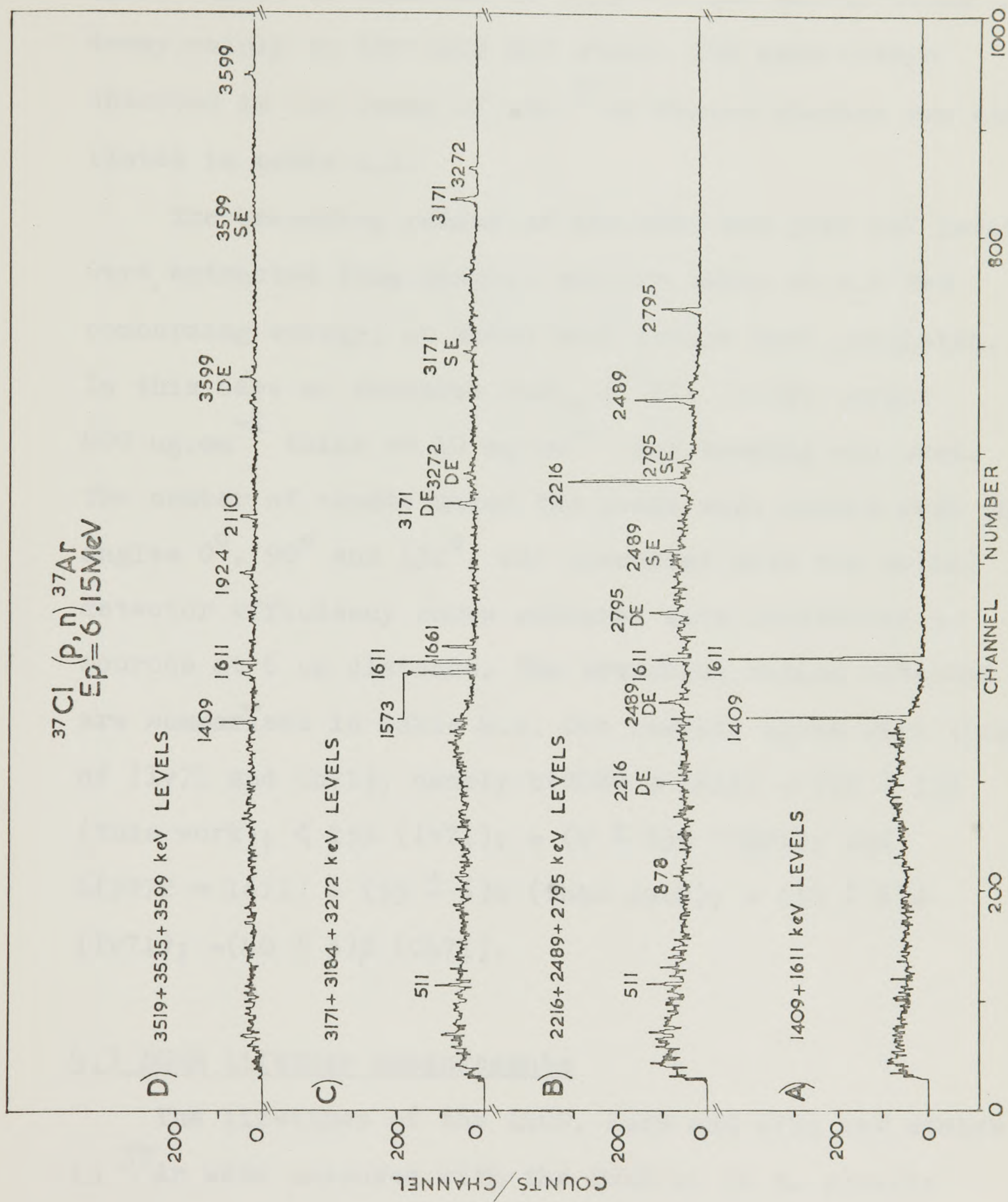


Fig.4.4 - Gamma ray spectra in coincidence with neutron groups populating the  $^{37}\text{Ar}$  states.

$3.52 \pm 0.02$  MeV has an energy of  $3535 \pm 6$  keV and predominantly decays to the 1611 keV state. The other member of the doublet, the well established  $3/2^-$  state (Ro65, Ho67) is observed at  $3519 \pm 6$  keV and is found to decay mainly to the 1409 keV state. The main  $\gamma$ -rays observed in the decay of the  $^{37}\text{Ar}$  states studied are also listed in table 4.1.

The branching ratios of the 2489 and 3272 keV levels were extracted from singles spectra taken at 5.6 MeV bombarding energy, at which both levels were populated. In this case an enriched  $\text{BaCl}_2$  ( $^{37}\text{Cl}$ : 78.2%) target  $400 \mu\text{g}\cdot\text{cm}^{-2}$  thick on  $10 \text{ mg}\cdot\text{cm}^{-2}$  lead backing was used. The number of counts under the peaks were summed over the angles  $0^\circ$ ,  $90^\circ$  and  $132^\circ$ , and corrected with the Ge(Li) detector efficiency curve measured with calibrated  $\gamma$ -sources at 6 cm distance. The branching ratios obtained are summarised in table 4.2. Our results agree with those of (Iv71 and Ch71), namely  $b(2489 \rightarrow 1611) = (12 \pm 3)\%$  (this work);  $< 15\%$  (Iv71);  $= (9 \pm 2)\%$  (Ch71); and  $b(3272 \rightarrow 1611) = (55 \pm 6)\%$  (this work);  $= (55 \pm 8)\%$  (Iv71);  $= (40 \pm 5)\%$  (Ch71).

#### 4.3 DSAM lifetime measurements

The lifetimes of the 1409, 2489 and 2795 keV states in  $^{37}\text{Ar}$  were measured with the DSAM so as to provide information on  $\gamma$ -transition widths in mass 37. Instead, this measurement turned out, as discussed in the next section, to be very interesting from the point of view

Table 4.2

Decay modes and branching ratios of the low-lying levels of  $^{37}\text{Ar}$

| $E_{x\text{fin}}$<br>(keV) | $E_{x\text{in}}$<br>(keV) | 1409 | 1611 | 2216 | 2489       | 2795 | 3171 | 3184 | 3272       | 3519 | 3535 | 3599 |
|----------------------------|---------------------------|------|------|------|------------|------|------|------|------------|------|------|------|
| 0                          |                           | 100  | 100  | 100  | 88 $\pm$ 3 | 100  | 100  | <10  | 45 $\pm$ 6 | <6   | <5   | 100  |
| 1409                       |                           |      |      | <2   | <4         | <6   | <3   | <6   | <11        | 100  | <12  | <5   |
| 1611                       |                           |      |      | <3   | 12 $\pm$ 3 | <5   | <5   | 100  | 55 $\pm$ 6 | <18  | 100  | <11  |
| 2216                       |                           |      |      |      |            | <9   | <3   | <4   | <5         | <7   | <6   | <5   |
| 2489                       |                           |      |      |      |            |      | <2   | <3   | <11        | <15  | <9   | <13  |
| 2795                       |                           |      |      |      |            |      | <2   | <4   | <2         | <6   | <9   | <3   |
| 3171                       |                           |      |      |      |            |      |      |      |            | <9   | <8   | <3   |
| 3184                       |                           |      |      |      |            |      |      |      |            | <7   | <7   | <3   |
| 3272                       |                           |      |      |      |            |      |      |      |            | <2   | <5   | <8   |

of a critical analysis of the current DSAM experiments.

The  $^{37}\text{Ar}$  levels were studied in singles spectra taken at  $0^\circ$  and  $132^\circ$  with respect to the beam axis by means of the  $^{37}\text{Cl}(p,n)^{37}\text{Ar}$  reaction. The targets used were made of natural  $\text{BaCl}_2$   $20\text{ }\mu\text{g.cm}^{-2}$  thick, evaporated onto different backings. As the abundance of  $^{35}\text{Cl}$  in natural chlorine is of 75.6%, a reasonable excitation of  $^{35}\text{Cl}$  levels through proton inelastic scattering was obtained. We therefore measured also the lifetimes of the 2646 and 2695 keV states in  $^{35}\text{Cl}$  for which only a limit ( $<30\text{ fs}$ ) in the case of the 2695 keV state and a value with large errors ( $300 \pm 90\text{ fs}$ ) in the case of the 2646 keV level existed in the literature (In69). The proton bombarding energy chosen for the (p,n) and the (p,p') reactions was 5.15 MeV. The  $^{60}\text{Co}$  and  $^{228}\text{Th}$   $\gamma$ -ray sources which were placed near the target provided continuous monitoring of the gain of the system.

The full Doppler shifts (or "vacuum" shifts) were measured between  $0^\circ$  and  $132^\circ$  by using the thin  $\text{BaCl}_2$  targets mounted on carbon backings  $10\text{ }\mu\text{g.cm}^{-2}$  thick, positioned with the backing upstream so as to allow the final nuclei to recoil freely into vacuum. The initial mean recoil velocity was thus measured. From formula (2.9) the ratio  $a_1/a_0$  was extracted and found in all cases but one (for the 2489 keV  $^{37}\text{Ar}$  level) to be within the estimate  $|a_1/a_0| \leq 1$  of (Wa67). The results of these measurements are shown in table 4.3; the negative signs of  $a_1/a_0$  correspond to forward peaked angular distributions of the outgoing light particles.

Table 4.3

Full Doppler shifts and initial mean recoiling velocities

| Nucleus          | level(keV)<br>$E_x = E_\gamma$ | vacuum shift<br>(keV) | $v_0/c$<br>(%)  | $a_1/a_0$      |
|------------------|--------------------------------|-----------------------|-----------------|----------------|
| $^{37}\text{Ar}$ | 1409                           | $5.1 \pm 0.6$         | $0.27 \pm 0.03$ | $-0.5 \pm 0.5$ |
|                  | 2489                           | $7.4 \pm 0.8$         | $0.25 \pm 0.04$ | $-1.6 \pm 0.6$ |
|                  | 2795                           | $13.0 \pm 0.4$        | $0.28 \pm 0.02$ | $0.1 \pm 0.2$  |
| $^{35}\text{Cl}$ | 2646                           | $10.9 \pm 0.3$        | $0.30 \pm 0.3$  | $-0.3 \pm 0.2$ |
|                  | 2695                           | $12.2 \pm 1.1$        | $0.30 \pm 0.4$  | $0 \pm 0.4$    |

Attenuated Doppler shifts were measured with targets evaporated onto gold and lead backings ( $10 \text{ mg.cm}^{-2}$  thick) and the nuclei were allowed to recoil into the backing material. The target thickness of  $20 \text{ }\mu\text{g.cm}^{-2}$  was chosen so that the initial velocity of the recoiling ion when entering the backing is spread by less than 10% in the target itself. With the use of two different backing materials (gold and lead) which have well defined properties, a way of checking the consistency of the results obtained for each case was provided. Three pairs of measurements ( $0^\circ$ ,  $132^\circ$ ) were done for both backings. The F-values were obtained dividing the attenuated shifts by the vacuum ones

$$F_{\text{Au}}^{\text{Au}} = \frac{\Delta E_{\text{Au}}}{\Delta E_{\text{F}}} \quad (2.6)$$

The 1409 and 2489 keV  $\gamma$ -rays in the decay of  $^{37}\text{Ar}$  for  $\theta_\gamma = 0^\circ$  and  $132^\circ$  are shown in fig.4.5. The amount of shift is indicated by the stepped lines for each  $\gamma$ -ray. The ions are recoiling in gold (top) and vacuum (bottom). Lifetimes were extracted by comparing the measured F-values with the theoretical  $F(\zeta)$  curves for gold and lead. These  $F(\zeta)$  curves were calculated by the Oxford DSAM programme of Lawson, Carlson and Hutcheon. The programme includes the effects of large angle scattering as dealt with by Blaugrund (Bl66) and the stopping powers used in the calculations are those predicted by the LSS theory (Li63). These  $dE/dx$  values can be corrected in the programme by multiplicative factors  $f_e$  and  $f_n$ . Since

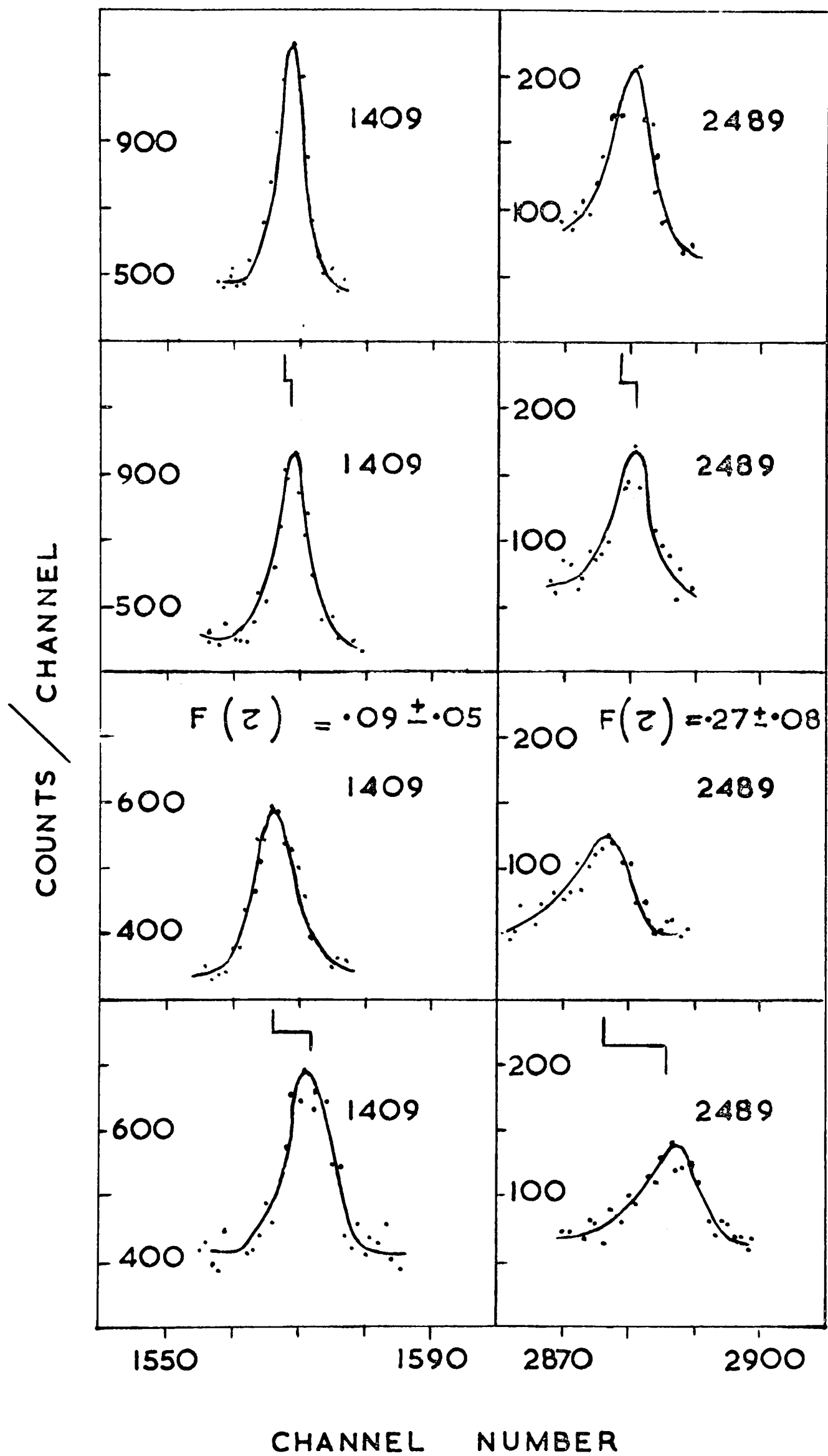


Fig.4.5 - The 1409 and 2489 keV  $\gamma$ -rays for  $\theta=0^\circ$  and  $132^\circ$  in the case of gold (top) and vacuum (bottom).

no experimental information was found for the stopping powers of argon and chlorine ions recoiling in gold and lead, the measurements of Andersen and Sørensen (An68) for potassium ions recoiling in gold were considered. Their conclusion that the electronic stopping power has to be increased by 20-30% for good agreement between theory and experiment in that particular situation was followed here. As experimentally determined stopping cross sections show a slow undulatory behaviour when plotted versus  $Z$  (Or65, Hv68) the deviations from (An68) are thought to be in our case of the order of 10% or less. These uncertainties, together with the uncertainties in the initial recoiling velocity  $V_0/c$  have been taken into account in the errors given for the final lifetimes.

The lifetime results are shown in table 4.4. The measurements for the gold and lead backings are in good agreement, and the values in the column  $\tau_{fin}$  were obtained averaging the  $F(\tau)$  values after transposing the lead  $F$ 's to the gold  $F(\tau)$  curves. The limit put on the 2795 keV level lifetime is obtained with  $F$ -values differing three standard deviations from the measured ones, as the corresponding peak always appeared to be fully shifted.

#### 4.4 Discussion of the reliability of DSAM measurements

If a comparison is made between the published values for the lifetimes measured in  $^{37}\text{Ar}$ , one is faced with a choice of values that vary over an order of magnitude in the worst case. The lifetimes of the 1409, 2489 and 2795 keV levels in  $^{37}\text{Ar}$  as obtained from (Iv71, Ra71, Lu72) and this work are shown in table 4.5. The existence of such discrepancies

Table 4.4

$^{37}\text{Ar}$  and  $^{35}\text{Cl}$  lifetime results

| Nucleus          | Level(keV)<br>$E_x = E_\gamma$ | $F(\tau)$       | Gold backing<br>$\tau$ (fs) | $F(\tau)$       | Lead backing<br>$\tau$ (fs) | $\tau_{\text{fin}}$<br>(fs) |
|------------------|--------------------------------|-----------------|-----------------------------|-----------------|-----------------------------|-----------------------------|
| $^{37}\text{Ar}$ | 1409                           | $0.09 \pm 0.05$ | $380^{+570}_{-150}$         | $0.16 \pm 0.05$ | $360^{+140}_{-100}$         | $370^{+190}_{-110}$         |
|                  | 2489                           | $0.27 \pm 0.08$ | $104^{+56}_{-30}$           | $0.49 \pm 0.08$ | $74^{+26}_{-20}$            | $88 \pm 24$                 |
|                  | 2795                           | $1.02 \pm 0.05$ | $< 7$                       | $1.07 \pm 0.05$ | $< 8$                       | $< 8$                       |
| $^{35}\text{Cl}$ | 2646                           | $0.36 \pm 0.03$ | $77 \pm 10$                 | $0.46 \pm 0.03$ | $90 \pm 10$                 | $83 \pm 21$                 |
|                  | 2695                           | $0.83 \pm 0.11$ | $9.5 \pm 7.0$               | $0.87 \pm 0.11$ | $12 \pm 11$                 | $11 \pm 7$                  |

Table 4.5

Published lifetime measurements in  $^{37}\text{Ar}$  and  $^{35}\text{Cl}$

| Nucleus          | Level (keV)<br>$E_x = E_\gamma$ | this work           | $\tau$ (fs)<br>{ Iv71 }<br>{ In69 } <sup>†</sup> | (Ra71)        | (Lu72)        |
|------------------|---------------------------------|---------------------|--------------------------------------------------|---------------|---------------|
| $^{37}\text{Ar}$ | 1409                            | $370^{+190}_{-110}$ | $650^{+350}$                                     | $1080^{+150}$ | $1220^{+150}$ |
|                  | 2489                            | $88^{+24}$          | $400^{+130}$                                     | $780^{+100}$  | $1040^{+190}$ |
|                  | 2795                            | $<8$                | $<25$                                            | $<25$         | $<40$         |
| $^{35}\text{Cl}$ | 2646                            | $83^{+21}$          | $300^{+90}$                                      |               | $260^{+120}$  |
|                  | 2695                            | $11^{+7}$           | $<30$                                            |               | $<120$        |

<sup>†</sup> The lifetime results for the 2646 and 2695 keV levels were taken from (In69)

as those seen in table 4.5 leads naturally to a discussion of the reliability of the DSAM lifetimes.

The measured  $F$ -values in all  $^{37}\text{Ar}$  experiments (except those corresponding to the 2795 keV state) are well suited for comparison with the theoretical  $F(Z)$  curves. Big differences exist, however, in the design of the various experiments. In this work, thin  $\text{BaCl}_2$  targets were used, so that the slowing down process of the recoiling nucleus is very little influenced by the target material. The backing materials where the slowing down of the ions takes place were gold and lead (which have very good uniformity properties) to avoid the uncertainties due to the granulate structure of some evaporated target compounds (Gi70). Also in this work, the full Doppler shifts were measured with a  $\gamma$ -detector. (Iv71) used thick  $\text{BaCl}_2$  targets ( $650 \mu\text{g}\cdot\text{cm}^{-2}$ ) and calculated the full Doppler shifts from kinematics as the recoils were well defined by a coincidence requirement. (Ra71) measured the lifetimes from singles spectra and calculated the full Doppler shifts from kinematics using the  $|a_1/a_0| \ll 1$  estimate of (Wa67). The targets used were thick  $\text{CdS}$  ( $450 \mu\text{g}\cdot\text{cm}^{-2}$ ). Finally, (Lu72) used thick  $\text{PbCl}_2$ ,  $\text{AgCl}$  and solid chlorine targets and calculated also from kinematics the maximum shifts. The initial recoil velocities  $V_0/c$  for the various experiments were 0.27% (this work), 0.41% (Iv71), 0.69% (Ra71) and 0.22-0.29% (Lu72). Considering the consistent trend of increase in the extracted lifetime values across table 4.5, it is noticeable that (Iv71, Lu72) and our measurements were done at rather low  $V_0/c$ , and therefore a considerable contribution from nuclear collisions to the stopping of the

recoiling ions is expected. Concerning ourselves for a moment with the discrepancies between (Iv71) and this work (as both (Ra71 and Lu72) did not have a coincidence requirement nor measured "vacuum" shifts and therefore only estimated the full shifts), two possible explanations emerge. First, structural changes may have occurred in the target compound of (Iv71) due to the evaporation process. However, we simulated several hypothetical targets of a mixture of  $\text{BaCl}_2$  and Ba atoms and found that for reasonable proportions of that compound the lifetime results of (Iv71) were unaffected within errors. Therefore, only the other possibility, namely that the LSS theory (Li63) is seriously in error in certain cases can remain. The LSS theory seems to overestimate the contribution of the nuclear part of the stopping cross section particularly when light ions with "low" initial velocities recoil in high Z materials. The agreement between our results for the gold and the lead backings only confirms this point. Furthermore, the discrepancies in the values presented in table 4.5 acquire a definite meaning under this assumption.

No systematic measurement of stopping powers for a wide range of recoiling ions, slowing down materials and initial recoil velocities has yet been made. But some papers have appeared which show the inadequacy of the LSS theory in certain cases. Currie et al. (Cu69a) measured the lifetime of the first excited state of  $^{30}\text{Si}$  using six different backings ranging from Mg to Au. A variation of a factor of two was obtained in the values of the extracted lifetimes for the different backings. By means of Monte Carlo computations Currie (Cu69) showed that the discrepancy stems from the

LSS predictions rather than from Blaugrund's treatment of  $\langle \cos\theta_i \rangle$  (see chapter 2), and concluded that the lifetimes measured with the DSAM had an uncertainty of the order of 15% or worse, depending on the ion-stopper combination. The observation of similar discrepancies in the case of aluminium ions recoiling in tantalum was reported by de Voigt et al. (Vo71) where a factor of two also occurred. The present work serves as a further example of this situation, where the uncertainty factors can be 3, 9 or even 11, when compared with the results of (Iv71, Ra71 and Lu72), respectively. A recent work by Broude et al. (Br72) reported the measurement of the lifetime of the second excited state in  $^{22}\text{Ne}$  using 39 different solid stopping materials ranging from carbon to bismuth. They obtained a full range of variation of 1.9 in the measured lifetimes. However, the observed oscillations about the mean value are not apparently related to the undulatory behaviour of the cross sections obtained by (Or65, Hv68) when varying the atomic number of the recoiling ions using the same stopping material. Further, the range of the initial recoil velocities in (Br72) is 0.62-1.35% of the speed of light, so that the contributions of both electronic and nuclear stopping vary in importance for the different backing materials.

It is therefore clear that DSAM lifetimes can have large systematic analysis errors. We have varied the nuclear and electronic parts of the stopping cross sections in the DSAM programme by means of the multiplicative correction factors  $f_n$  and  $f_e$  (c.f. section 4.3), respectively in order to test the sensitivity of our  $^{37}\text{Ar}$  results. The lifetimes were quite

unaffected by changes of 20-30% in  $f_e$  whereas an increase in their values by a factor of three was obtainable using  $f_n = 0.4$ , in agreement with the findings of (Cu69a). Also, the  $^{35}\text{Cl}$  lifetime results are amenable to a similar discussion. The lifetime of the 1219 keV state of  $^{35}\text{Cl}$  has not been included in table 4.5. However, if the DSAM analysis described in section 4.3 is applied to this case, one obtains a value of  $(55 \pm 20)$  fs for the lifetime of this state using the lead and gold backings, to be compared with the published values of  $(210^{+100}_{-80})$  fs (In69) and  $(160 \pm 50)$  fs (Ha69).

Summarising, we can say that the method of extracting lifetimes from measured  $F$ -values obtained in Doppler shift experiments by comparison with calculated  $F(\zeta)$  values is at present under severe criticism. Therefore, until a systematic experimental study of stopping powers has been done which hopefully will enable the experimenters to apply corrections in a consistent and well defined manner, great care must be taken in order to avoid combinations of ions and recoiling velocities that so far have emerged as critical.

In the lifetime measurements in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  (which were populated by means of the  $^{28}\text{Si}(^3\text{He},n)^{30}\text{S}$  and  $^{32}\text{S}(^3\text{He},n)^{34}\text{Ar}$  reactions) described in chapter 6, the range of initial recoiling velocities was  $(0.38-0.47)\%$  of the speed of light (cf. tables 6.2 and 6.4). At these speeds, a considerable contribution from nuclear collisions to the stopping of the recoiling ions is expected. However, the experimental evidence published so far seems to suggest that when the atomic numbers of both the stopping material and the recoiling ion are similar, one may have some confidence in the lifetimes obtained

with the DSAM. The addition of a systematic error of  $\sim 20\%$  to the normal experimental errors should therefore be expected to cover the uncertainties introduced by the LSS theory in the  $^{30}\text{S}$  and  $^{34}\text{Ar}$  experiments.

To check the validity of our DSAM analysis, we measured the lifetimes of the first two excited states in  $^{35}\text{Cl}$ , populated by means of the  $^{32}\text{S}(\alpha, p)^{35}\text{Cl}$  reaction, and compared our results with those published in the literature (In69, Ha69). Our measurements agreed very well with those of (In69, Ha69),  $\tau(1219) = (205 \pm 75)$  fs to be compared with  $(210_{-80}^{+100})$  fs (In69) and  $(160 \pm 50)$  fs (Ha69); and  $\tau(1763) = (490 \pm 100)$  fs to be compared with  $(550 \pm 150)$  fs (In69) and  $(555 \pm 50)$  fs (Ha69). The  $^{35}\text{Cl}$  and  $^{34}\text{Ar}$  lifetime analyses proved equally sensitive to the occurrence of inhomogeneities or thin sulphur layers on the target. For example, inconsistent results within errors were obtained in both cases, when layers of sulphur thicker than  $20 \mu\text{g}\cdot\text{cm}^{-2}$  were considered on the target. Furthermore, both analyses behaved similarly under variations in the theoretical LSS cross sections yielding inconsistent results within the experimental errors when the nuclear stopping was reduced by more than 40%.

The above agreement is believed to be due to the closeness of the atomic numbers of recoiling ions and target material (as opposed to the measurements of the previous section, where heavy backings - gold and lead - were used). This then leads to the conclusion that, having allowed for an additional 20% systematic error, the lifetime values measured in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  may be accepted with reasonable confidence.

## 5. Study of $^{18}\text{Ne}$ gamma decay

### 5.1 Introduction

The properties of mass 18 nuclei can be thought of arising primarily from the motion of two particles outside an inert  $^{16}\text{O}$  core. However, this simple shell-model picture does not describe very successfully the decay modes of the low-lying positive parity states. Numerous theoretical calculations on mass 18 nuclei have been performed, of which the treatments of Benson and Irvine (Be66) and Engeland and Ellis (En72) which include the effect of core excitation provide a better overall agreement with experiment. The success of the Benson and Irvine model when applied to  $^{18}\text{O}$ , naturally motivated the experimental study of its proton-rich mirror nucleus  $^{18}\text{Ne}$ , as the same core effects should be exhibited by both nuclei.

Several investigations concerning level positions, spins, branching ratios and lifetimes of excited states in  $^{18}\text{Ne}$  have been made in recent years. Level excitation energies and spin assignments based on the angular distributions of light outgoing particles have been made using the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  (To68,Ad70) and the  $^{20}\text{Ne}(p,t)^{18}\text{Ne}$  reactions (Ec70,Fa70). The lowest negative parity state in  $^{18}\text{Ne}$  (a  $1^-$  state) has an excitation energy of approximately 4.5 MeV, thus being already unbound with respect to proton emission by  $\sim 0.5$  MeV. The study of  $\gamma$ -angular distributions and decay modes in  $^{18}\text{Ne}$  (Ro69,Ro69a,Sh70) together with the measurement of the lifetimes of the bound excited states (Gi68,Ro69) was enabled by the use of n- $\gamma$  coincidence

techniques. Though most of the properties of the excited states in  $^{18}\text{Ne}$  had been obtained, a number of questions about its decay had still to be solved: (i) the location of the first excited  $0^+$  state, (ii) the measurement of the lifetime of this level, (iii) a measurement of the lifetime of the 3376 keV,  $4^+$  level, by the Doppler shift recoil-distance method, and (iv) the strength of the cross over branch from the 3616 keV,  $2^+$  state to the ground state, together with (v) the measurement of the  $E2/M1$  mixing ratio of the decay of the 3616 keV to the 1887 keV,  $2^+$  state.

Questions (i), (iv) and (v) arose because of discrepancies in the literature, namely after the publication of the results of (Sh70). Question (ii) originated from the extensive theoretical calculations currently available on mass 18 nuclei and in view of their comparisons with experiment. Only a limit,  $\tau > 2$  ps (Gi68,Ro69), existed for the 3576 keV,  $0^+$  state lifetime. The theoretical predictions for the lifetime of this level were in the region of 15 ps ( (Be66) and (Ar68) as quoted in (Ro69) and (En72) ) and therefore the plunger method was adequate to its study. Finally, question (iii) arose due to the recently established inadequacies of the LSS theory in certain cases (as discussed in the previous chapter). The DSAM value for the lifetime of the 3376 keV,  $4^+$  state was  $1.9^{+1.0}_{-0.4}$  ps (Gi68,Ro69) and so its measurement by the plunger method was of great interest.

The level scheme of  $^{18}\text{Ne}$  is shown in fig.5.1. Excitation energies, spin assignments and lifetimes are from (Gi68, Ro69) and this work. The branching ratio of the 3616 keV

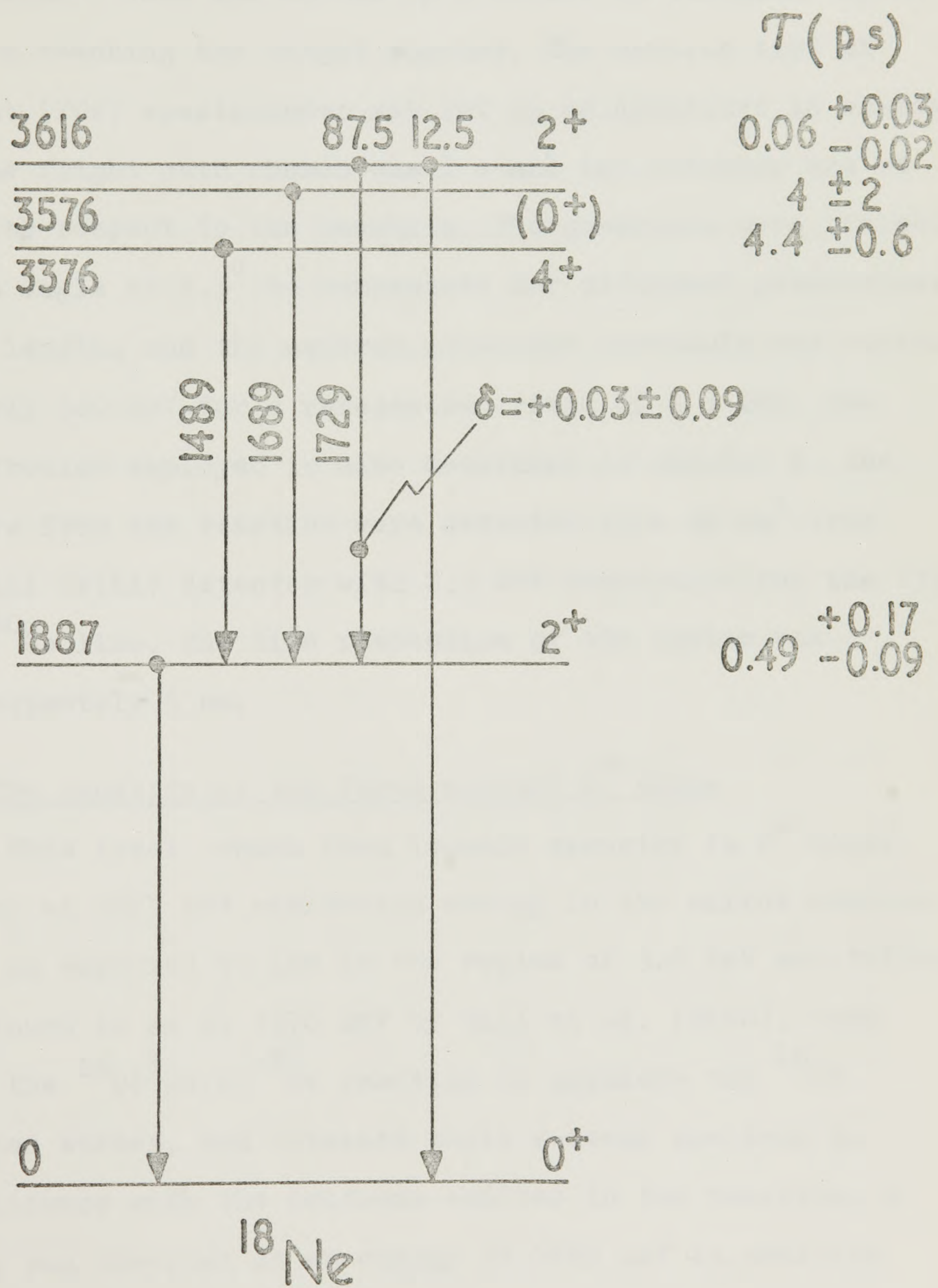


Fig.5.1 - Level scheme of  $^{18}\text{Ne}$ .

level  $\gamma$ -decay and the mixing ratio  $\delta$  are also from this work.

The  $^{18}\text{Ne}$  states studied were populated with the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction ( $Q = -3.196$  MeV). The  $^3\text{He}$  beams - which were obtained from the Oxford Tandem Van de Graaff Generator - were collimated by a series of tantalum annuli before reaching the target chamber. The neutron time of flight (TOF) spectrometer was set up as described in chapter 2; the flight path chosen was 2 m and the detector was at  $0^\circ$  with respect to the beam axis. The quadrants were pivoted at an angle of  $6.5^\circ$  to compensate for different geometrical path lengths and the neutron detection threshold was approximately 500 keV for a  $\gamma$ -rejection ratio of 1 : 100. The electronics employed is also described in chapter 2. The  $\gamma$ -rays from the reaction were detected in a  $36\text{ cm}^3$  true coaxial Ge(Li) detector with 2.3 keV resolution for the 1332 keV  $^{60}\text{Co}$  line. The time resolution of the system was approximately 5 ns.

## 5.2 The location of the first excited $0^+$ state

This level, which from isospin symmetry (a  $0^+$  state occurs at 3627 keV excitation energy in the mirror nucleus  $^{18}\text{O}$ ) is expected to lie in the region of 3.6 MeV excitation, was found to be at 3576 keV by Gill et al. (Gi68). They used the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction to populate the  $^{18}\text{Ne}$  excited states, and obtained their  $\gamma$ -decay spectrum in coincidence with the neutrons emitted in the reaction. A  $\gamma$ -ray was observed at an energy of 1689 keV in addition to the 1489 keV, 1729 keV and 1887 keV  $\gamma$ -rays which had their origin in the transitions  $3376 \rightarrow 1887$ ,  $3616 \rightarrow 1887$  and

$1887 \rightarrow 0$ , respectively. As no neutron time of flight system to select specific excited states populated was used, three different checks were made to confirm that the 1689 keV  $\gamma$ -ray did come from the decay of  $^{18}\text{Ne}$  (Ro69). As a result, these workers could conclude that a state at 3576 keV existed which yielded the 1689 keV  $\gamma$ -ray. The existence of such state was also confirmed by triple  $n$ - $\gamma$ - $\gamma$  coincidences performed following the  $(^3\text{He}, n)$  reaction on  $^{16}\text{O}$  (Ro69a). Evidence for the existence of that state was also patent in particle work done in connection with both the  $(^3\text{He}, n)$  and the  $(p, t)$  reactions (Ad70, Ec70, Fa70). Furthermore, the 3376 keV and 3616 keV states having been unambiguously assigned spins of  $4^+$  and  $2^+$  respectively (from both particle and  $\gamma$ -work), an inspection of the measured  $\gamma$ -angular distribution obtained by (Ro69) shows that the only distribution compatible with  $J = 0$  is the 1689 keV  $\gamma$ -ray one, resulting from the decay of the 3576 keV state.

It was against all the above experimental evidence that Shapiro et al. (Sh70) proposed that the  $0^+$  state was located at 3353 keV excitation energy rather than at 3576 keV. This was based on the observation of a 1466 keV  $\gamma$ -ray in coincidence with the neutrons from the  $^{16}\text{O}(^3\text{He}, n)^{18}\text{Ne}$  reaction populating the  $^{18}\text{Ne}$  3.5 MeV triplet. However, in the two published spectra of (Sh70) at bombarding energies of 9 and 10 MeV, the 1689 keV  $\gamma$ -ray always appear, while the presumable 1466 keV  $\gamma$ -ray, inexistent at 9 MeV bombarding energy, has a width of 2.5 channels when all the other  $\gamma$ -rays in the spectrum (even the 1689 keV one) have a

width of at least 4 channels. Further, the evidence for a 1466 keV  $\gamma$ -ray due to the statistical significance of the 10 MeV spectrum of (Sh70) in that region is non conclusive.

In view of both this discrepancy, and the remaining questions about  $^{18}\text{Ne}$  (see section 5.1) it was decided to employ the neutron time of flight spectrometer in association with the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction, to make use of its level selection facility.

The target used was a  $500\text{ }\mu\text{g.cm}^{-2}$  thick layer of  $\text{WO}_3$  evaporated onto a  $10\text{ mg.cm}^{-2}$  lead backing and the beam energy chosen was 10.3 MeV. The Ge(Li) detector was at a distance of 6 cm from the target. The neutron time of flight spectrum obtained for an integrated target current of 5 mC is shown in fig.5.2. This figure, where the remainder of the "prompt"  $\gamma$ - $\gamma$  peak after PSD can be seen on the left of the spectrum, shows the two separated neutron groups obtained at this energy. The larger peak corresponds to the neutrons populating the  $4^+$ ,  $0^+$  and  $2^+$  triplet at 3.5 MeV whereas the smaller neutron peak corresponds to the population of the first excited state ( $2^+$ ) at 1.89 MeV. At 10.3 MeV bombarding energy (chosen as a balance between the excitation of the 3.58 MeV level (Ro69) and <sup>the</sup>neutron energy resolution) the three neutron groups populating the states at 3.38, 3.58 and 3.62 MeV are not separated. However, by selecting adequate TOF digital windows (W1, W2 and W3 in fig.5.2) in sorting the two dimensional data, one is able to study the  $\gamma$ -decay of the  $^{18}\text{Ne}$  excited states. In window 2 the presence of the 3.58 and 3.62 MeV states is virtually suppressed whereas the  $\gamma$ -rays in the decay of these states are highly enhanced

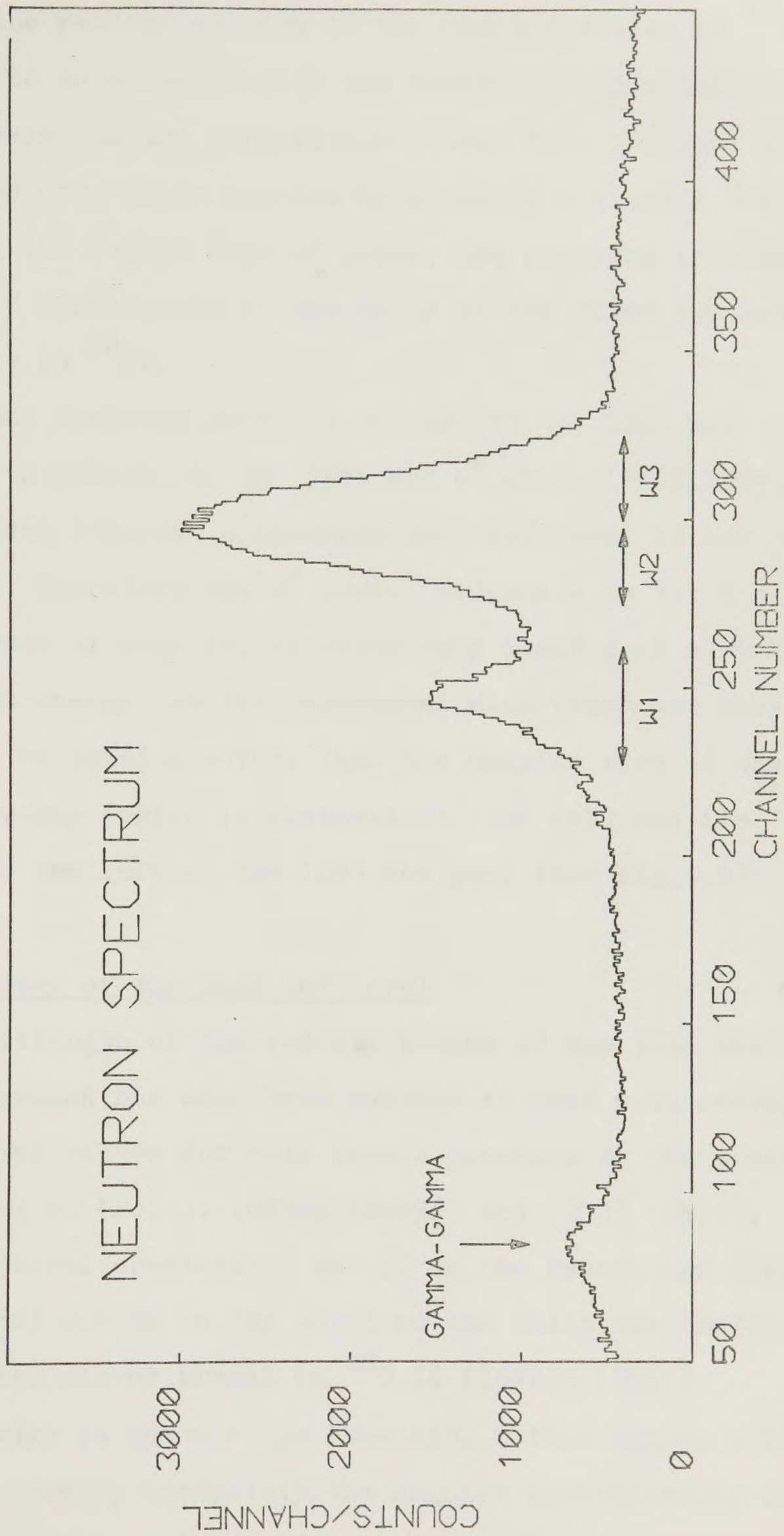


Fig. 5.2 - Neutron time of flight spectrum at  $E_{\text{He}} = 10.3 \text{ MeV}$ .

in the spectrum of window 3, as shown in fig.5.3. Fig.5.3 depicts the  $\gamma$ -decay spectra of the excited states in  $^{18}\text{Ne}$ , obtained in coincidence with the neutron groups populating those levels. Random coincidences (less than 5%) have been subtracted from those spectra by choosing a digital TOF window in the region free of peaks. The spectrum labelled "window 1" corresponds to the decay of the first excited ( $2^+$ ) state in  $^{18}\text{Ne}$ .

In the spectrum labelled "window 3" the 1689 keV  $\gamma$ -ray corresponding to the 3576 keV  $0^+$  state (Gi68,Ro69) is clearly seen (whereas a possible 1466 keV  $\gamma$ -ray is non existent). Therefore the  $0^+$  level, necessary in the  $T = 1$  level scheme of mass 18, is definitely located at 3576 keV excitation energy, in full agreement with (Gi68 and Ro69). It should be noted however, that the Compton edge of the 1729 keV  $\gamma$ -ray (which is centered at 1506 keV) has its maximum to the left of the 1489 keV peak (see fig.5.3).

### 5.3 The decay of the 3616 keV level

The strength of the  $\gamma$ -decay branch of the 3616 keV state to ground has also been subject to some controversy. Experimental values for this branch previous to the present work were  $< 9\%$  (Ro69),  $(8 \pm 2\%)$  (Ro69a) and  $< 3\%$  (Sh70). The theoretical predictions are 3% in the Benson and Irvine model (Be66) and 8% in the Engeland and Ellis one (En72). The measured mirror branch in  $^{18}\text{O}$  is  $(15 \pm 2)\%$  (Ol65).

In order to measure the branching ratios of the 3616 keV state  $\gamma$ -decay accurately the angular distributions of the  $3616 \rightarrow 0$  and  $3616 \rightarrow 1887$   $\gamma$ -transitions have to be

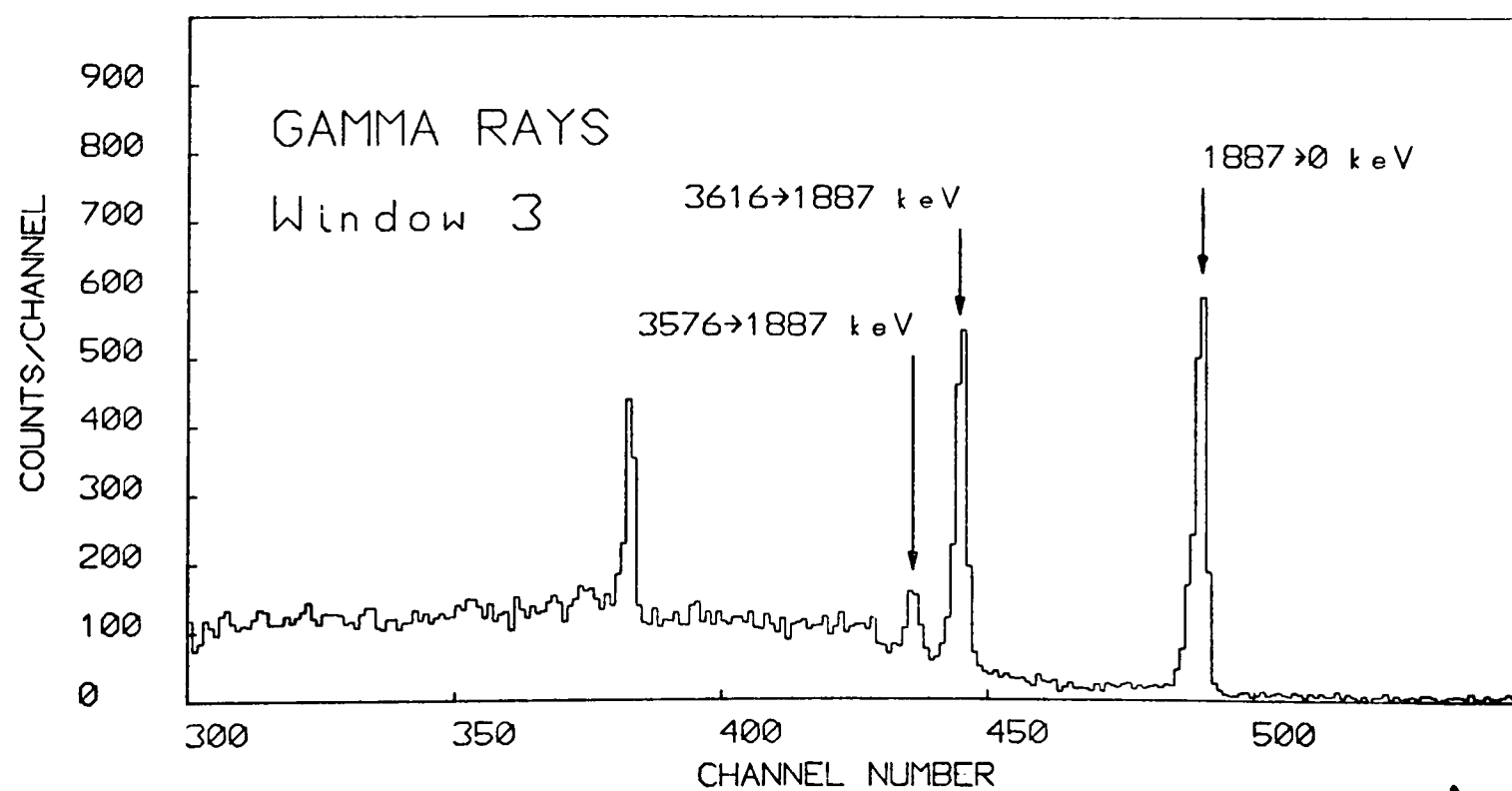
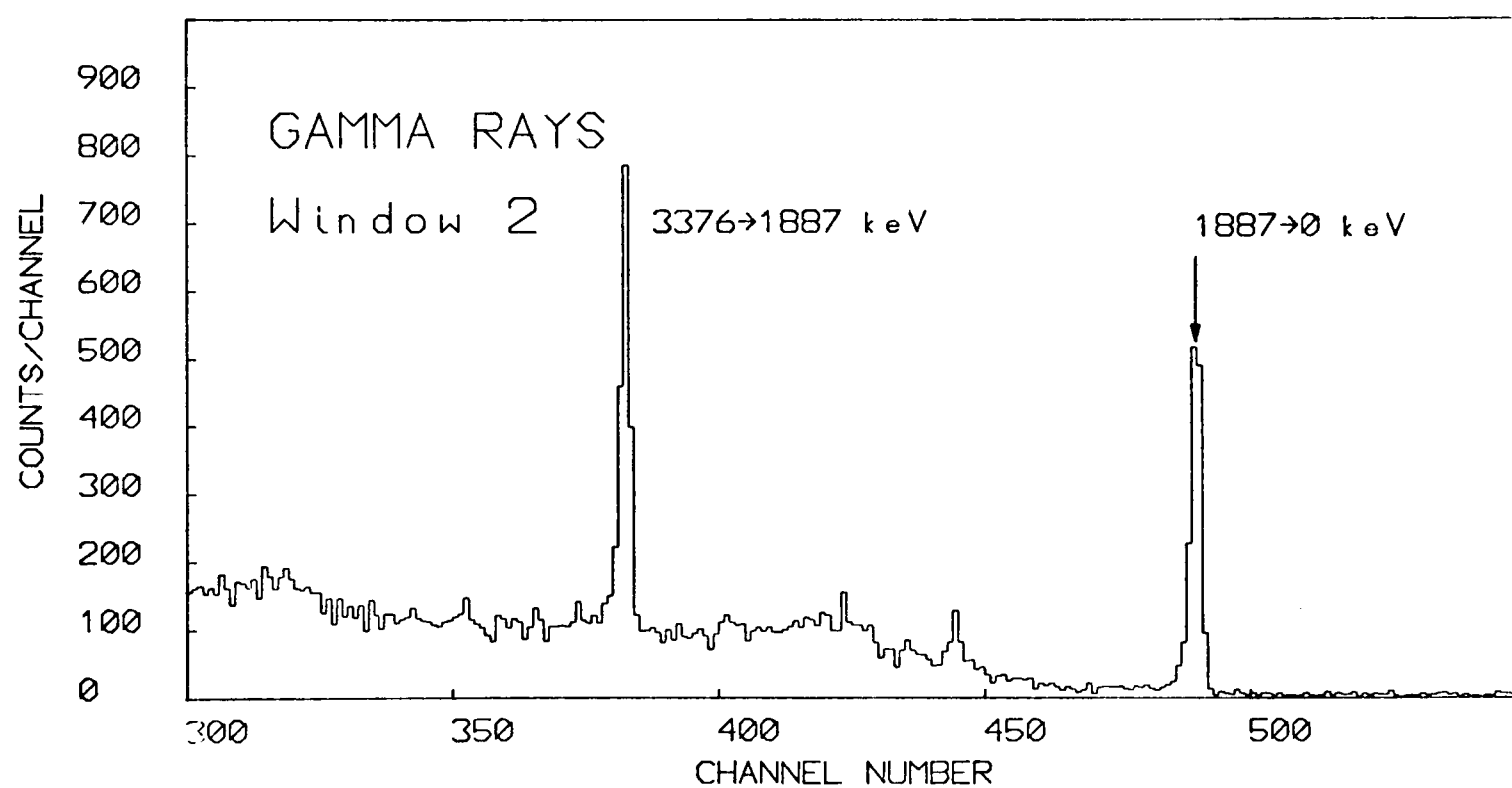
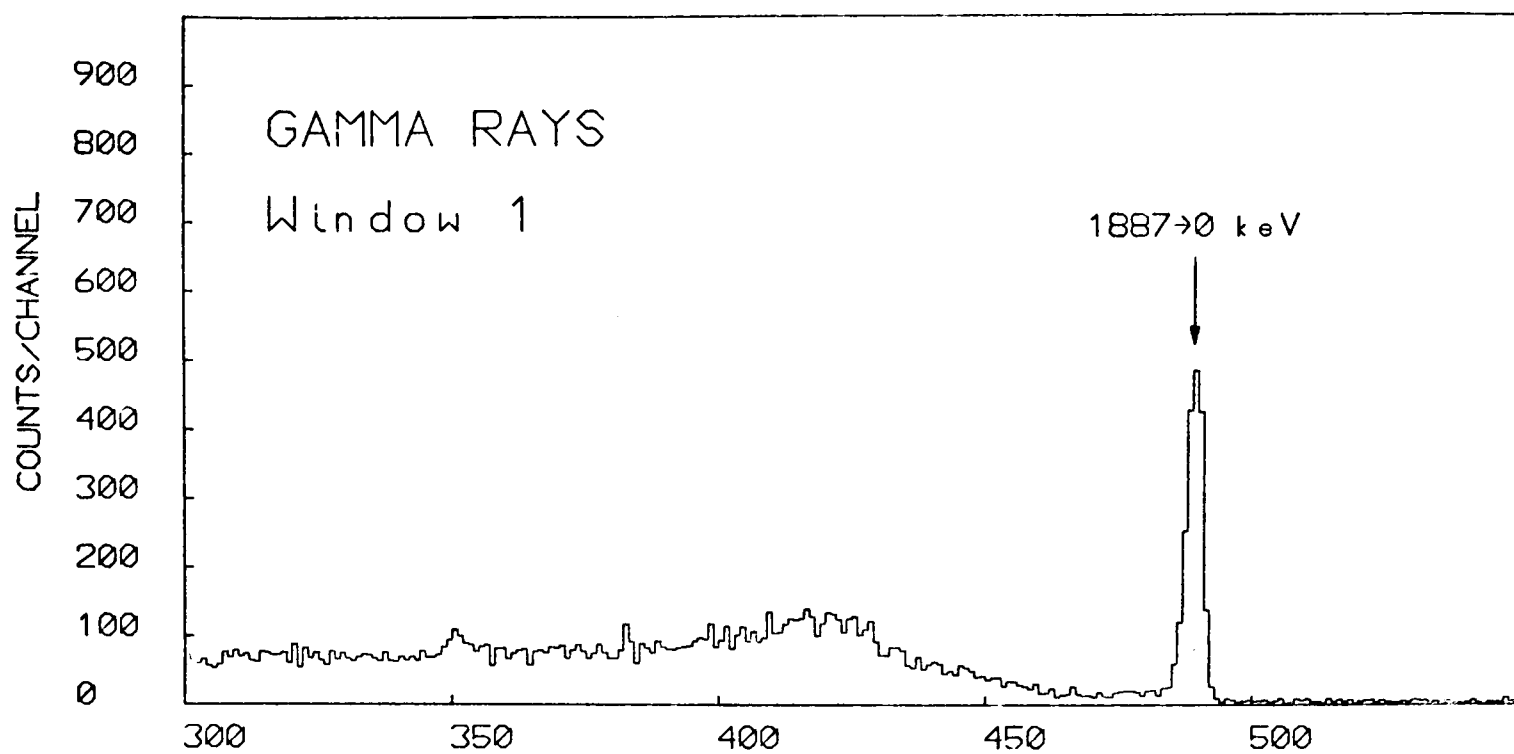


Fig.5.3 - Gamma decay  
spectra of  $^{18}\text{Ne}$  excited

determined, as big effects are expected from their anisotropy. The bombarding energy chosen was 10.3 MeV and a  $\text{WO}_3$  target of  $500 \mu\text{g.cm}^{-2}$  thickness evaporated onto a  $10 \text{ mg.cm}^{-2}$  lead backing was used. The geometry chosen in the experimental arrangement was the "method II" (Li61) or cylindrical one. For this purpose the Ge(Li) detector was placed on a rotating trolley and measurements done at  $90^\circ$ ,  $115^\circ$ ,  $125^\circ$ ,  $135^\circ$ ,  $140^\circ$  and  $145^\circ$  in order to determine the n- $\gamma$  angular correlation. The  $\gamma$ -counter was at a distance of 7.9 cm from the target. Possible anisotropies of the system were checked with the  $^{16}\text{O}(\text{d,p})^{17}\text{O}$  and  $^{16}\text{O}(\text{d,n})^{17}\text{F}$  reactions at a deuteron energy of 3.5 MeV. Making use of the known isotropic  $\gamma$ -decay of the  $1/2^+$  states at 871 keV and 500 keV in  $^{17}\text{O}$  and  $^{17}\text{F}$ , respectively which are strongly populated with those reactions, it was found that the anisotropy of the system was smaller than 1%.

The total neutron time of flight spectrum accumulated during the angular correlation runs (which is similar to the one of fig.5.2) is shown in fig.5.4, for a corresponding integrated target current of approximately 18 mC; the time dispersion is 0.8 ns per channel. Also shown in fig.5.4 is the digital window selected for the study of the  $\gamma$ -decay of the 3616 keV state. In fig.5.5 the  $\gamma$ -rays originated in the decay of this state are shown. Spectra obtained by sorting the two dimensional data and normalised to 3 mC integrated target current are presented for three measuring angles, namely  $90^\circ$ ,  $125^\circ$  and  $145^\circ$ . Randoms have been subtracted from these spectra by choosing a TOF digital window in the region free of peaks. The ground state decay

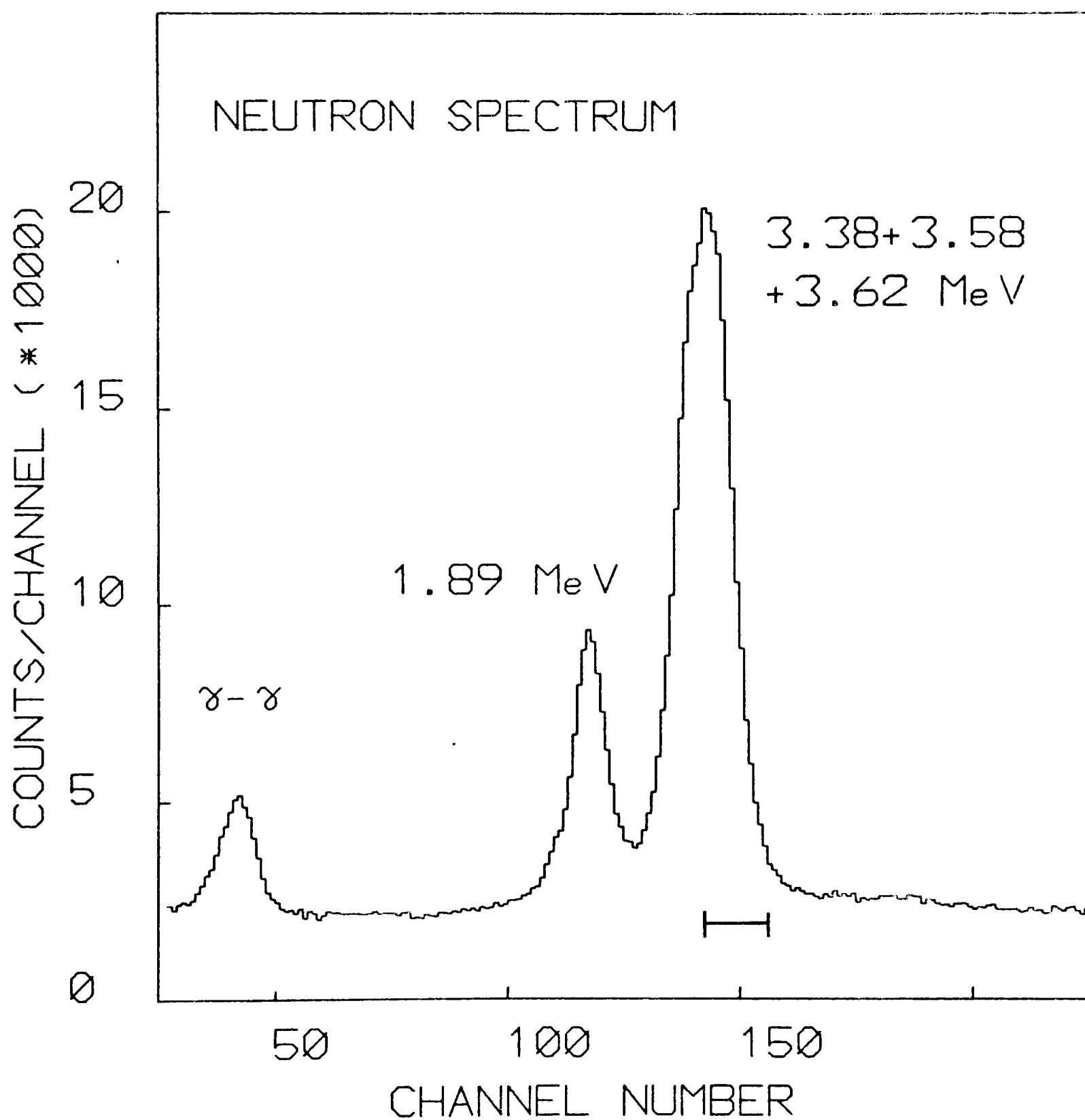


Fig.5.4 - Neutron time of flight spectrum accumulated during the angular correlation runs.

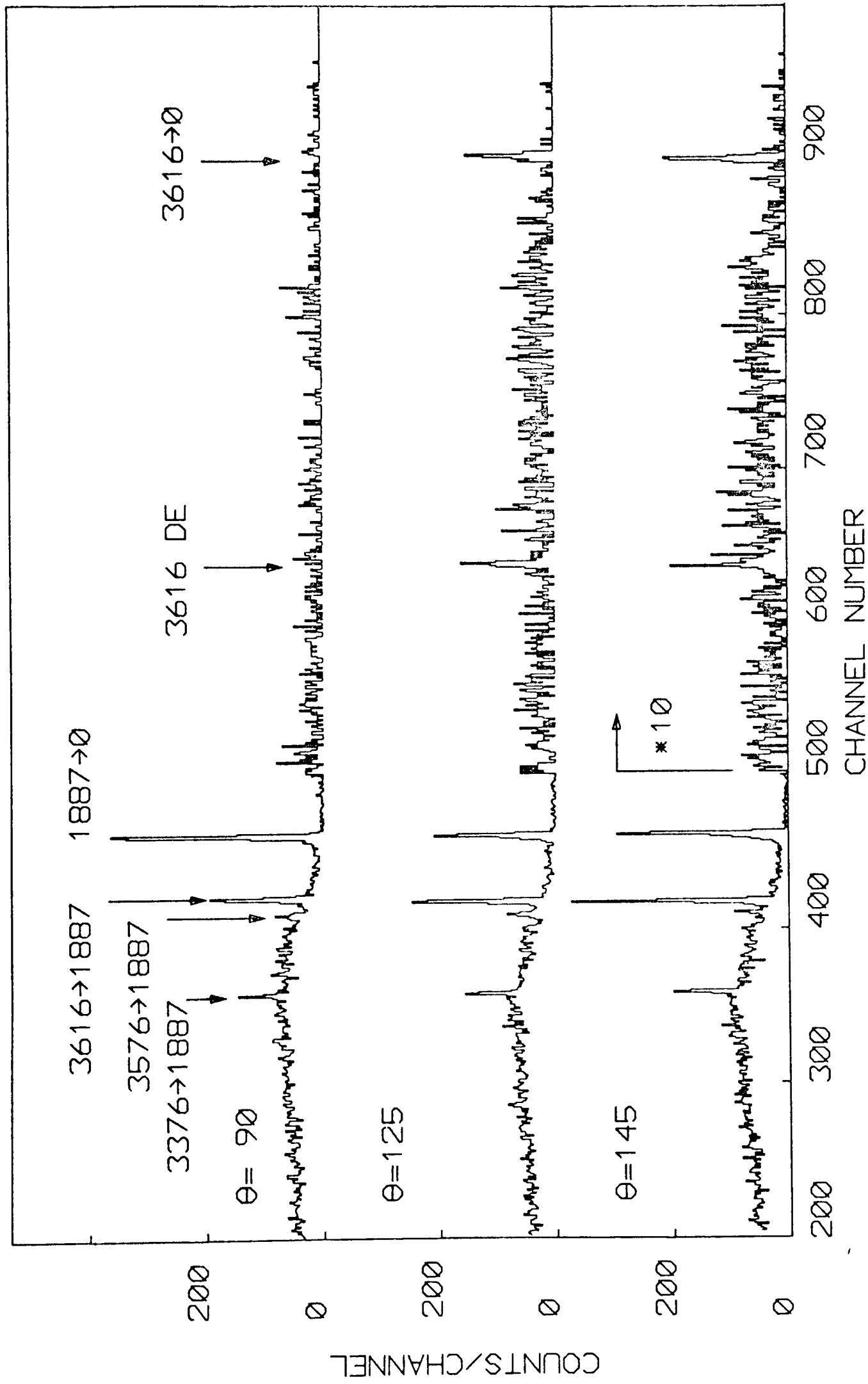


Fig.5.5 - The  $\gamma$ -ray spectra in coincidence with the window of fig.5.4 for  $\theta=90^\circ$ ,  $125^\circ$  and  $145^\circ$ .

of the 3616 keV level is clearly seen in fig.5.5. A small admission of  $\gamma$ -rays originating from the decay of the 3376 keV and 3576 keV levels can also be seen in the spectra of fig.5.5.

Angular distributions were extracted from spectra similar to those shown. The contribution from the population of the 3376 keV and 3576 keV states to the  $1887 \rightarrow 0$  transition was corrected for, when determining the angular distribution of the 1887 keV  $\gamma$ -ray arising from the decay of the 3616 keV state. This was done using  $\gamma$ -spectra sorted with a TOF digital window on the left of the neutron peak at 3.5 MeV. The angular distributions obtained are shown in fig.5.6. A simultaneous least squares fit of the angular distributions predicted by the theory presented in chapter 3 to the three experimental distributions was made, in order to determine the mixing ratio  $\delta$  of the  $3616 \rightarrow 1887$  transition. The geometrical  $Q_K$  coefficients (which correct for the finite size of the Ge(Li) detector) were calculated for the  $\gamma$ -counter used in this experiment by Griffiths (Gr71). A least squares fitting programme aimed at minimising  $S(\underline{a})/f$  (cf. formula (3.23) ) for this case was written by R.D.Gill. The number of free parameters allowed in the fit was five, namely the three normalisation constants, the mixing ratio  $\delta$  of the  $3616 \rightarrow 1887$  transition and the population parameter  $w(0)$  of the initial 3616 keV state (see chapter 3 for the definition of these quantities). Therefore, the number of degrees of freedom is  $f = N - p = 18 - 5 = 13$ . The mixing ratios for the transitions  $3616 \rightarrow 0$  and  $1887 \rightarrow 0$  are identically zero as the initial and

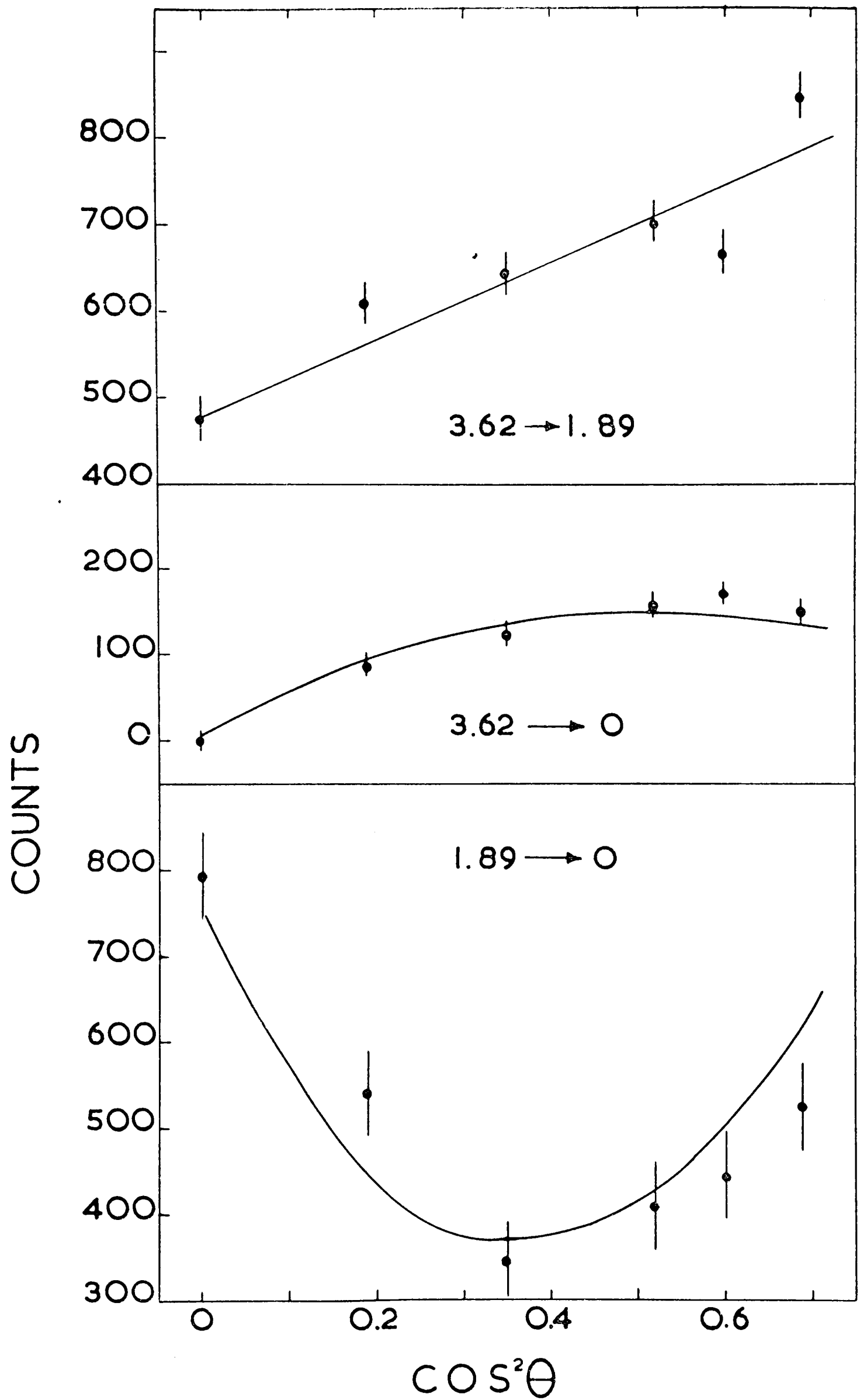


Fig.5.6 - The angular distributions of the three  $\gamma$ -rays originating from the 3616 keV level.

final states in both transitions have spins  $2^+$  and  $0^+$ , respectively. Also, from equation (3.19) only the  $M_1 = 0, \pm 1$  magnetic substates are populated (as the angular acceptance of the neutron detector at 2 m is 92 mstr, cf. discussion following (3.20) ) so that  $w(0) + 2w(1) = 1$ .

From the least squares fit, a mapping of  $(S(\underline{a})/f)(\equiv \chi^2)$  as a function of  $\delta$  and  $w(0)$  was obtained. The values taken from this mapping which correspond in each case to a minimisation with respect to the population parameter  $w(0)$  are plotted in fig.5.7, where  $S(\underline{a})/f$  is simply called  $\chi^2$ . From the plot of 5.7 the minimum of  $\chi^2$  (the value  $S(\underline{a}^*)/f$ ) is clearly found and thus the angular correlation experiment yields a measurement of the mixing ratio  $\delta$  (this value of  $\delta$  is the one which minimises  $\chi^2$ , as discussed in chapter 3). The error associated with the measurement of  $\delta$  was determined using the method described also in chapter 3. Entering with the value of  $F(1, 13, 0.683)$  - taken from table 3.1, page 56 - in formula (3.28) the value  $\delta = +0.03 \pm 0.09$  was found for the  $3616 \rightarrow 1887$   $\gamma$ -transition. The population parameter  $w(0)$  of the 3616 keV state was found to be  $>0.75$  at 10.3 MeV bombarding energy. In fig.5.6, the theoretical angular distributions corresponding to the set of parameters which minimise  $\chi^2$  are represented by the solid lines.

The previously measured values for this mixing ratio were  $-1.1^{+1.0}_{-0.3}$  (Ro69),  $-0.9 \pm 0.7$  (Ro69a) and  $+0.09 \pm 0.07$  (Sh70). In spite of the different methods used by the various authors to determine the mixing ratio errors, if a weighted average of those results and the present one of

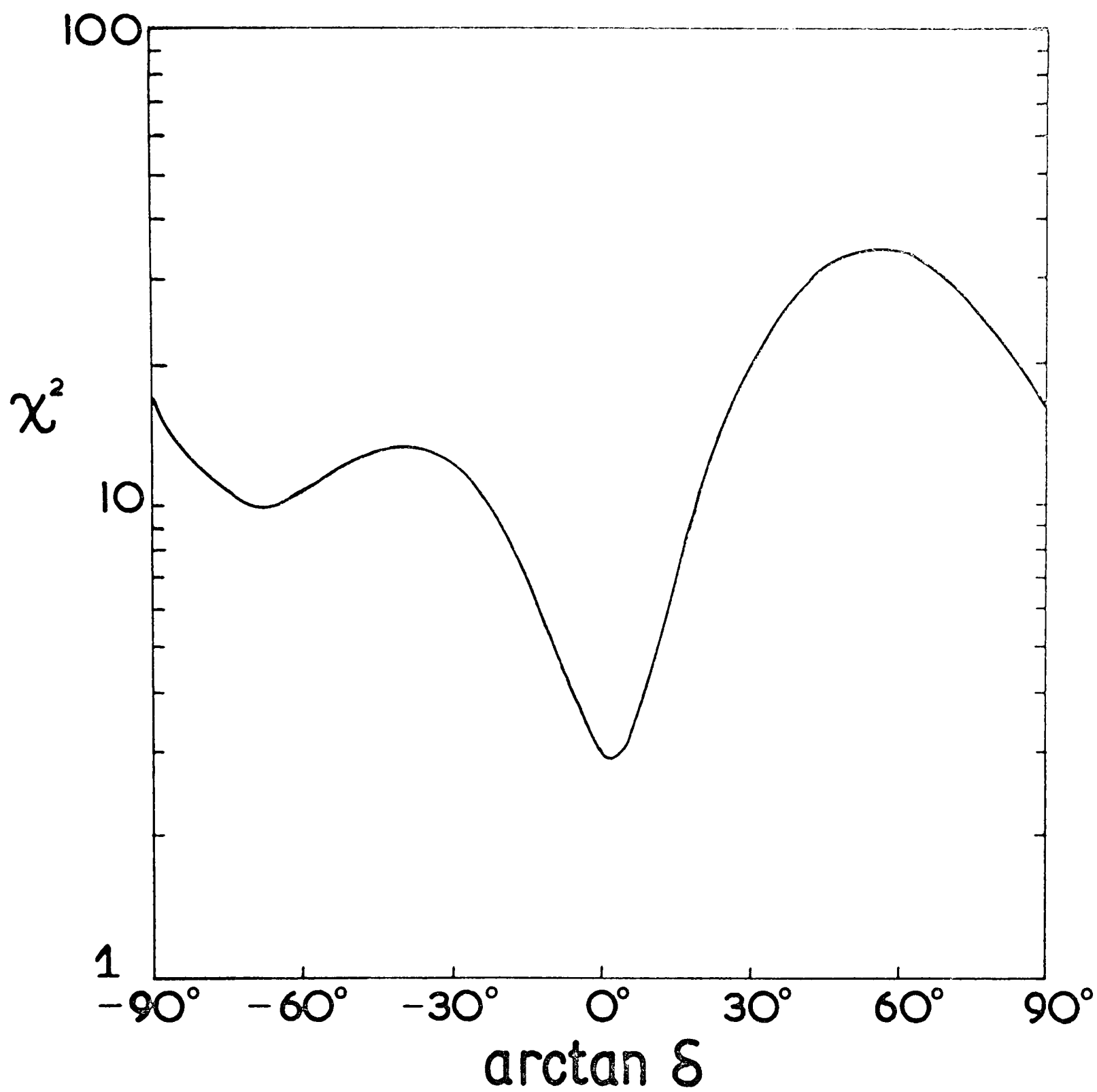


Fig.5.7 - The  $\chi^2$  versus  $\arctan \delta$  plot.

$+0.03 \pm 0.09$  is made, a value  $\delta(3616 \rightarrow 1887) = +0.06 \pm 0.06$  is obtained.

As a result of the angular distribution measurements, the branching ratios of the 3616 keV state  $\gamma$ -decay were also determined. A branching ratio of  $(12.5 \pm 2.5)\%$  for the cross over transition from the 3616 level to the ground was extracted from the distributions. This was done by correcting the normalisation constants (obtained from the simultaneous theoretical fit) using an efficiency curve of the Ge(Li) detector, measured with calibrated  $\gamma$ -sources at 7.9 cm distance. The limit  $< 9\%$  (Ro69), was obtained from spectra taken at  $55^\circ$ . On the other hand, the difference between the present result and that of (Ro69a) may result from the fact that the latter was obtained solely from an assumed theoretical angular distribution. However, the present measurement of  $(12.5 \pm 2.5)\%$  badly disagrees with the limit  $< 3\%$  proposed by (Sh70).

## 5.4 Lifetime measurements

### 5.4.1 The 3376 keV level

As mentioned in 5.1 the lifetime of this level, for which a DSAM determination had been made (Gi68, Ro69), was interesting to measure with the Doppler shift recoil-distance method. The plunger method has been described in chapter 2, where also a description and the techniques of operation of the plunger apparatus were provided.

As the 1489 keV  $\gamma$ -ray (from the transition  $3376 \rightarrow 1887$ ) can be clearly seen in the spectra obtained when bombarding  $^{16}\text{O}$  with  $^3\text{He}$  particles even without a neutron coincidence, the lifetime of the 3376 keV state was studied in singles

experiments, with the Ge(Li) detector at  $0^\circ$  with respect to the beam axis and at a distance of 8 cm from the target. The target was a  $WO_3$  layer of  $120 \mu\text{g.cm}^{-2}$  thickness evaporated onto a gold foil  $5 \text{ mg.cm}^{-2}$  thick. The incident beam energy was 10.8 MeV, and as the energy loss in the foil was approximately 0.7 MeV, the bombarding energy at the target was approximately 10.1 MeV. Singles spectra were taken at various target-stopper separations ( $D$ ) and portions of these spectra showing the shifted and the stopped peaks resulting from the 1489 keV  $\gamma$ -ray for  $D = 0.6, 1.0$  and  $3.0$  thou. (of an inch) are shown in fig.5.8. From spectra similar to those presented in fig.5.8 the experimental ratios  $R$  (defined in chapter 2) were determined. A plot of the variation of  $R$  as a function of the target-stopper distance  $D$  is shown in fig.5.9. It was observed that for large distances the ratio  $R$  tended for a constant value different from zero, in this case 0.25. This reflects the oxygen contamination of the stopper surface, the effect of which is to give rise to a constant component under the unshifted 1489 keV  $\gamma$ -ray. From (2.15) the ratio  $R$  is

$$R = \frac{n}{n_I + n} \exp(-D_0/V_0\tau) + \frac{n_I}{n_I + n} \quad (2.15)$$

The experimental points of fig.5.9 were fitted by a least squares method to an expression of the type  $R = a \exp[-(D-\Delta)/V_0\tau] + 1 - a$  in order to determine the lifetime of the state. Three variables were allowed:  $V_0\tau$ , the zero of the target-stopper separation ( $\Delta$ ) and the constant  $a$ . A mapping of  $S(\underline{a})/f$  (cf. chapter 3) as a function

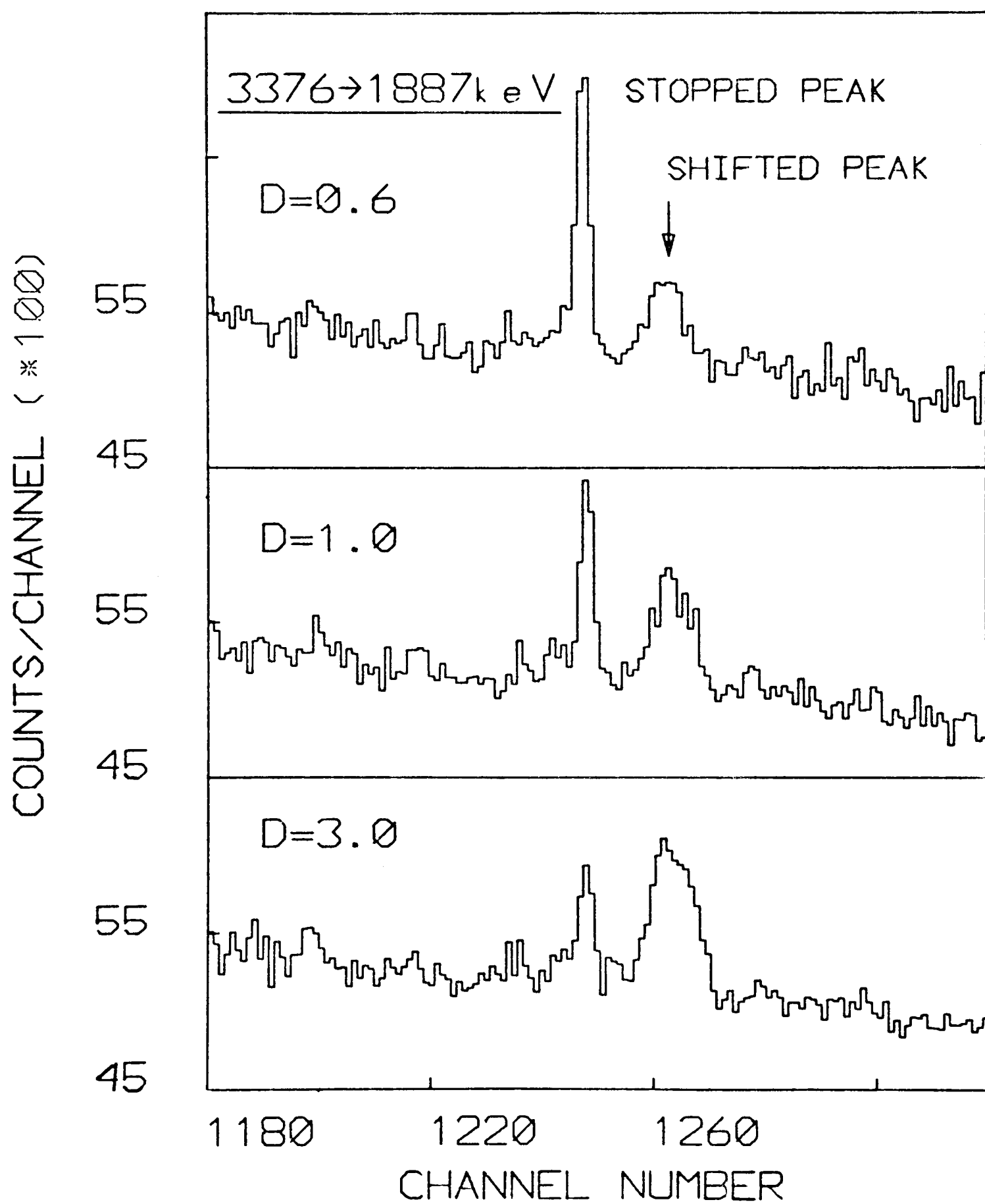


Fig.5.8 - Singles spectra of the 1489 keV  $\gamma$ -ray for D=0.6, 1.0 and 3.0 thou.

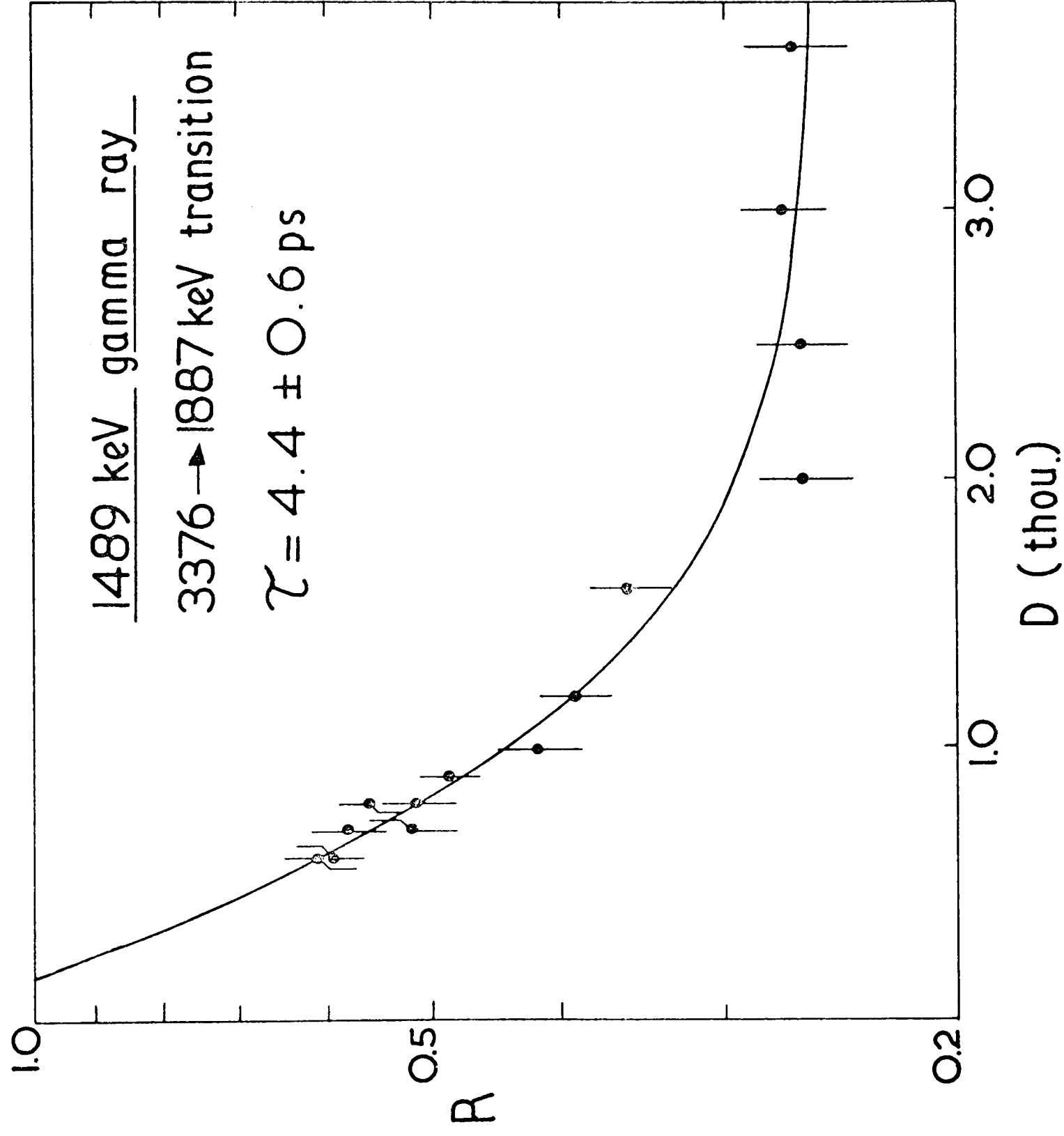


Fig. 5.9 - The ratio R as a function of the target-stopper distance D.

of  $V_0\zeta$  and  $\Delta$  was obtained from which the minimum  $S(\underline{a}^*)/f$  could be found, therefore providing a set of results of the experiment. From the fit,  $\Delta$  was determined to be 0.15 thou, which, making an allowance of 0.1 thou for the gold foil thickness, is 0.05 thou away from the expected value. This small difference with respect to the zero-position as determined by the Michelson interferometer measurement is presumably due to the contraction of the stopper block motivated by the water cooling. The error associated with the value of  $V_0\zeta$  was determined using the method described in chapter 3 for the mixing ratio error evaluations. In the present case the number of degrees of freedom is  $f = N-p = 14-3 = 11$ , and therefore the  $F(1, 11, 0.683)$  value taken from table 3.1 (page 56) was used.

To determine the lifetime of the level from the measured value of  $V_0\zeta$  it is necessary to know  $V_0$ .  $V_0$  can be calculated provided the differential cross sections for the formation of the reaction products are accurately known for the bombarding energy employed. This is not the case however, though it is established that the cross sections are highly peaked in the forward directions in our range of incident beam energy (To68, Ad70). We therefore determined  $V_0$  from the measurement of the mean Doppler shift between the shifted and the stopped peaks (cf. section 2.2). The mean recoil velocity was determined to be  $V_0/c = (1.17 \pm 0.01)\%$  in units of the speed of light, which is in agreement with the assumption of a highly peaked neutron distribution. Also, from the spectra of fig.5.8, it can be seen that the neutrons are emitted predominantly in the forward direction, as the width

due to pure Doppler broadening ( $2\Delta V_0$ ) is (as evaluated from the FWHM of the stopped and shifted peaks) approximately 9 channels. As the mean shift is  $\sim 18$  channels, the value  $\xi = \frac{\Delta V_0}{V_0}$  (defined in (Jo69)) is, in this case,  $\xi \sim 0.25$ . Therefore, the corrections due to the angular distribution of the recoils have been neglected, as using the method prescribed by (Jo69) the experimental intensity ratios  $R$  are affected by less than 1%.

Using the measured values of  $V_0\tau$  and  $V_0$ , a lifetime of  $\tau = 4.4 \pm 0.6$  ps for the 3376 keV level was extracted. The fit to the experimental ratios for this value of  $\tau$  (and for  $\Delta = 0.15$  thou.) is shown as the solid line of fig.5.9. The error 0.6 ps in the measured lifetime also incorporates the uncertainty in the determination of the mean recoil velocity.

The comparison between the present measurement and the DSAM one of  $1.9^{+1.0}_{-0.4}$  ps (Gi68, Ro69) also confirms the concerns about the validity of the LSS stopping theory expressed in chapter 4.

#### 5.4.2 The 3576 keV level

The lifetime of this level was also investigated with the plunger method, but as the 1689 keV  $\gamma$ -ray (originated in the transition  $3576 \rightarrow 1887$ ) is, in singles experiments, completely dominated by  $\gamma$ -rays from the  $^{16}_0(^3\text{He}, p)^{18}_\text{F}$  reaction, a neutron coincidence requirement is necessary. The same beam energy and target as in the measurement of the 3376 keV state lifetime were used. Due to the small cross section for excitation of the 1689 keV line in our energy range, the neutron detector was placed at 1 m distance from

the target. The quadrants were pivoted of an angle of  $10.4^\circ$  to compensate different geometrical and kinematical path lengths at 10.1 MeV bombarding energy. The Ge(Li) detector was at  $30^\circ$  with respect to the beam axis and at a distance of 8 cm from the target. Gamma spectra in coincidence with the 3.5 MeV triplet peak (in the TOF spectrum) were taken for three target-stopper distances  $D$ , namely  $D = 0.50, 0.65$  and  $0.80$  thou. The relevant part of the  $\gamma$ -spectrum for  $D = 0.5$  thou. is shown in fig.5.10. It is seen in this figure that the intensity of the shifted peak is considerably bigger than that of the stopped peak, and therefore only a limit for the lifetime of this level can be extracted. This arises due to the contamination of the stopper surface with oxygen, which was found to account for virtually all the excitation of the unshifted line in the three spectra taken. The amount of oxygen contamination on the tungsten stopper was determined by measuring the experimental ratio  $R$  of the  $1887 \rightarrow 0$   $\gamma$ -transition in coincidence with the 1.89 MeV peak in the TOF spectrum. The lifetime of the 1887 keV level is  $\sim 0.5$  ps and its attenuated shift  $F$  approximately 0.2 (Gi68, Ro69). Thus, all excited nuclear states emanating from the target will decay in flight and produce a fully shifted peak while the  $\gamma$ -rays originated in <sup>the</sup> stopper surface contamination are only 20% shifted and therefore clearly separated from the target ones. In this case, the experimental "ratio  $R$ " measures the level of contamination. Allowing for the contamination present in the different coincidence runs made and taking the value of  $\Delta$  determined in the previous section into account, a limit of  $\tau < 6$  ps is

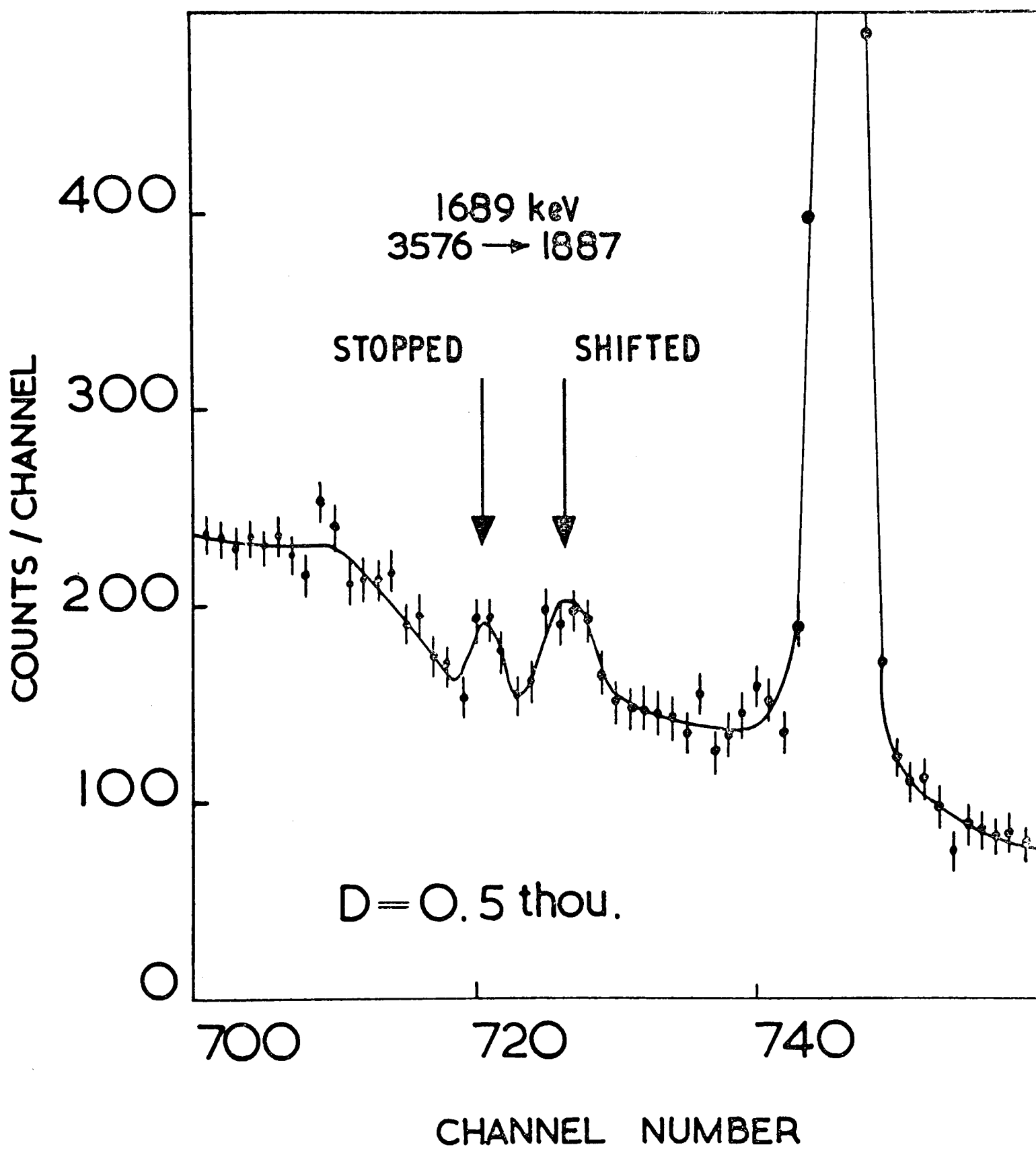


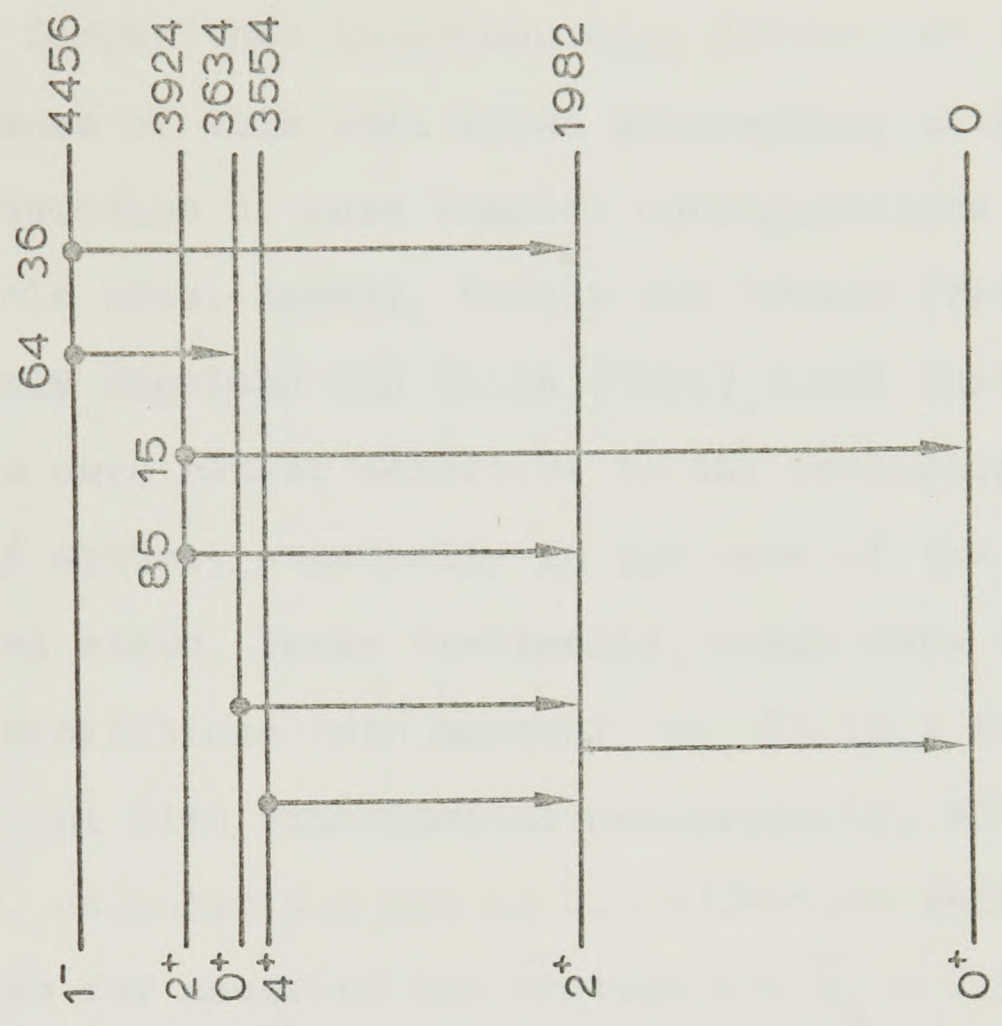
Fig.5.10 - Portion of the  $\gamma$ -ray spectrum taken in coincidence with the 3.5 MeV neutron group. The large peak to the right of the 1689 keV  $\gamma$ -ray is the 1729 keV  $\gamma$ -ray.

placed on the lifetime of the 3576 keV level. The mean recoil velocity, which was needed for this determination, is  $(1.01 \pm 0.01)\%$  of the speed of light. It was calculated from the  $(^3\text{He}, n)$  reaction kinematics, averaging (using the results of (To68 and Ad70) ) the energy of the outgoing neutrons over the surface of the neutron detector. The present limit,  $\tau < 6$  ps, together with the previous one of  $\tau > 2$  ps (Gi68, Ro69), give a value  $\tau(3576) = 4 \pm 2$  ps for the lifetime of this level, where the error quoted determines the lower and upper limits for this lifetime.

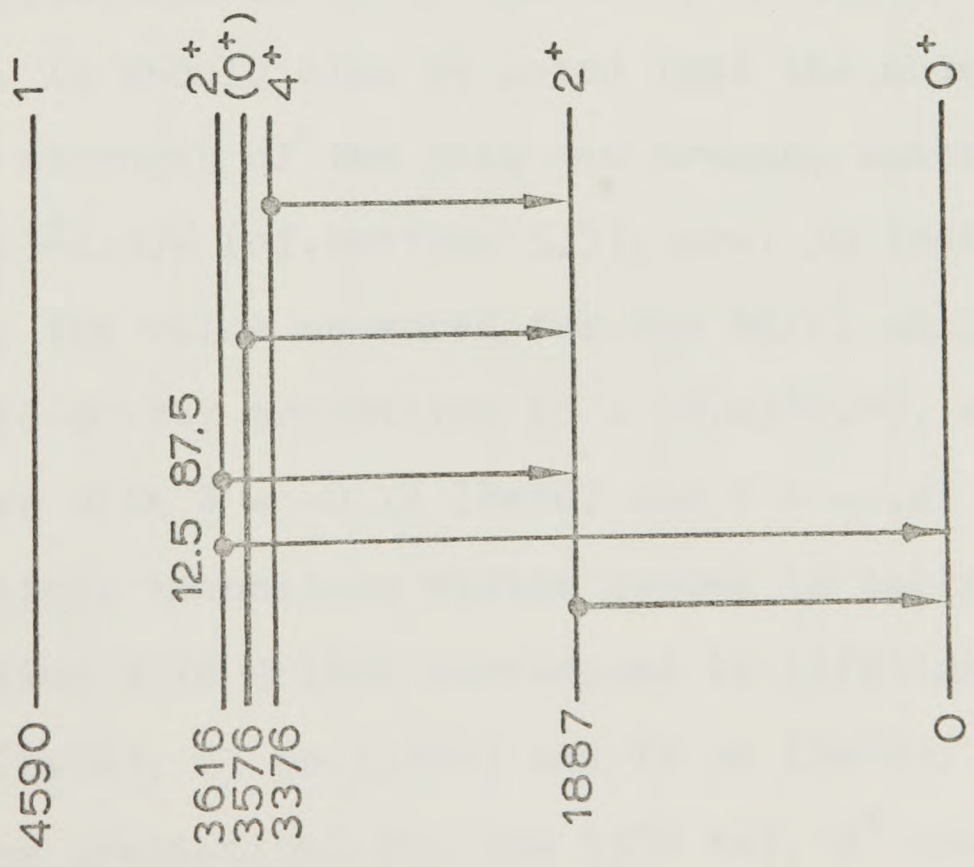
### 5.5 Discussion of results

The  $T = 1$  symmetry of mass 18 is well patent in fig. 5.11, where the low-lying level positions and decay schemes of both  $^{18}\text{Ne}$  and  $^{18}\text{O}$  are presented. Information about  $^{18}\text{O}$  was taken from (Ol65) and (La68a); data referring to  $^{18}\text{Ne}$  was taken from (Gi68), (Ro69) and this work.

As mentioned in section 5.1, shell-model descriptions of mass 18 based on the interactions of two valence particles in the sd shell outside an inert  $^{16}\text{O}$  core have been attempted, e.g. (Fl64), (Ar68). From a least squares fit to a set of two-body interaction matrix elements extracted from experimental low-lying levels in the mass region 18-20, and using a basic space which included all particle states in the  $(s_{1/2})$  and  $(d_{5/2})$  shells, Arima et al. (Ar68) obtained wave functions for many positive parity states in those nuclei. They also calculated electromagnetic transition rates (using a total (effective) charge  $\tilde{e}_n = 0.7$  for the



$^{18}\text{O}$



$^{18}\text{Ne}$

Fig. 5.11 -  $^{18}\text{Ne}$  and  $^{18}\text{O}$  decay schemes.

neutron) which, in the  $^{18}\text{O}$  case, gave rise to a predicted lifetime for the first excited  $0^+$  state approximately 50-60 times larger than experimentally determined (La68a). The existence of this well known discrepancy motivated the consideration of more complex configurations than the 2 particle ones. Namely, Benson and Irvine (Be66) and more recently Engeland and Ellis (En72) found that the transition widths were rather sensitive to the inclusion of 4 particle-2 hole states, especially in the case of the mentioned  $0^+$  excited state. These treatments, which take the effect of core excitations into account, result in a much better agreement with experimental measurements. Both (Be66) and (En72) calculations use an 0.5 effective charge (the total charges for neutrons and protons are  $\tilde{e}_n = 0.5\text{ e}$  and  $\tilde{e}_p = 1.5\text{ e}$ , respectively). As a further test to these models, the results obtained for  $^{18}\text{Ne}$  are presented in table 5.1, together with the predictions of (Be66 and Ar68) as quoted in (Ro69) and (En72). It should also be noted that the model estimates of the strength of the  $3616 \rightarrow 0$  branch, which experimentally is  $(12.5 \pm 2.5)\%$  (cf. section 5.3), are: 3% (Be66) and 8% (En72); the value measured for the E2/M1 mixing ratio of the  $3616 \rightarrow 1887$  transition ( $\delta = +0.03 \pm 0.09$ , cf. section 5.3), compares with  $\delta = -0.17$  (Be66) and  $\delta = -0.21$  (En72). The theoretical transition widths quoted in table 5.1 for the transition  $3576 \rightarrow 1887$  correspond to lifetime values of 13 ps (Be66), 23 ps (Ar68) and 16 ps (En72). It can be seen that the predictions for the 3576 keV,  $0^+$  state lifetime are not in good agreement with the experimental value.

Table 5.1

Experimental and theoretical  $^{18}\text{Ne}$  transition widths

| Transition<br>(keV)     | Multipole | experiment<br>a) | $\Gamma_\gamma$ (meV) |              | (En72) |
|-------------------------|-----------|------------------|-----------------------|--------------|--------|
|                         |           |                  | (Be66)<br>b)          | (Ar68)<br>b) |        |
| $2^+ \rightarrow 0^+$   | E2        | $1.3 \pm 0.3$    | 0.82                  | 0.60         | 0.64   |
| $4^+ \rightarrow 2^+$   | E2        | $0.15 \pm 0.02$  | 0.15                  | 0.14         | 0.16   |
| $(0^+) \rightarrow 2^+$ | E2        | $0.16 \pm 0.08$  | 0.05                  | 0.03         | 0.04   |
| $2^+ \rightarrow 2^+$   | M1        | $9.1 \pm 4.5$    | 9.4                   |              | 6.7    |
|                         | E2        | $0.5 \pm 0.3$    | 1.6                   |              | 0.30   |
| $2^+ \rightarrow 0$     | E2        | $1.4 \pm 0.7$    | 0.40                  | 0.60         | 0.64   |

a) The 1887 and 3616 keV lifetimes were taken from (Gi68,Ro69).

b) As quoted in (Ro69).

This value is, as derived from (Gi68, Ro69) and the present work, of  $\sim 4$  ps. However, the theoretical calculations for the lifetime of the 3376 keV,  $4^+$  state (including those of (Ar68), based on pure 2 particle configurations) yield results in very good agreement with the measured one,  $\tau(3376) = (4.4 \pm 0.6)$  ps. This value compares with 4.3 ps, 4.7 ps and 4.1 ps, obtained from (Be66), (Ar68) and (En72), respectively.

## 6. Spectroscopy of $^{30}\text{S}$ and $^{34}\text{Ar}$

### 6.1 Introduction

There has been less experimental study of proton-rich nuclei of the sd shell than of their mirrors, mainly because the neutrons emitted in the reactions which populate these nuclei cannot be detected as easily or efficiently as light charged particles. However, with the large amount of information available on low-lying levels of nuclei with  $N \gtrsim Z$ , the study of proton-rich nuclei becomes interesting due to the possibility of testing the isospin dependence of electromagnetic transition strengths throughout whole multiplets. On the theoretical side, the shell-model has been applied, with some success, to understand the structure of nuclei in the upper half of the sd shell (Gl64, Er66, Wi69). Recently, calculations of electromagnetic transition rates in mass 30-35 nuclei have been performed (Gl71, Wi71) thus stimulating the measurement of lifetimes in lesser known nuclei of this region.

The ( $^3\text{He},n$ ) reaction has emerged as widely useful for studying nuclei two protons away from the  $Z = N$  line, as has also the ( $p,t$ ) reaction. Measurements have been made of excitation energies and angular distributions of the outgoing light particles for both the ( $^3\text{He},n$ ) (Mc67, Mi67, Ha68) and ( $p,t$ ) (Br69, Pa72) reactions leading to  $^{30}\text{S}$  and  $^{34}\text{Ar}$ . However, the lifetime of the first excited state of  $^{30}\text{S}$  was the only  $\gamma$ -decay property reported in the literature (Bi70) for these two nuclei, before the completion of the present work.

The excited states studied in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  were populated with the  $^{28}\text{Si}(^3\text{He},n)$  and  $^{32}\text{S}(^3\text{He},n)$  reactions, respectively since the large negative Q-values of (p,t) reactions do not favour the study of  $\gamma$ -decay modes. The  $^3\text{He}$  beams-which were obtained from the Oxford Tandem Van de Graaff Generator -were collimated by a series of tantalum annuli before reaching the target chamber. The neutron time of flight (TOF) spectrometer was used to select the individual states excited in  $^{30}\text{S}$  and  $^{34}\text{Ar}$ ; its set up procedure was described in chapter 2. As the measuring times for each spectrum accumulation were of several hours, an  $^{88}\text{Y}$   $\gamma$ -ray source spectrum was collected simultaneously, (to allow the monitoring of the gain of the system) using the electronics scheme also described in chapter 2. The neutron flight path chosen was 2 m and the detector was located at  $0^\circ$  with respect to the beam axis. The quadrants were pivoted by an angle of  $6.5^\circ$  to compensate for different geometrical path lengths and the neutron detection threshold was approximately 600 keV for a  $\gamma$ -rejection ratio of 1 : 200. The  $\gamma$ -rays were detected in an 82 cm<sup>3</sup> time coaxial Ge(Li) detector with 2.8 keV resolution for the 1332 keV  $^{60}\text{Co}$  line. The time resolution of the system was  $\sim 6$  ns.

## 6.2 The $^{30}\text{S}$ nucleus

### 6.2.1 Decay scheme

$^{30}\text{S}$  was studied with the  $^{28}\text{Si}(^3\text{He},n)^{30}\text{S}$  reaction ( $Q = -0.573$  MeV) at 6.5 and 7.5 MeV bombarding energy. A natural silicon 220  $\mu\text{g.cm}^{-2}$  thick target on a 100  $\text{mg.cm}^{-2}$  gold backing was used. In fig.6.1 the level scheme and decay

$$\frac{4.43}{^{29}\text{P} + \text{p}}$$

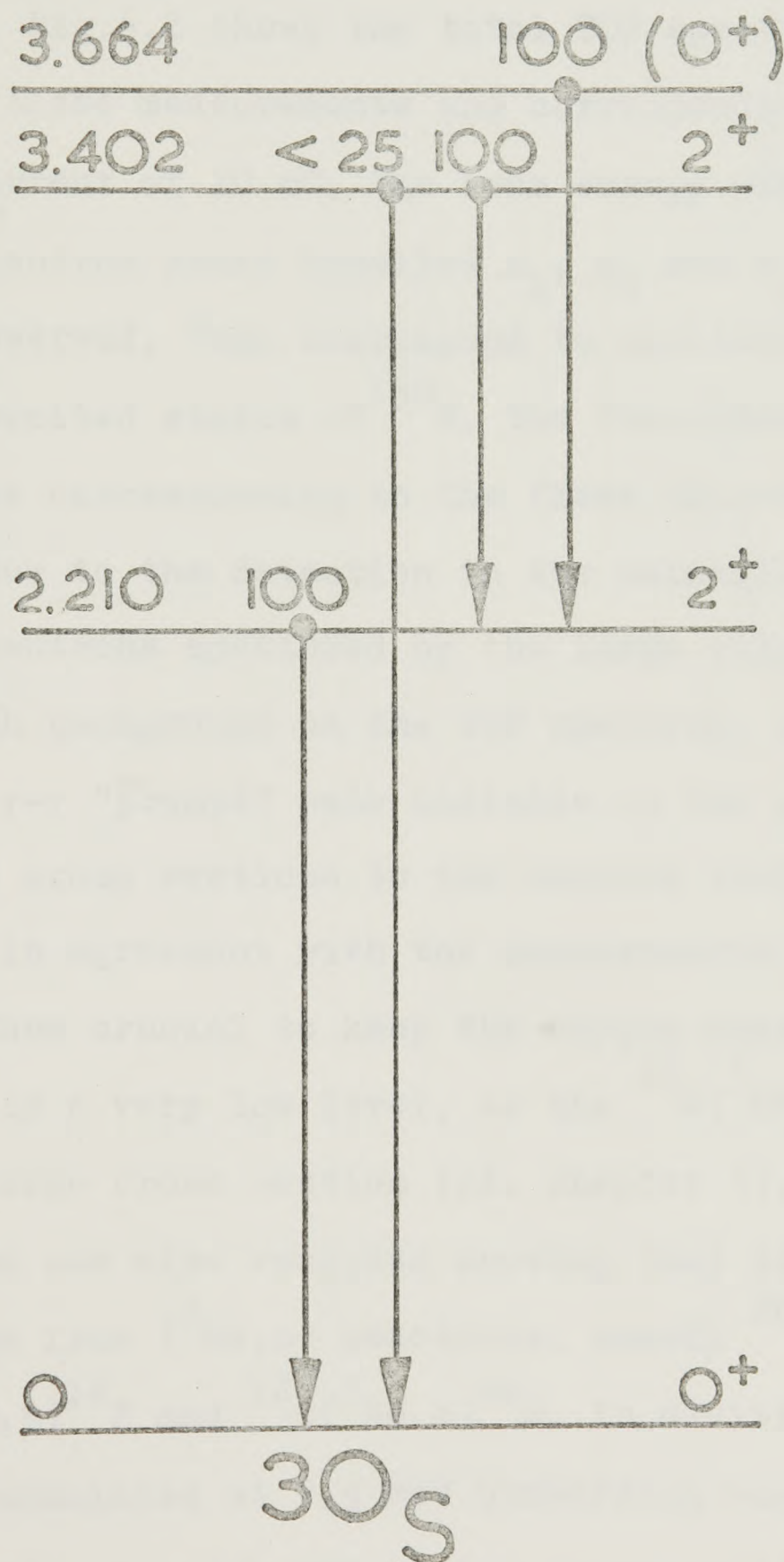


Fig.6.1 - Decay scheme of  $^{30}\text{S}$ .

modes of  $^{30}\text{S}$  as determined in this work are presented. The spin assignments are from (Mc67) and (Pa72).

The  $\gamma$ -detector was placed at a distance of 8 cm from the target on a rotating trolley, and alternate measurements were made at  $35^\circ$  and  $145^\circ$  in order to obtain the decay scheme and Doppler shifts of the  $\gamma$ -rays associated with the decay of  $^{30}\text{S}$ . Fig.6.2 shows the total TOF spectrum accumulated during those measurements and corresponds to an integrated beam current of 20 mC. The beam energy was 6.5 MeV. The three neutron peaks labelled  $n_1$ ,  $n_2$  and  $n_3$  were the only ones observed. They correspond to excitations of the first three excited states of  $^{30}\text{S}$ . The "shoulder" on the left of the peak corresponding to the first excited state was thought to be due to the detection in the scintillator of ground state neutrons scattered by the large volume Ge(Li) detector. The high background on the TOF spectrum, and the pre-eminence of the  $\gamma$ - $\gamma$  "prompt" peak indicate on the other hand that the  $(^3\text{He},n)$  cross sections to the excited states are fairly small, in agreement with the measurements of (Mc67 and Mi67). It is then crucial to keep the oxygen contamination in the target to a very low level, as the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction has a large cross section (cf. chapter 5). A  $\gamma$ -singles spectrum was also recorded showing that its dominant  $\gamma$ -rays all came from  $(^3\text{He},p)$  reactions, namely  $^{28}\text{Si}(^3\text{He},p)^{30}\text{P}$ ,  $^{16}\text{O}(^3\text{He},p)^{18}\text{F}$  and  $^{12}\text{C}(^3\text{He},p)^{14}\text{N}$ . In addition, TOF spectra were accumulated at 7.5 MeV bombarding energy and the  $\gamma$ -spectra in coincidence with the neutron groups emitted were investigated; however, they showed no evidence for the

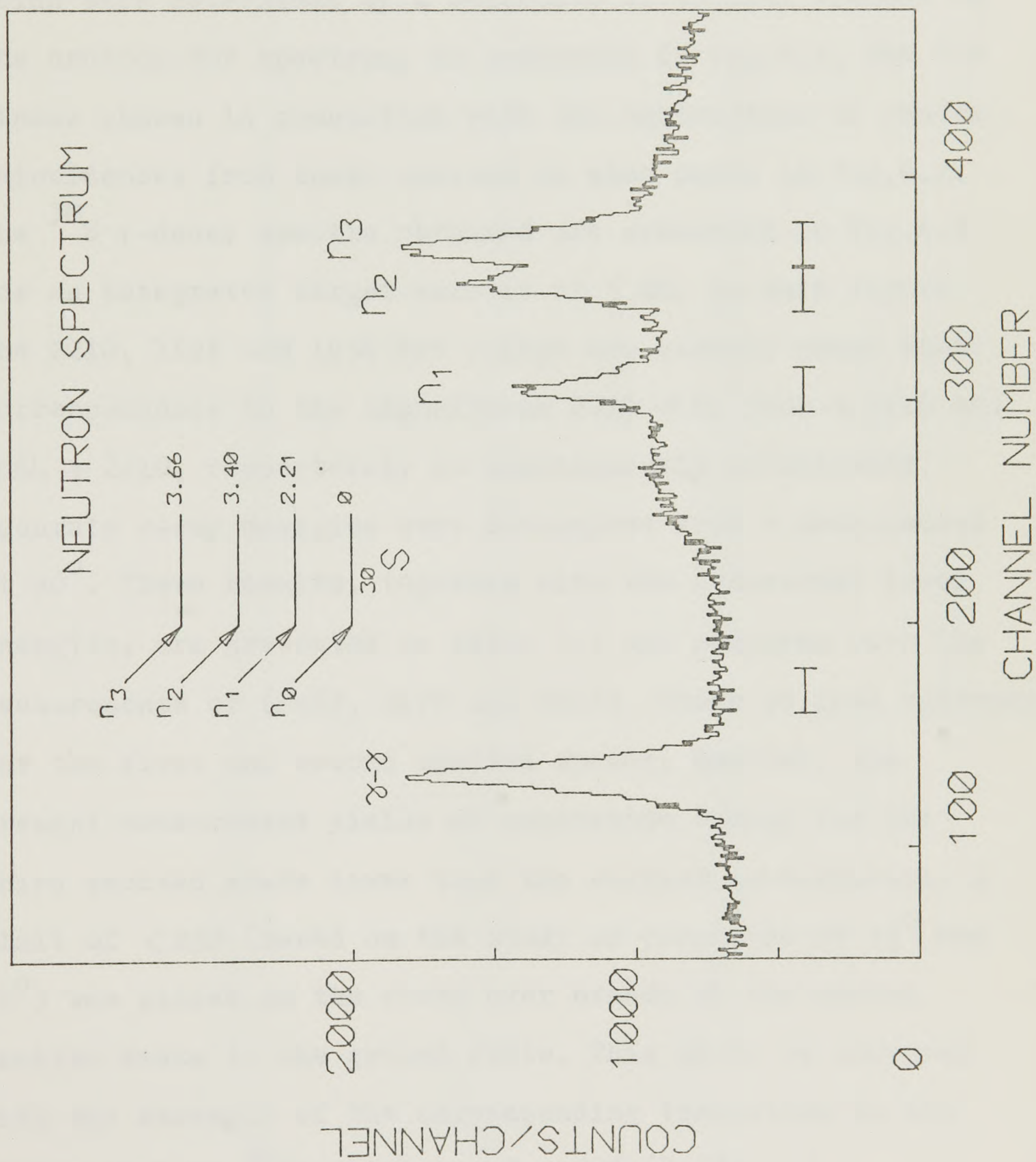


Fig.6.2 - Neutron time of flight spectrum at  $E_{^3\text{He}} = 6.5 \text{ MeV}$ .

excitation of states other than those observed at 6.5 MeV bombarding energy.

The  $\gamma$ -decay spectra of the  $^{30}\text{S}$  states excited by the  $(^3\text{He}, n)$  reaction at a bombarding energy of 6.5 MeV were obtained by sorting the two dimensional data into slices which were determined by a selection of digital windows on the neutron TOF spectrum, as indicated in fig.6.2. The TOF window chosen in connection with the subtraction of random coincidences from those spectra is also shown in fig.6.2. The  $^{30}\text{S}$   $\gamma$ -decay spectra obtained are presented in fig.6.3 for an integrated target current of 5 mC. In this figure the 2210, 1192 and 1454 keV  $\gamma$ -rays are clearly seen; their correspondence to the transitions  $2210 \rightarrow 0$ ,  $3402 \rightarrow 2210$  and  $3664 \rightarrow 2210$ , respectively is unambiguously established. Accurate  $\gamma$ -ray energies were determined from a measurement at  $90^\circ$ . These results, together with the associated level energies, are presented in table 6.1 and compared with the measurements of (Mc67, Bi70 and Pa72). There is good agreement for the first and second excited states; however, the present measurement yields an excitation energy for the third excited state lower than the earlier measurements. A limit of  $< 25\%$  (based on the study of  $\gamma$ -spectra at  $35^\circ$  and  $90^\circ$ ) was placed on the cross over branch of the second excited state to the ground state. This is to be compared with the strength of the corresponding transition in the mirror nucleus  $^{30}\text{Si}$  which is of  $\sim 50\%$  (Br67).

### 6.2.2 Lifetime measurements

The lifetimes of the first three excited states in  $^{30}\text{S}$  at 2210, 3402 and 3664 keV, respectively were investigated

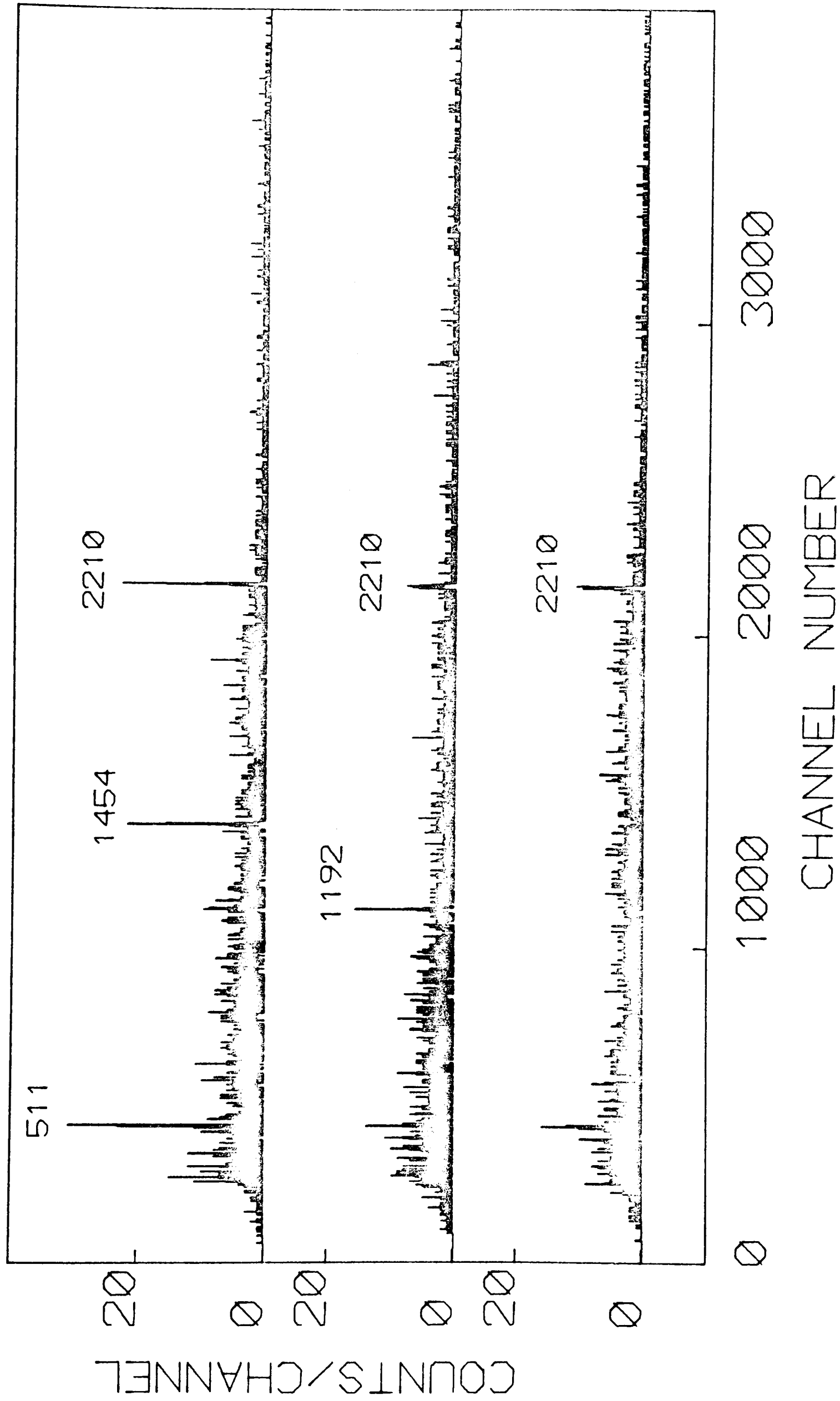


Fig.6.3 -  $^{30}\text{S}$   $\gamma$ -decay spectra.

Table 6.1

$\gamma$ -ray and excitation energies in  $^{30}\text{S}$

| $E_{\gamma}$ (keV) | Transition              | $E_x$ (keV)     |             |               |
|--------------------|-------------------------|-----------------|-------------|---------------|
|                    |                         | Present work    | (Bi70)      | (Mc67) (Pa72) |
| $2209.9^{+1.1}$    | $2210 \rightarrow 0$    | $2209.9^{+1.1}$ | $2210^{+1}$ | $2239^{+18}$  |
| $1192.3^{+0.9}$    | $3402 \rightarrow 2210$ | $3402.2^{+1.4}$ |             | $3438^{+14}$  |
| $1454.3^{+0.7}$    | $3664 \rightarrow 2210$ | $3664.2^{+1.3}$ |             | $3707^{+25}$  |

with the Doppler shift attenuation method (DSAM). This method has been described in chapter 2. Measurements were made at a beam bombarding energy of 6.5 MeV. The shifts of the  $\gamma$ -rays obtained in coincidence with the neutron groups populating the three levels excited are shown in fig.6.4. In this composite figure only the relevant part of each decay spectrum is shown, i.e. the  $2210 \rightarrow 0$   $\gamma$ -ray<sup>as</sup> in coincidence with the  $n_1$  peak, and the  $3402 \rightarrow 2210$  and  $3664 \rightarrow 2210$   $\gamma$ -rays as in coincidence with the  $n_2$  and  $n_3$  peaks, respectively (cf. fig.6.2).

Experimental F-values were obtained dividing the mean Doppler shifts (between  $\theta = 35^\circ$  and  $\theta = 145^\circ$ , as shown in fig.6.4) by the respective maximum shifts as obtained from kinematics. The initial recoil velocity  $V_0$  was determined from the reaction kinematics assuming an isotropic angular distribution in the centre of mass system and averaging the energy of the outgoing neutrons over the surface of the neutron detector. Lifetimes were then extracted by comparing the experimental F-values with the theoretical  $F(\tau)$  curves. These curves were calculated by the Oxford DSAM programme (cf. section 4.3), which treats large angle scattering effects as suggested by Blaugrund (Bl66). The  $dE/dx$  values used in the programme were those of Lindhard et al. (Li63). As no experimental data for the stopping power of sulphur ions recoiling in silicon were available for the range of initial velocities encountered in the present experiment, no corrections were made to the theoretical stopping powers. Only a 20% systematic error due to uncertainties in the LSS theory was added to the statistical error in each case,

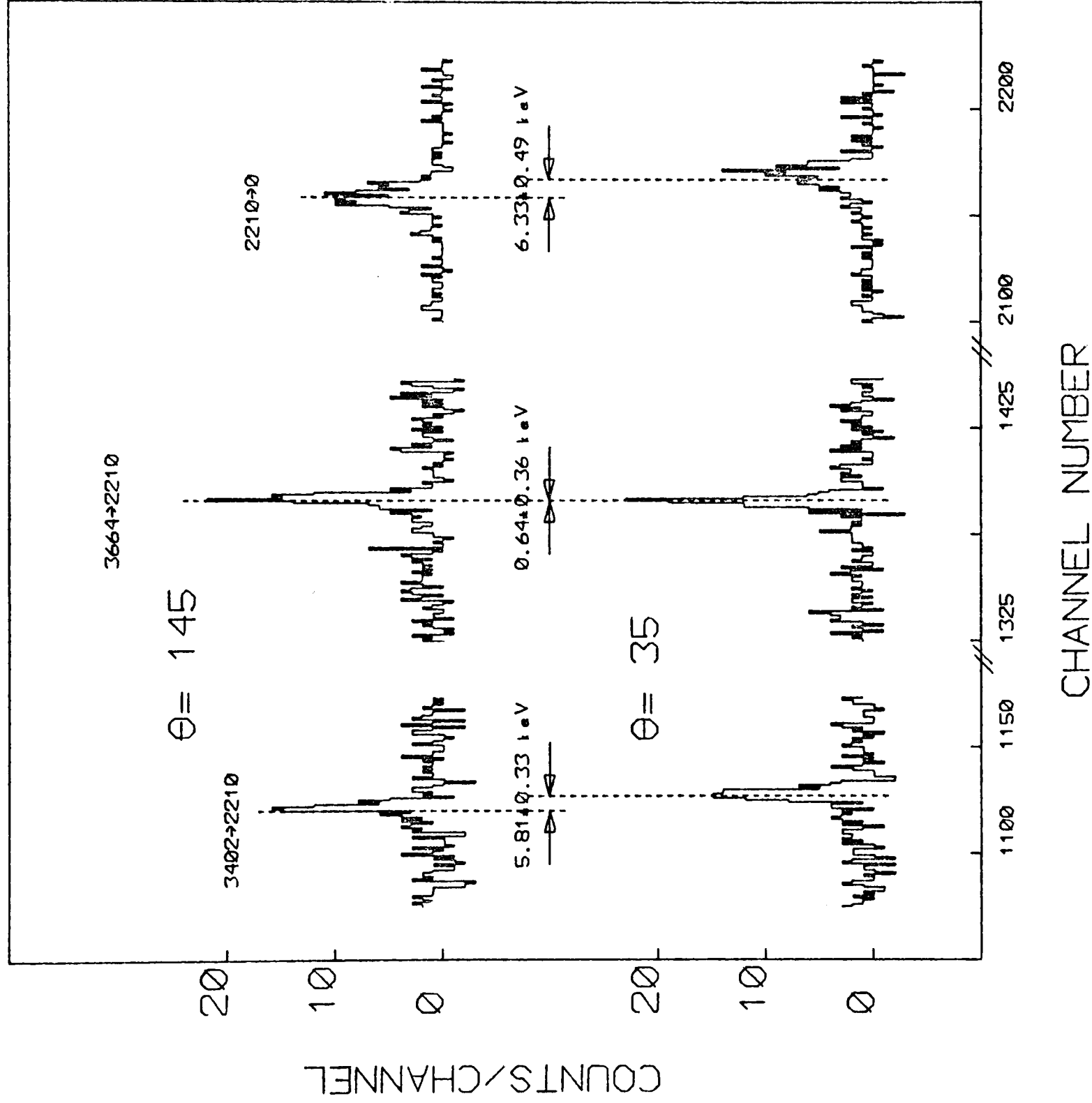


Fig.6.4 - Relevant parts of the  $\gamma$ -decay spectra taken in coincidence with the digital windows shown in fig.6.2 for  $\theta = 145^\circ$  and  $35^\circ$ .

following the suggestion of Currie et al. (Cu69a). A critical analysis of the present DSAM measurements is made in section 4.4, p.82.

The  $^{30}\text{S}$  lifetime results are shown in table 6.2. The earlier measurement of the 2210 keV level lifetime by Bini et al. (Bi70) (using a  $^3\text{He}$  bombarding energy of 4.4 MeV but no neutron coincidences) is only marginally in agreement with the present value.

### 6.3 The $^{34}\text{Ar}$ nucleus

#### 6.3.1 Decay scheme

The nucleus  $^{34}\text{Ar}$  was investigated with the  $^{32}\text{S}(^3\text{He},n)^{34}\text{Ar}$  reaction ( $Q = -0.759$  MeV) at 7.5, 8.5 and 10 MeV bombarding energy. In a naïve shell model picture the target nuclei  $^{32}\text{S}$  and  $^{28}\text{Si}$  should look more or less the same, one representing closed shells up to  $(2s_{1/2})$  and the other up to  $(1d_{5/2})$ , respectively. Adding two protons by the  $(^3\text{He},n)$  reaction with similar  $Q$ -values, then leads one to expect that both reactions should proceed in roughly the same way. However, no appreciable level excitation was observed below  $E_{^3\text{He}} = 7.5$  MeV and the neutron TOF spectra obtained at 7.5, 8.5 and 10 MeV were dominated by a single state situated approximately at 4.51 MeV excitation energy. A further difficulty arises at these higher bombarding energies because any oxygen contamination of the target leads to neutrons from the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction, which in this case begin to overlap with the  $^{32}\text{S}(^3\text{He},n)^{34}\text{Ar}$  reaction peaks. Natural  $\text{Ag}_2\text{S}$   $500 \mu\text{g.cm}^{-2}$  thick targets on  $100 \text{mg.cm}^{-2}$  gold backings were used. In fig.6.5 the level scheme and decay modes of  $^{34}\text{Ar}$  as determined in this work are presented.

Table 6.2

$^{30}\text{S}$  lifetime results

| $E_x(\text{keV})$ | $V_0/c(\%)$ | $E_\gamma(\text{keV})$ | $F(\tau)$              | $\tau(\text{fs})$ | $\tau(\text{fs})$<br>(B170) |
|-------------------|-------------|------------------------|------------------------|-------------------|-----------------------------|
| 2210              | 0.400       | 2210                   | $0.45^{+0.04}_{-0.04}$ | $310^{+75}_{-75}$ | $175^{+50}_{-50}{}^b)$      |
| 3402              | 0.456       | 1192                   | $0.66^{+0.04}_{-0.04}$ | $160^{+45}_{-45}$ |                             |
| 3664              | 0.471       | 1454                   | $0.06^{+0.03}_{-0.03}$ | $>1400{}^a)$      |                             |

- a) Limit corresponds to three standard deviations from the measured value
- b) The original error has been increased by 20% (of the measured lifetime value) to include additional uncertainties arising from the use of the LSS theory as discussed in the text.

$$\frac{4.67}{^{33}\text{Cl}+p}$$

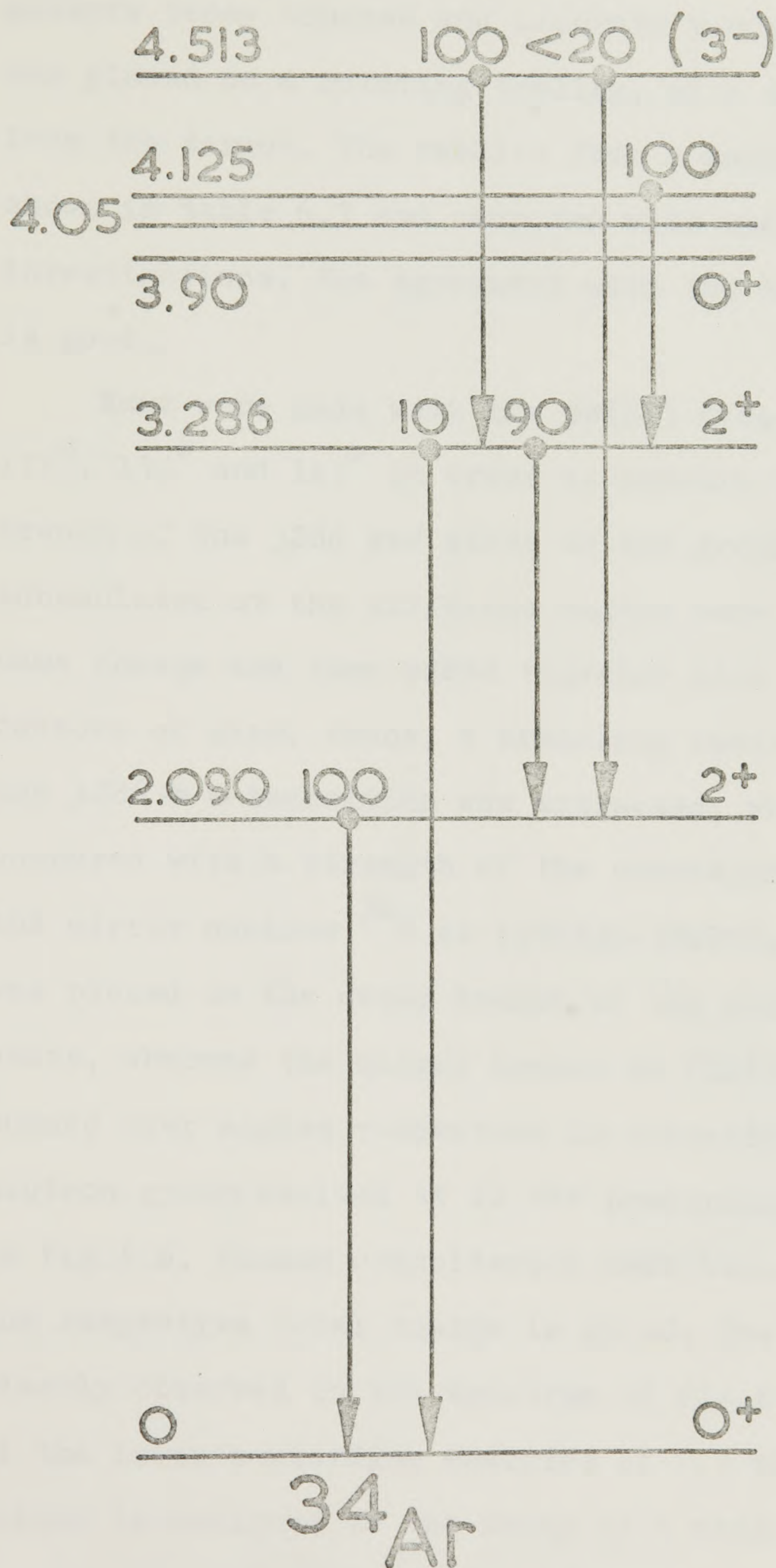


Fig.6.5 - Decay scheme of  $^{34}\text{Ar}$ .

The spin assignments are from (Br69), from which the excitation energies for the levels not observed in this work are also taken.

A beam bombarding energy of 10 MeV was chosen to measure decay schemes and accurate  $\gamma$ -energies. The  $\gamma$ -detector was placed on a rotating trolley, at a distance of 8.3 cm from the target. The results from a measurement at  $90^\circ$  are shown in table 6.3 and compared with those of previous investigations. The agreement with the earlier determinations is good.

Runs were made with the Ge(Li) detector at  $90^\circ$ ,  $115^\circ$ ,  $125^\circ$ ,  $135^\circ$  and  $145^\circ$  in order to measure the cross over branch of the 3286 keV state to the ground. The spectra accumulated at the different angles were normalised to the same charge and then added together with individual weighting factors of  $\sin\theta$ . Hence, a branching ratio of  $(10 \pm 7)\%$  for the  $3286 \rightarrow 0$  transition was extracted, which is to be compared with a strength of the corresponding decay in the mirror nucleus  $^{34}\text{S}$  of  $(50 \pm 5)\%$  (Mo70). A limit of  $<20\%$  was placed on the decay branch of the 4513 keV to 2090 keV state, whereas the mirror branch is  $(24 \pm 5)\%$  (Mo70). The summed over angles  $\gamma$ -spectrum in coincidence with all the neutron groups excited at 10 MeV bombarding energy is shown in fig.6.6. Random coincidences have been subtracted and the respective total charge is 55 mC. The 839 keV  $\gamma$ -ray as clearly observed in the spectrum of fig.6.6 is not excited at the lower bombarding energies of 7.5 and 8.5 MeV. Its origin is assigned to the decay of a state at an excitation energy of 4125 keV, thus confirming the existence of a level at  $(4150 \pm 30)$  keV as reported by (Ha68).

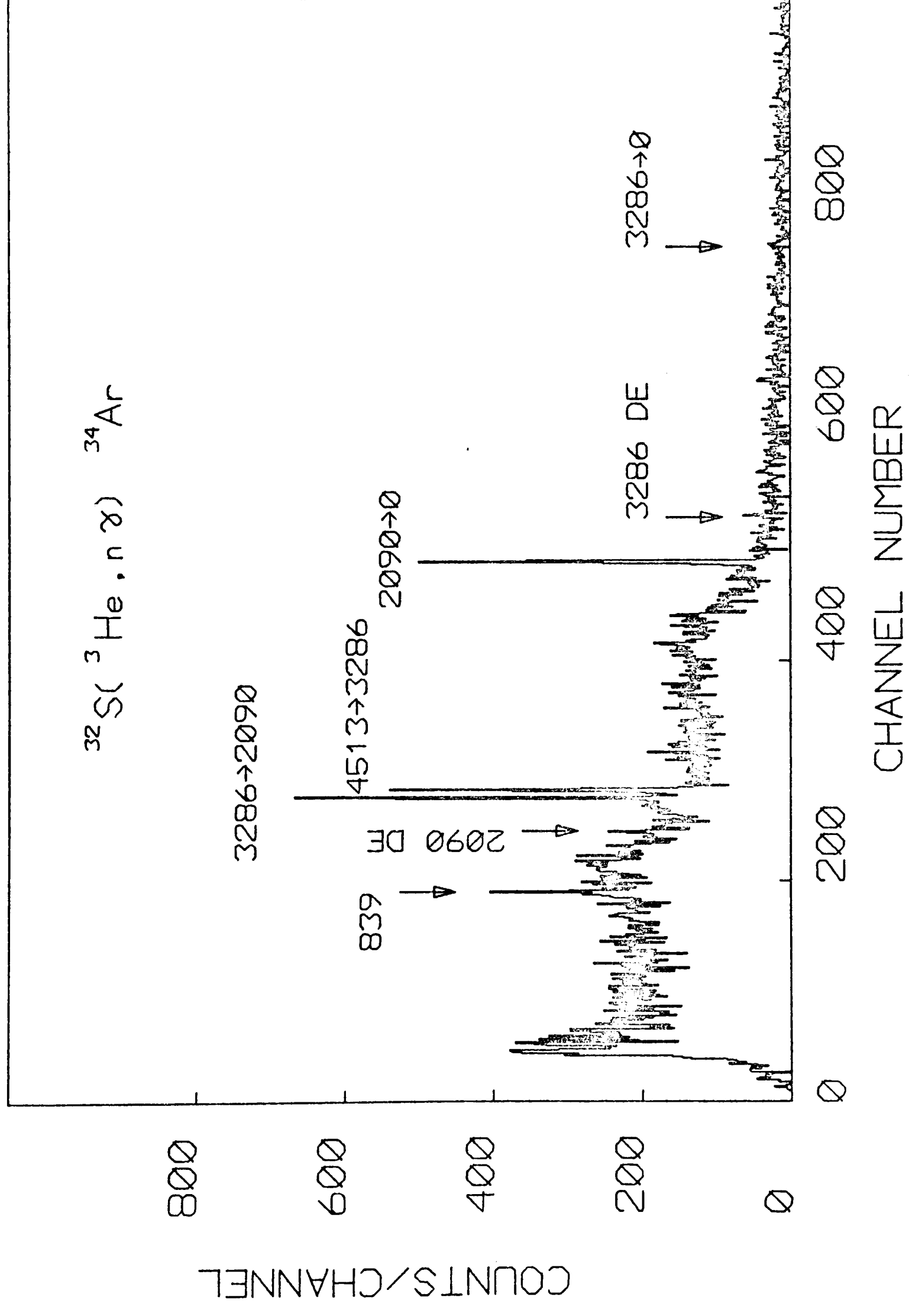


Fig.6.6 -  $^{34}\text{Ar}$   $\gamma$ -decay spectrum.

Table 6.3

$\gamma$ -ray and excitation energies in  $^{34}\text{Ar}$

| $E_\gamma$ (keV) | transition              | Present work     | $E_x$ (keV)<br>(Pa72) | (Br69)        | (Ha68)        |
|------------------|-------------------------|------------------|-----------------------|---------------|---------------|
| $2090.0 \pm 0.7$ | $2090 \rightarrow 0$    | $2090.0 \pm 0.7$ | $2094 \pm 11$         | $2097 \pm 20$ | $2100 \pm 30$ |
| $1195.8 \pm 1.2$ | $3286 \rightarrow 2090$ | $3285.8 \pm 1.4$ | $3288 \pm 14$         | $3303 \pm 25$ | $3300 \pm 30$ |
|                  |                         |                  | $3879 \pm 15$         | $3899 \pm 25$ | $3900 \pm 30$ |
|                  |                         |                  | $4050 \pm 14$         |               | $4050 \pm 30$ |
| $839.1 \pm 1.8$  | $4125 \rightarrow 3286$ | $4124.9 \pm 2.2$ |                       |               | $4150 \pm 30$ |
| $1226.7 \pm 0.7$ | $4513 \rightarrow 3286$ | $4512.5 \pm 1.6$ | $4522 \pm 14$         | $4560 \pm 40$ |               |

### 6.3.2 Lifetime measurements

The lifetimes of the 2090, 3286 and 4513 keV states in  $^{34}\text{Ar}$  were investigated with the Doppler shift attenuation method (DSAM) at 7.5 and 8.5 MeV bombarding energy. These energies were chosen to allow a better separation of the neutron TOF peaks corresponding to the first and second excited states, although a lower  $\gamma$ -ray yield had to be accepted. The Doppler shift attenuation method has been described in chapter 2.

The Ge(Li) detector was at a distance of 6.5 cm from the target and alternate measurements were made at  $\theta = 30^\circ$  and  $140^\circ$  for  $E_{^3\text{He}} = 8.5$  MeV and at  $\theta = 60^\circ$  and  $145^\circ$  for  $E_{^3\text{He}} = 7.5$  MeV. The total neutron TOF spectrum as obtained from all runs at 8.5 MeV bombarding energy is shown in fig.6.7. The accumulated charge was approximately 20 mC. Also shown in fig.6.7 are the digital windows used in the analysis of the decay  $\gamma$ -rays. The anomalous width of the 4.51 MeV level peak is due to the oxygen contamination of the target giving rise to a neutron peak from the  $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$  reaction.

The details of the DSAM analysis were already described, in section 6.2.2, in reference to the  $^{30}\text{S}$  lifetime measurements. Again, no corrections were made to the theoretical stopping powers, as no experimental data for the stopping power of argon ions recoiling in sulphur were available for the initial recoiling velocities used. A 20% systematic error due to uncertainties in the LSS theory was added to the statistical error in each case, following the suggestion of Currie et al. (Cu69a). A critical analysis of

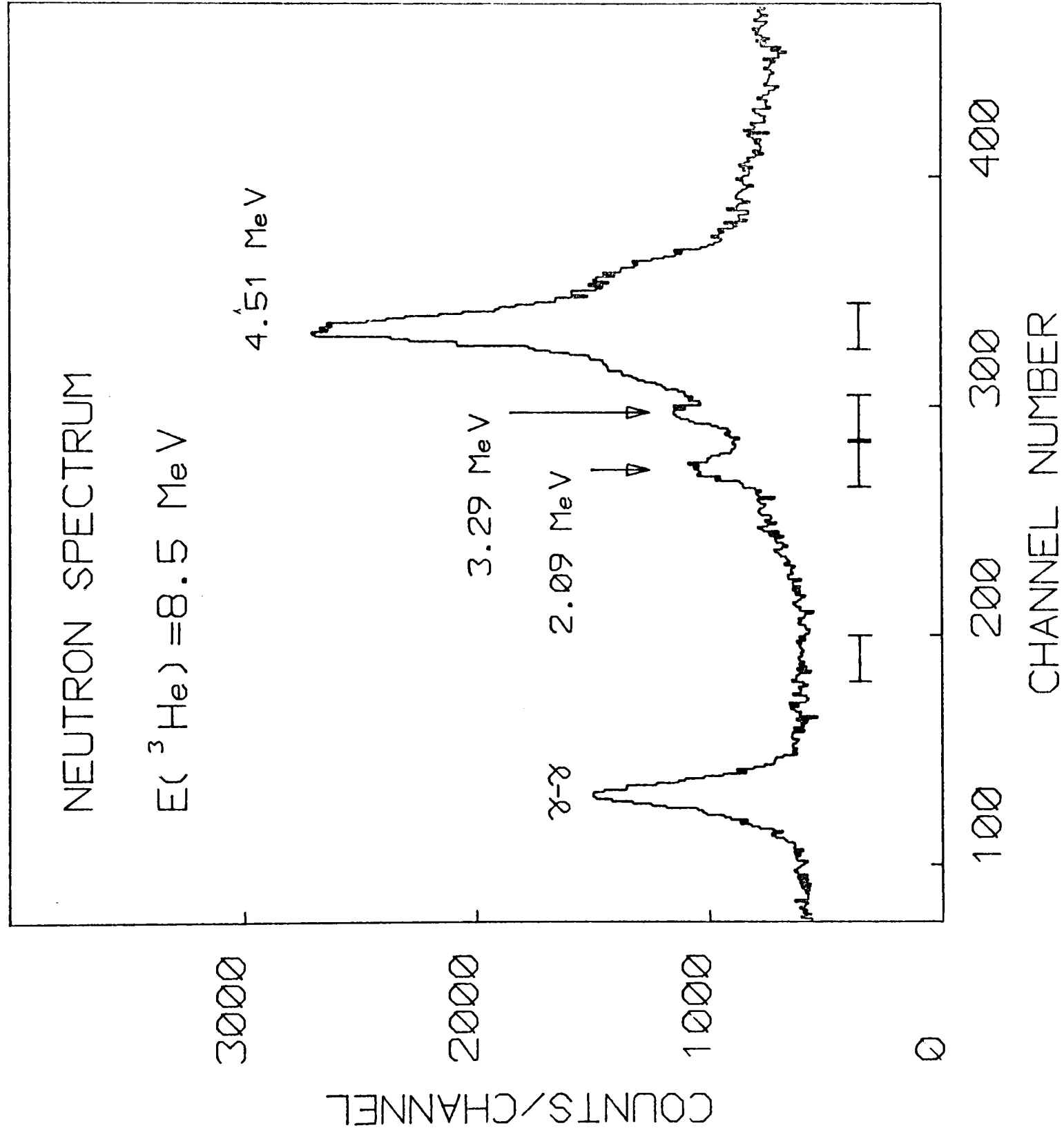


Fig.6.6.7 - Neutron time of flight spectrum at  $E_{^3\text{He}} = 8.5 \text{ MeV}$ .

the  $^{34}\text{Ar}$  DSAM measurements is made in section 4.4, p.82.

The 2090 keV level lifetime was determined from measurements both at 7.5 and 8.5 MeV bombarding energy. The  $F(\tau)$  and  $\tau$ -values extracted are in very good agreement and a weighted average of the results was made to give  $\tau(2090) = (150 \pm 50)$  fs. The 3286 keV level however, was weakly excited at  $E_{^3\text{He}} = 7.5$  MeV and therefore the value  $\tau(3286) = (120 \pm 65)$  fs was solely derived from the spectra obtained at  $E_{^3\text{He}} = 8.5$  MeV. For the 4513 keV level, clearly seen at both bombarding energies, a weighted average of the  $\tau$ -values obtained (also in very good agreement with each other) gives  $\tau(4513) = (300 \pm 80)$  fs. The  $^{34}\text{Ar}$  lifetime results are shown in table 6.4.

## 6.4 Discussion

### 6.4.1 The $^{30}\text{S}$ and $^{34}\text{Ar}$ results

The decay modes and spin assignments of the  $T = 1$  states in mass 30 and 34 are summarised in fig.6.8. The selection of the  $T = 1$  states from the complete level schemes of  $^{30}\text{P}$  and  $^{34}\text{Cl}$  was based on (Br69, Ha69a and Gl71).

The present investigations were concerned with the  $T = 1$  members  $^{30}\text{S}$  and  $^{34}\text{Ar}$  of the two triplets. In the nucleus  $^{30}\text{S}$ , spin-parity assignments of  $2^+$  for the first two excited states were made by McMurray et al. (Mc67) and Paddock (Pa72). A tentative assignment of  $J^\pi = 0^+$  was also made by these workers to the spin of the 3664 keV level. Our lifetime measurements do not disagree with this assumption, since it implies a transition strength of  $< 16$  E2 Weisskopf units (W.u.) (Wi60) for the  $3664 \rightarrow 2210$  decay.

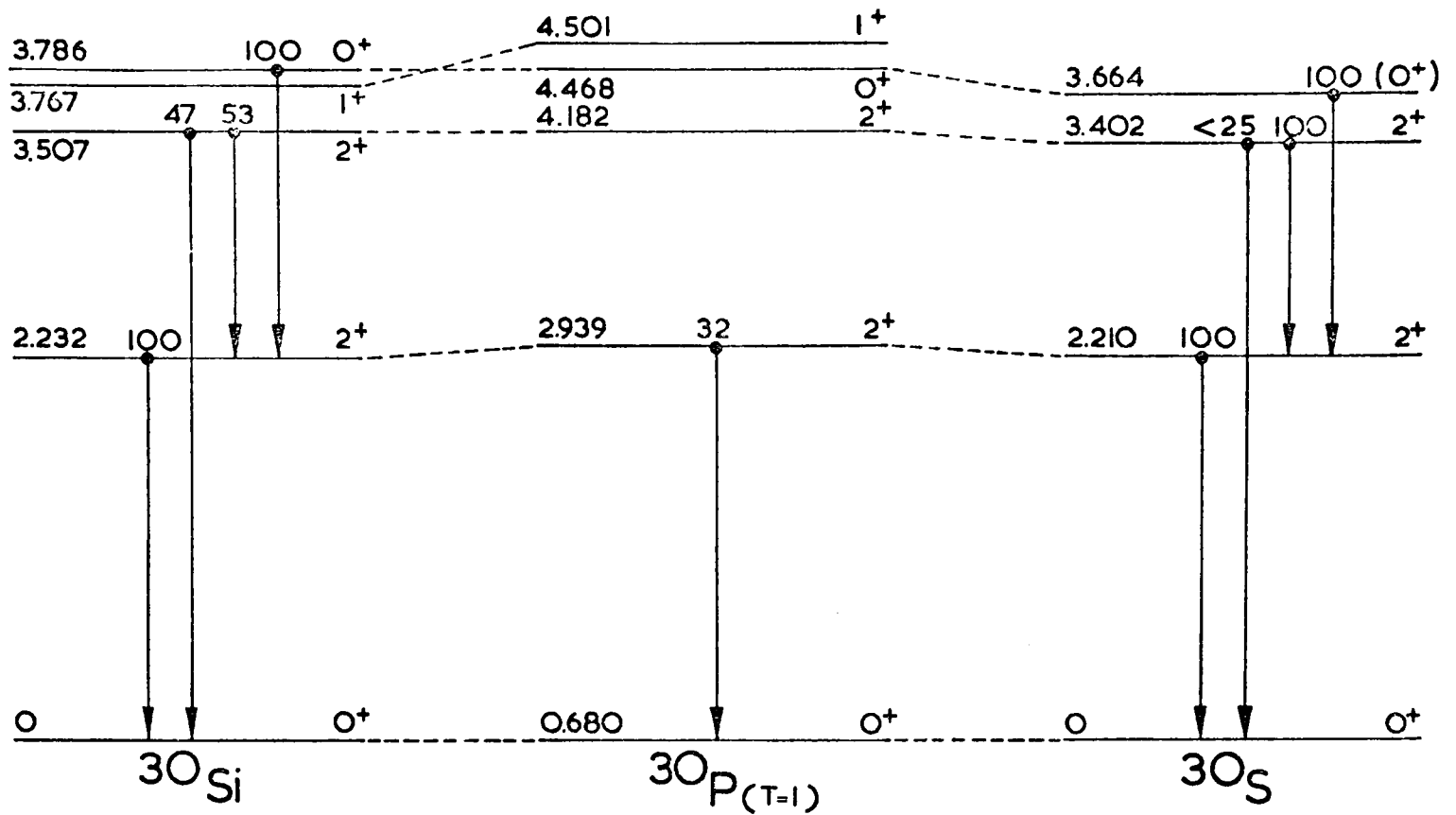
Table 6.4

$^{34}\text{Ar}$  lifetime results

| $E_x$ (keV) | Beam energy<br>(MeV) | $v_0/c$ (%) | $E_\gamma$ (keV) | $F(\tau)$              | $\tau$ (fs)         | $\tau$ (fs)<br>weighted<br>average |
|-------------|----------------------|-------------|------------------|------------------------|---------------------|------------------------------------|
| 2090        | 8.5                  | 0.380       | 2090             | $0.44^{+0.08}_{-0.06}$ | $155^{+70}_{-70}$   | $150^{+50}_{-50}$                  |
|             | 7.5                  | 0.363       |                  | $0.45^{+0.06}_{-0.06}$ | $140^{+70}_{-70}$   |                                    |
| 3286        | 8.5                  | 0.420       | 1196             | $0.52^{+0.15}_{-0.15}$ | $120^{+65}_{-65}$   | $120^{+65}_{-65}$                  |
| 4513        | 8.5                  | 0.470       | 1227             | $0.32^{+0.06}_{-0.06}$ | $290^{+110}_{-110}$ | $300^{+80}_{-80}$                  |
|             | 7.5                  | 0.461       |                  | $0.30^{+0.07}_{-0.07}$ | $310^{+120}_{-120}$ |                                    |

# T=1 MASS TRIPLETS

## MASS 30



## MASS 34

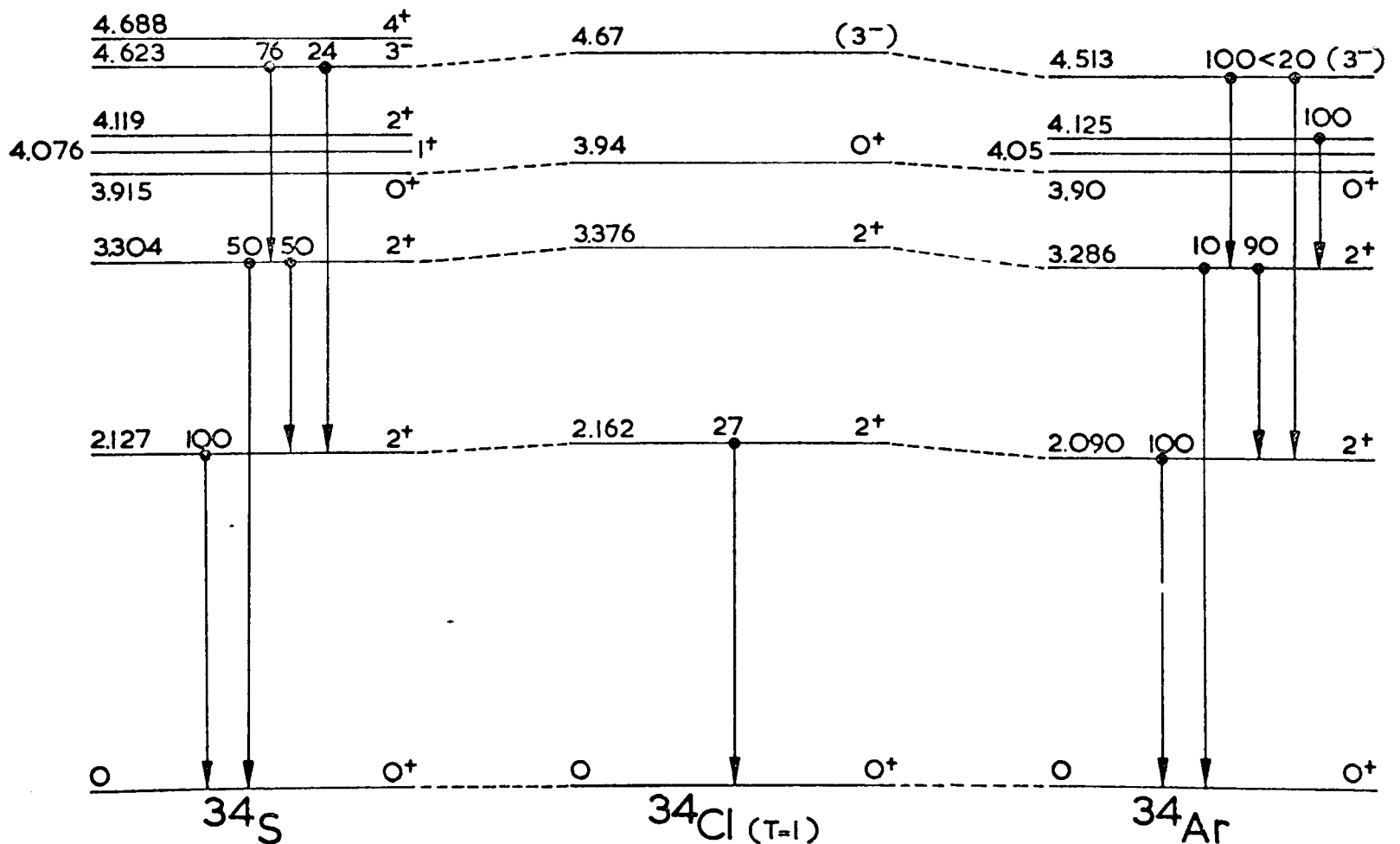


Fig.6.8 - The T=1 level schemes in mass 30 and mass 34. The measured branching ratios in  $^{30}\text{Si}$ ,  $^{30}\text{P}$ ,  $^{34}\text{S}$  and  $^{34}\text{Cl}$  (taken from (Br67,Mo70 and Gl71)) which correspond to the ones measured in this work are shown for comparison.

However, transition strengths of  $< 1.6 \times 10^{-4}$  E1 W.u. or  $< 7.3 \times 10^{-3}$  M1 W.u. are obtained in the case of a  $J = 1$  spin.

In the nucleus  $^{34}\text{Ar}$ ,  $2^+$  spins have been assigned to the first and second excited states (Mc67, Br69, Pa72). A tentative assignment of  $J^\pi = 3^-$  was made by Brunnader et al. (Br69) to the spin of the 4513 keV level. Our result for the lifetime of this state is not in disagreement with a  $3^-$  assignment but does not exclude  $J = 1, 2$  either. It is interesting to note that a  $3^-$  level was predicted at 4.57 MeV excitation energy by Erne' (Er66) in a shell-model calculation based on a  $(d_{3/2})^1 (f_{7/2})^1$  configuration.

Both the weak coupling and the shell models have been applied to describe the structure of the low-lying levels of mass 30 and 34 nuclei, though the weak coupling calculations are still at an early stage (Th62, Ca71). However, some recent calculations seem to suggest that the extension of the weak coupling model to even-even nuclei of that mass region may yield profitable results (Si72, Ca71). Shell-model calculations of electromagnetic transition rates for nuclei in the mass region 30-35 have been performed by Wildenthal et al. (Wi71) and Glaudemans et al. (Gl71). In both calculations the basic space includes all particle states in the  $(s_{1/2})$  and the  $(d_{3/2})$  shells and up to two holes in the  $(d_{5/2})$  shell. An effective two-body interaction has been used - the modified surface delta interaction (MSDI) of (Gl67). Wildenthal et al. (Wi71) consider two different Hamiltonians, namely the MSDI Hamiltonian and a free parameter (FPSDI) Hamiltonian. This FPSDI Hamiltonian

is derived from the MSDI one by treating the two-body matrix elements involving the  $(s_{1/2})$  and the  $(d_{3/2})$  shells only as independent parameters in a fit to experimental excitation energies. In both cases the E2 transition rates are calculated assuming total (effective) charges  $\tilde{e}_p = 1.5 e$  and  $\tilde{e}_n = 0.5 e$  for protons and neutrons, respectively. Glaudemans et al. (Gl71) used the MSDI wave functions to obtain empirical effective charges for the mass region 30-34 by fitting experimental E2 data. They obtain  $\tilde{e}_p = 1.44 e$  and  $\tilde{e}_n = 0.68 e$  for the total charges of protons and neutrons but the results of their calculations of transition rates are not significantly different from those of (Wi71).

The results from the calculations of (Gl71,Wi71) for  $^{30}\text{S}$  and  $^{34}\text{Ar}$  are compared in terms of Weisskopf units with our measurements in tables 6.5 and 6.6, respectively. It can be seen that there is an overall fair agreement between theory and experiment, the shell-model calculations being able to predict E2 strengths almost as large as experimentally determined.

#### 6.4.2 The E2 transition strengths in mass 30 and mass 34 isospin triplets

Another interesting investigation can be made by comparing the transition strengths of analogue decays in tables 6.5 and 6.6 throughout the isospin triplets. The E2 transition from the first excited  $2^+$ ,  $T=1$  state to the first excited  $0^+$ ,  $T=1$  state ("ground" state) is especially suited for this purpose, as mentioned in section 3.3, as measurements for all the three analogue decays in both masses

Table 6.5

$^{30}\text{S}$  transition strengths

| Transition<br>(keV)                             | Branching<br>ratio(%) | $\Gamma$<br>(meV) | Multipole | $\Gamma/\Gamma_W$ (W.u.)       |                     |                      |
|-------------------------------------------------|-----------------------|-------------------|-----------|--------------------------------|---------------------|----------------------|
|                                                 |                       |                   |           | experiment                     | (G171)<br>MSDI      | (W171)<br>FPSDI      |
| $2^+ \rightarrow 0^+$ 2210 $\rightarrow$ 0      | 100                   | $2.1^{+0.5}$      | E2        | $8.8 \pm 2.1$                  | 6.4                 | 6.0                  |
| $2^+ \rightarrow 2^+$ 3402 $\rightarrow$ 2210   | 100                   | $4.1 \pm 1.2$     | M1        | $(11.5^{+3.3}) \times 10^{-2}$ | $15 \times 10^{-2}$ | $9.4 \times 10^{-2}$ |
| $2^+ \rightarrow 0^+$ 3402 $\rightarrow$ 0      | $< 25$                | $< 1.0$           | E2        | $< 0.5$                        | 0.2                 | 0.07                 |
| $(0^+) \rightarrow 2^+$ 3664 $\rightarrow$ 2210 | 100                   | $< 0.47$          | (E2)      | $< 16$                         | 2.8                 | 2.4                  |
|                                                 |                       |                   |           |                                |                     | 4.8                  |

Table 6.6

$^{34}\text{Ar}$  transition strengths

| Transition<br>(keV)     | Branching<br>ratio(%) | $\Gamma$<br>(meV)      | Multipole | experiment                            | $\Gamma/\Gamma_w$ (W.u.) |                |                 |
|-------------------------|-----------------------|------------------------|-----------|---------------------------------------|--------------------------|----------------|-----------------|
|                         |                       |                        |           |                                       | (GL71)                   | (Wi71)<br>MSDI | (Wi71)<br>FPSDI |
| $2^+ \rightarrow 0^+$   | 100                   | $4.4^{+1.5}_{-1.5}$    | E2        | $20^{+7}_{-7}$                        | 8.3                      | 7.2            | 7.5             |
| $2^+ \rightarrow 2^+$   | 90                    | $5.0^{+2.7}_{-2.7}$    | M1        | $(13.8^{+7.4}_{-2} \times 10^{-2})$   | $1.7 \times 10^{-2}$     |                |                 |
| $2^+ \rightarrow 0^+$   | 10                    | $0.55^{+0.30}_{-0.30}$ | E2        | $0.27^{+0.15}_{-0.15}$                | 0.3                      | 0.5            | 0.01            |
| $(3^-) \rightarrow 2^+$ | 100                   | $2.2^{+0.6}_{-0.6}$    | (E1)      | $(1.6^{+0.45}_{-0.3} \times 10^{-3})$ |                          |                |                 |

30 and 34 are now available.

Assuming isospin to be a good quantum number, and following the treatment of section 3.3, the transition matrix element from a state  $|1T_3; J_1 M_1\rangle$  to a state  $|1T_3; J_2 M_2\rangle$  can be separated into two parts, arising from the separation of the interaction multipole operators into isoscalar and isovector terms. Thus, the three analogue decays in each triplet can be described by two parameters only. Recalling expression (3.37), the  $(11T_3 0 | 1T_3)$  Clebsch-Gordan coefficient in it has values  $0, \pm 1/\sqrt{2}$  for  $T_3 = 0, \pm 1$ , respectively and therefore the matrix element for the E2 transition considered is a linear function of  $T_3$  (cf. (3.37a)).

The  $T_3 = +1$  members of the mass 30 and 34 isospin triplets are  $^{30}\text{Si}$  and  $^{34}\text{S}$ ;  $^{30}\text{P}$  and  $^{34}\text{Cl}$  are the  $T_3 = 0$  and  $^{30}\text{S}$  and  $^{34}\text{Ar}$  are the  $T_3 = -1$  members, respectively. Information about the measured  $2^+ \rightarrow 0^+$   $T = 1$  transition strengths for  $A = 30$  and  $A = 34$  nuclei has been taken from the compilation of (G171) and from this work. The transition widths for mass 30 are: (expressed in terms of Weisskopf units)  $\Gamma_{E2}(^{30}\text{P}) = 8.9 \pm 1.6$  W.u.,  $\Gamma_{E2}(^{30}\text{Si}) = 7.2 \pm 0.4$  W.u. and  $\Gamma_{E2}(^{30}\text{S}) = 8.8 \pm 2.1$  W.u. In mass 34 the errors in the transition strengths are somewhat larger:  $\Gamma_{E2}(^{34}\text{Cl}) = 15 \pm 7$  W.u.,  $\Gamma_{E2}(^{34}\text{S}) = 6.4 \pm 0.7$  W.u. and  $\Gamma_{E2}(^{34}\text{Ar}) = 20 \pm 7$  W.u. In fig. 6.9 the square roots of the experimental transition strengths are plotted as a function of  $T_3$ .

A least squares fit was made to these data in order to extract the ratio of the isovector part to the isoscalar part in the transition matrix element. This ratio,  $\alpha$  (as defined in (3.43)) is written

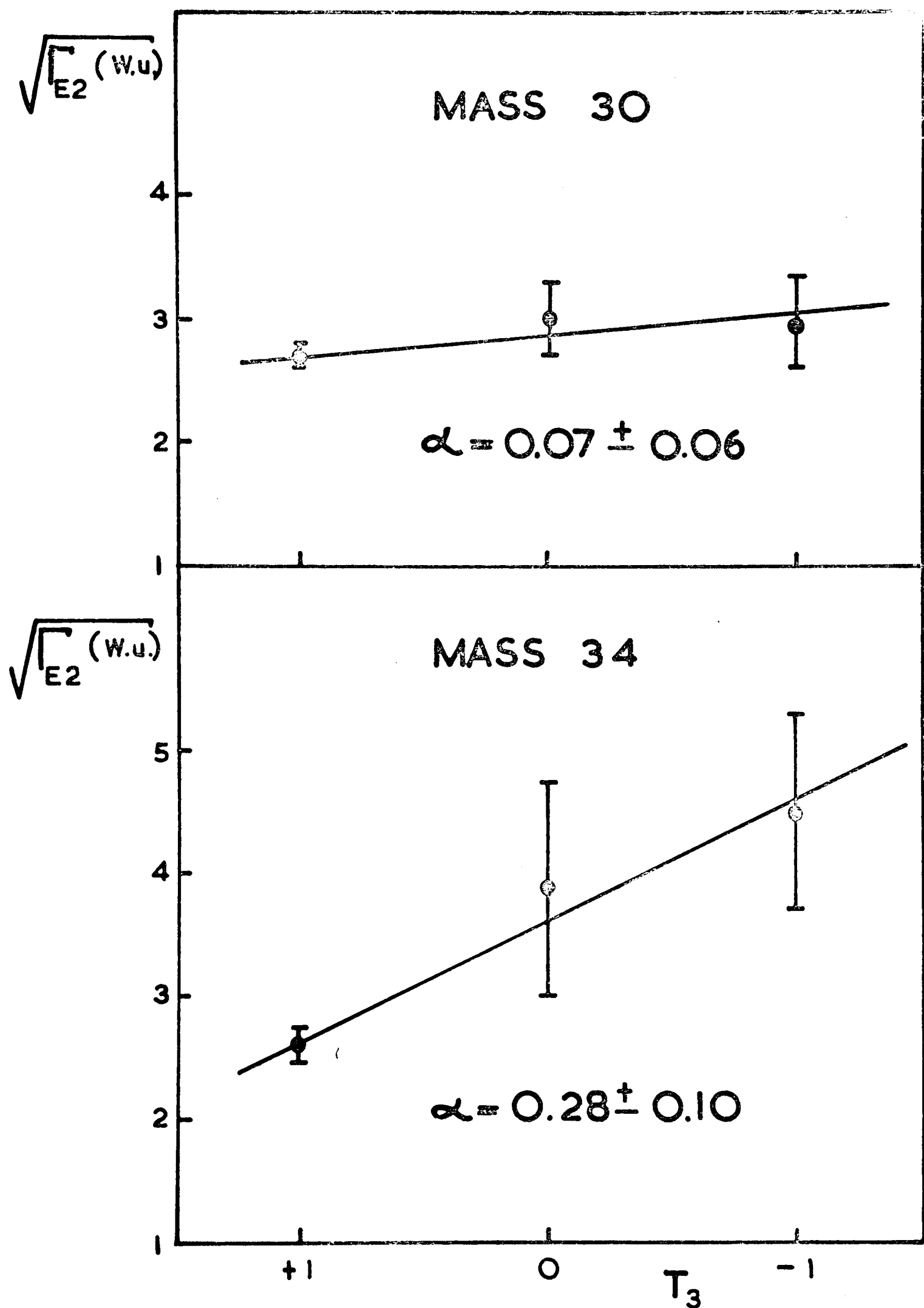


Fig.6.9 - The square roots of the experimental E2 transition strengths in mass 30 and mass 34 plotted as a function of  $T_3$ .

$$\alpha = \sqrt{3/2} \frac{\tilde{e}_p - \tilde{e}_n}{\tilde{e}_p + \tilde{e}_n} \quad (3.43)$$

where  $\tilde{e}_p$  and  $\tilde{e}_n$  are the total proton and neutron charges, respectively. Hence,  $\tilde{e}_p - \tilde{e}_n$  is the total isovector charge and  $\tilde{e}_p + \tilde{e}_n$  the total isoscalar charge. We obtain for mass 30 the value  $\alpha(30) = 0.07 \pm 0.06$ , the linear isospin dependence of the transition matrix element being verified with  $\chi^2 = 0.24$ . For mass 34 the result is  $\alpha(34) = 0.28 \pm 0.10$  with  $\chi^2 = 0.13$ . The fits to the experimental data are shown as the solid lines of fig.6.9. It is seen in fig.6.9 that in spite of the substantial experimental uncertainties associated with lifetime measurements a good test of the validity of the isospin concept is provided.

The total proton and neutron charges used in the model calculations discussed in section 6.4.1 imply values for the ratio  $\alpha$  of  $\alpha = 0.61$  (Gl71) and  $\alpha = 0.44$  (Wi71). The smallness of the above experimental values of  $\alpha$ , especially  $\alpha(30)$ , suggests, however, that for the beginning of the  $(s_{1/2} - d_{3/2})$  shells almost equal total proton and neutron charges should be used. This situation is similar to the one experienced in the  $(f_{7/2})$  shell where a value of  $\alpha$  of 0.03 is found (Za65). In this case, as pointed out by Warburton and Weneser (Wa69), the additional isovector charge  $[(\tilde{e}_p - \tilde{e}_n)/e] - 1$  (which arises from  $T = 1$  core excitations) is comparable to the additional isoscalar charge  $[(\tilde{e}_p + \tilde{e}_n)/e] - 1$  arising from  $T=0$  core excitations. The present results therefore confirm the existence of appreciable  $T=1$  E2 transition strengths arising from polarisation of the  $^{28}\text{Si}$  core.

## 7. List of Publications

The experimental investigations reported in this thesis have all been published. The description of the neutron time of flight spectrometer, its associated electronics and performance tests made in chapter 2, section 2.1, has been published in Nucl.Instr.93(1971)417. The study of  $^{37}\text{Ar}$  described in chapter 4 has been published in Nucl.Phys.A176(1971)273. The questions involving the  $^{18}\text{Ne}$  gamma decay investigated in chapter 5 have been published in Particles and Nuclei 1(1971)453 and Nucl. Phys.A180(1972)79. Finally, the decay scheme and lifetime measurements in  $^{30}\text{S}$  and  $^{34}\text{Ar}$  described in chapter 6 have been published in Nucl.Phys.A193(1972)1.

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