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A SEMICONDUCTOR COUNTER TELESCOPE FOR NEUTRON REACTION STUDIES

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P r e p r i n t

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A b s t r a c t

A counter telescope consisting of two or three semiconductor counters for $\Delta E/\Delta x$ vs. E analysis was made for studying nuclear reactions induced by 14.4 MeV neutrons. Various factors important for the telescope performance are discussed in details and some solutions for getting an optimum resolution and a low background are given.

Protons, deuterons and alpha particles resulting from scattering and reactions of 14.4 MeV neutrons on deuterium, tritium, praseodymium and niobium were detected, and pulses from the counters recorded on a two-dimensional analyzer. These experiments have shown that the telescope compares favorably with other types of telescopes with regards to the upper limit of neutron flux which can be used, $\Delta E/\Delta x$ and E resolution, versatility and compactness.

INTRODUCTION

In studies of nuclear reactions induced by fast neutrons extensive use has been made of counter telescopes which make possible the identification of various charged particles and the measurement of their energies. Among the various systems used for this purpose telescopes of different combinations of proportional and scintillation counters have found the widest aplication (1-5). In such telescopes charged particles are identified by their specific (dE/dX) energy losses in a proportional counter, and their energies (E) are measured in a scintillation counter. With a careful telescope design and by using a tripple coincidence circuit a fairly good distinction of various charged particles, for example protons, deuterons, tritons, etc., can be achieved, and the background can be reduced to a very low level. Thus, it is possible to study complex reactions having cross-sections of the order of 0.1 millibarn (6). However, this kind of telescope is not quite satisfactory as regards two important requirements. For heavy particles the energy resolution of the scintillation counter is not better than several percents (e.g. about 4 percent at 12 MeV is best achievable). On the other hand, as a consequence of slow operation of proportional counters, the coincidence resolving time of these telescopes is limited to 1-2 microseconds. In practice, in the latter case an upper limit of about 10^9 neutrons/sec in 4   is imposed for the neutron flux which can be used in reaction studies. Hence, much higher neutron fluxes available at present cannot be used in the study of reactions with very low cross-sections.

The advent of semiconductor counters, which are characterized by excellent energy resolution, fast pulse rise time and simplicity of operation, has made possible further improvement of the counter telescope in these lines. Various telescopes using these counters, or their combinations with gas counters, have been successfully employed in the studies of nuclear reactions induced by high energy charged particles (7-9). For the study of fast neutron reactions we have built several types of semiconductor counter telescopes and investigated their characteristics by detecting charged particles produced by 14.4 MeV neutrons in deuterium, tritium, paseodymium and niobium. A detailed study of the background of the telescopes has also been made.

TELESCOPES

Three basically different counter telescopes have been designed and investigated. The first one (Telescope I) consists of two surface barrier semiconductor counters, one of which, a thin detector, is used for the $\Delta E/\Delta x$ analysis, and the other for the energy measurement. The two other telescopes are a combination of Telescope I with a thin semiconductor counter (Telescope II) or with a thin proportional counter (Telescope III). Each of these telescopes has several variations regarding transmission counter thicknesses.

A view of Telescope I is given in Fig.1. This telescope enables the detection of protons in the energy range from 2-14 MeV, and of other particles, deuterons, tritons, etc., in the corresponding energy range. Alpha particles with energies above 5 MeV can also be detected.

A schematic diagram of Telescopes II and III is shown in Fig.2. The proportional counter in Telescope III was filled with CO_2 to a pressure of 10 cm Hg. The total thickness of CO_2 plus the mica window was equivalent to 3 mg/cm^2 of silicon. This counter, tested with thorium alpha particles, gave a satisfactory performance, but it has not been used in experiments with neutrons. Telescopes II and III could detected protons of energies down to 2.5 MeV when the thinnest transmission counters were used.

COUNTERS

Several $\Delta E/\Delta x$ counters of various thicknesses ranging from 23 (5.4 mg/cm^2) to 100 microns, and with sensitive areas from 75 to 150 mm^2 were used in these telescopes. Large surfaces are essential for neutron reaction studies because of low reaction yields per unit time with neutron fluxes available and also because the semiconductor counter life-time is limited to a dose of about 10^{12} fast neutrons/cm^2. The thin counters are made of N-type silicon crystals of resistivities from 35 to 2.000 Ohm-cm*, cut and polished to a desired thickness according to the procedure described by Irving (10) and Stojić and Slavić (11), and then chemically treated.

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* Supplied by Monsanto Chemicals, Ltd, London.

After etching, the silicon slides were fastened to rigid teflon rings by means of Apiezon W-wax. Gold and aluminium (about 30-50 microgram/cm^2) were then evaporated through a mask onto the front and back surfaces, respectively. Contacts were made by attaching thin gold wires with silver paste. With careful work we achieved almost 100 percent efficiency in making these counters.

The thickness of each thin crystal was first determined with a micrometer after the polishing, and the effect of etching was then determined by weighting. However, the final data for the counter thickness were obtained by measuring the energy losses of Th(C+C′) alpha particles in totally depleted counters.

As was expected (12) the energy resolution of these counters for alpha particles which passed through them was not quite good. For example, the 23 micron thick counter, with a sensitive area of 100 mm^2, gave an energy resolution of 275 keV or 11% (FWHM) for 8.78 MeV alpha particles which had an energy loss of 2.55 MeV in it (Fig.3). This value was obtained with the whole sensitive area exposed to alpha particles. The widths of the peaks are believed to be mainly due to the nonuniform thickness of the counter and to the Landau spread, since the corresponding spread appeared in the E counter for alpha particles which passed through the thin counter. By adding coincident pulses from the E and $\Delta E/\Delta x$ counter an improvement in the energy resolution from 250 to 150 keV was obtained. This indicated that the inherent resolution of the thin counter is better than 100 keV. Measurements with counters thicker than 35 microns conconfirmed this. The Landau spread, calculated according to the formula:

$$R = \frac{1.46 \cdot Z \cdot x^{1/2}}{\Delta E}$$

R - resolution in percent

Z - atomic charge of the incident particle

ΔE - energy loss in MeV

x - counter thickness in microns

contributes about 150 keV.

The noise of thin counters was typically equivalent to about 50 keV, but the best examples had a noise below 30 keV.

An important consideration of the noise of thin semiconductor counters concerns the resistivity of the silicon crystal. This should be such that the desired depletion region is obtained with a bias voltage optimum with respect to the noise (see Ref.12 and 13). Another consideration of the noise problem concerns the capacitances of thin counters, which are rather high. For example, a 25 micron counter with a useful surface area of 150 mm^2 has a capacitance of 600 pF, which is a great burden even for a charge sensitive preamplifier. Thus, this seriously limits the size of the sensitive area for a given thickness of thin counters. The high capacitance of thin counters with large sensitive areas also affects the pulse rise time. It is therefore very important to investigate the problem of contact resistances, especially at the back, and to reduce it as much as possible.

The E counters are made of 1.5-2 mm thick silicon crystal slices, with nominal resistivities of 16.000 Ohm-cm. The sensitive area of each is 1.5 cm^2.The counters can be depleted with a reverse bias of 500 Volts, under which conditions the inverse current is 0.5 microamp. Their energy resolution for Th(C+C′) alpha particles is 50 keV.

ELECTRONIC APPARATUS

The electronic apparatus used for the two-dimensional analysis of pulses produced in the counters is essentially the same as the one employed for the proportional counter - scintillation counter telescope described by Konrad et al. (14). However, in order to avoid a high random coincidence rate a faster coincidence circuit having a resolving time of 0.3 microseconds was used. To use Telescope II with it the system was further developed by enabling it to record pulses from all the three counters as well as a sum of pulses from any two counters. A block scheme of the electronic apparatus used for the tritium break-up experiment (15) is shown in Fig.4. In this case, the second thin counter was sufficiently thick to stop H^4 which might be created by neutron capture in tritium.

PERFORMANCE IN EXPERIMENTS

The performance of the telescopes was studied by using 14.4 MeV neutrons produced by the 200 keV accelerators in the Rudjer Bošković Institute in Zagreb and in the Boris Kidrič Institute in Belgrade. Throughout the experiments the neutron flux was mainly held at 10^9 n/sec in 4π, but in some experiments the flux approached

10^{10} n/sec. The absolute value of the neutron flux was determined by a long BF_3 counter.

In the preliminary experiments, charged particles from deuterium and tritium were detected, and the background was thouroughly studied. Since the first results were encouraging it was decided to proceed immediately with studies of some reactions. Two different experiments were made. The break-up of tritium was studied, and (n, alpha) reactions produced in praseodymium and niobium were investigated in details (16). Both Telescope I and II were used in each experiment. In the first experiment in which the telescope was set at 0° with respect to the neutron direction, the distance of the target from the neutron source was 10 cm, so the maximum spread of the angle of charged particles detected by the E-counter was 10°. The second experiment was made at a target-source distance of 7 cm, and with a target-E detector distance of 5.4 cm.

The most serious source of the background is to be expected from neutron induced reactions in the silicon crystal. The total neutron cross-section at 14.4 MeV for silicon is 1.7 b. Almost any event produced in thin counters by 14.4 MeV neutrons, including elastic and inelastic scattering, will practically result in a detectable pulse for a discriminator bias set at above 100 keV, while in the case of the E counter only reactions involving charged particle emission will produce pulses with amplitudes sufficient for triggering the coincidence circuit. The counting rate for a 23-micron thick detector, placed at a distance of 11 cm from the neutron source was about 200 count/sec, and for the E counter placed 9 cm further from the neutron source and depleted to 700 microns, it was about 700 counts/sec for 10^9 n/sec in 4π. For Telescope I this gives a total random coincidence rate of 5 counts/min for a coincidence resolving time of 0.3 microseconds. The total background rate was 15 counts/min. Thus, the true coincidence background counting rate corresponds to a target having atomic mass 30, a thickness of 10 mg/cm^2 and a cross-section for charged particle emission of 100 mb/ster. When this background is distributed in two dimensions the situation is much better for a particular particle in a certain energy interval. For example, for deuterons in the energy range from 3 to 12 MeV the background corresponds to only 25 mb/ster. For studying reactions with very low cross sections this background, especially the random coincidence contribution, is fairly high.

With Telescope II, using triple coincidence, the random coincidence problem is definitely solved. In fact, with the coincidence resolving time of 0.1 microsecond, which can easily be achieved with semiconductor counters using amplifiers with bipolar pulses (17), it should be possible to employ Telescope II with a neutron flux as high as 5.10^{10} n/sec in 4π. In a geometry similar to that used in the tritium experiment, a random coincidence rate of a few counts per hour which is much lower than the background counting rate, should be obtained.

Apart from having a low random coincidence rate the telescope with two thin detectors has another important advantage. Since the first thin counter is only required to produce a pulse for triple coincidence it can be made very thin. In this case the background coming from reactions produced in silicon is diminished, and at the same time the dE/dX analysis based on pulses from the second thicker detector is not aggravated. On the other hand, pulses from the first and the second counter due to particles originating in the target must have amplitudes proportional (within the energy resolution) to the thicknesses of these counters. For particles coming from other sources such a relation is not valid. Therefore, this fact can be used to eliminate part of the background. We applied this criterion in the case of Telescope II, in which each thin counter was 25 microns thick. Since the pulses in them were required to be equal within 40 percent, about 35 percent of the background pulses was eliminated. At the same time practically all pulses due to elastically scattered deuterons fell within this limit, which shows that this criterion did not reduce the efficiency in the detection of particles coming from the target. The background of Telescope II was studied by placing various materials with low cross-sections in front of the first thin counter. Figure 5 shows the proton and deuteron spectra obtained with gold, lead and carbon. Here, the rejection of pulses not having equal amplitudes in both thin counters was not applied. Thus it is seen that the background of the telescope itself permits studies of nuclear reactions of the (n,p) and (n,d) type with cross-sections down to 1 mb/ster per one MeV interval of outgoing particles. The two-dimensional analysis has shown that the bulk of the total number of background pulses falls below the proton region. In the region between deuterons and alpha particles the background is more than two orders of magnitude lower.

In the experiment on (n, alpha) reactions in praseodymium and niobium which are characterised by positive Q-values, it was not neccessary to utilize the two-dimensional analysis. In view of high energy losses of alpha particles in thin counters other particles were eliminated by a proper setting of the levels of the discriminators. The alpha particle spectrum from praseodymium obtained at 0° is shown in Fig.6.

One should obtain even a lower background with Telescope III in which a gas proportional counter replaces the first $\Delta E/\Delta x$ silicon counter. This is due to the fact that the proportional counter has a smaller total thickness (3 mg/cm^2 including a mica window) and a small cross-section for neutron reactions in CO_2 gas filling. However, compared with semiconductor counters the disadvantage of this counter is in the speed of response and the pile-up of pulses. The proportional counter sets a limit to a value of about 5.10^9 n/cm^2 in 4π which can be used.

The resolution of thin detectors for fast particles was limited by the Landau spread. For example, for 12.7 MeV deuterons losing 275 keV in the 23-micron counter we obtained a resolution of 22 percent (FWHM) which is close to the Landau width (Fig.7). It is important to notice here that there does not exist a high energy tail, which is characteristic for proportional counters exposed to high neutron fluxes. By adding the pulses from two thin counters having thicknesses of 25 and 50 microns in Telescope II the resolution was imprcved to 16 percent. In this case the separation of protons and deuterons even at high energies is almost complete (Fig.8).

The energy resolution of the E counter for 12.4 MeV deuterons and 10.3 MeV tritons was 1.9 and 3.4 percent, respectively (Fig.9). The widths of the peaks are a result of the angular spread of particles (100 keV), the target thickness (100 keV for deuterons and 250 keV for tritons), and the Landau spread in the thin counter (70 keV) and the inherent detector resolution (50 keV). Addition of pulses from all counters should improve the energy resolution for thin targets.

The energy resolution of the E counter begins to deteriorate after a dose of 10^{12} fast neutrons per cm^2. However, this effect was not observed for thin counters for more than five times higher doses. It is clear that for each particular experiment there is an optimum choice of thin counter thicknesses and of the depletion layer of the E counter. This latter can be simply accomplished by adjusting the reverse bias voltage.

CONCLUSION

The main characteristics of semiconductor counter telescopes are summarized in Table I. For comparison, characteristics of other telescopes used for the same purpose are also presented.

As can be seen the semiconductor counter telescope is superiod in the E and $\Delta E/\Delta x$ resolution and in the upper limit of the neutron flux. It allows experiments with the highest neutron fluxes available at present. Its main disadvantage is a relatively short life of rather expensive semiconductor detectors if they are exposed to fast neutrons. The other important features are excellent stability and small size of semiconductor detectors. The latter makes possible experiments with two telescopes in coincidence, e.g. for studying events in which two or more charged particles are emitted. In general, the versatility of this telescope is great. It is very suitable for studies of reactions produced by charged particles and gamma rays. Due to its insensitivity to strong gamma radiation and high thermal neutron fluxes it can also be applied in ternary fission studies.

The application of this telescope for cross-section and angular distribution measurements in fast neutron reactions on praseodymium, niobium and tritium has shown that valuable data can be obtained in a time chorter than that usually required for the same kind of experiments.

A C K N O W L E D G M E N T S

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T A B L E   I

COUNTER TELESCOPES FOR NEUTRON REACTION STUDIES

Telescope	Highest flux* n/cm^2 sec in 4π	Energy range for protons MeV	Energy resolution keV	ΔE energy resolution %	Background	Life of counters n/cm^2	Dimensions	Stability
2 prop. ΔE Scint. E	10^9	2	500	30	very low	not limited	Large	not satisfactory
Scint. ΔE Scint. E	10^9	5	500	13**	very high	not limited	Large	not satisfactory
Semicond. ΔE Semicond. E	10^9	2-15	< 250	25	high	10^{12}	small	good
2 semicond. ΔE Semicond. E	5.10^{10}	2.5-15	< 250	20	low	10^{12}	small	good
One prop. ΔE One semicond. ΔE Semicond. E	10^9	2.5-15	< 250	25	very low	10^{12}	medium	good

* For typical experimental geometries

** For 2 MeV energy loss

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FIGURE CAPTIONS

Fig.1 Telescope I

Fig.2 Schematic diagram of Telescopes II and III

Fig.3 Resolution of the thin counter

Fig.4 Block scheme of the electronic system used with Telscope II in the tritium break-up experiment (15)

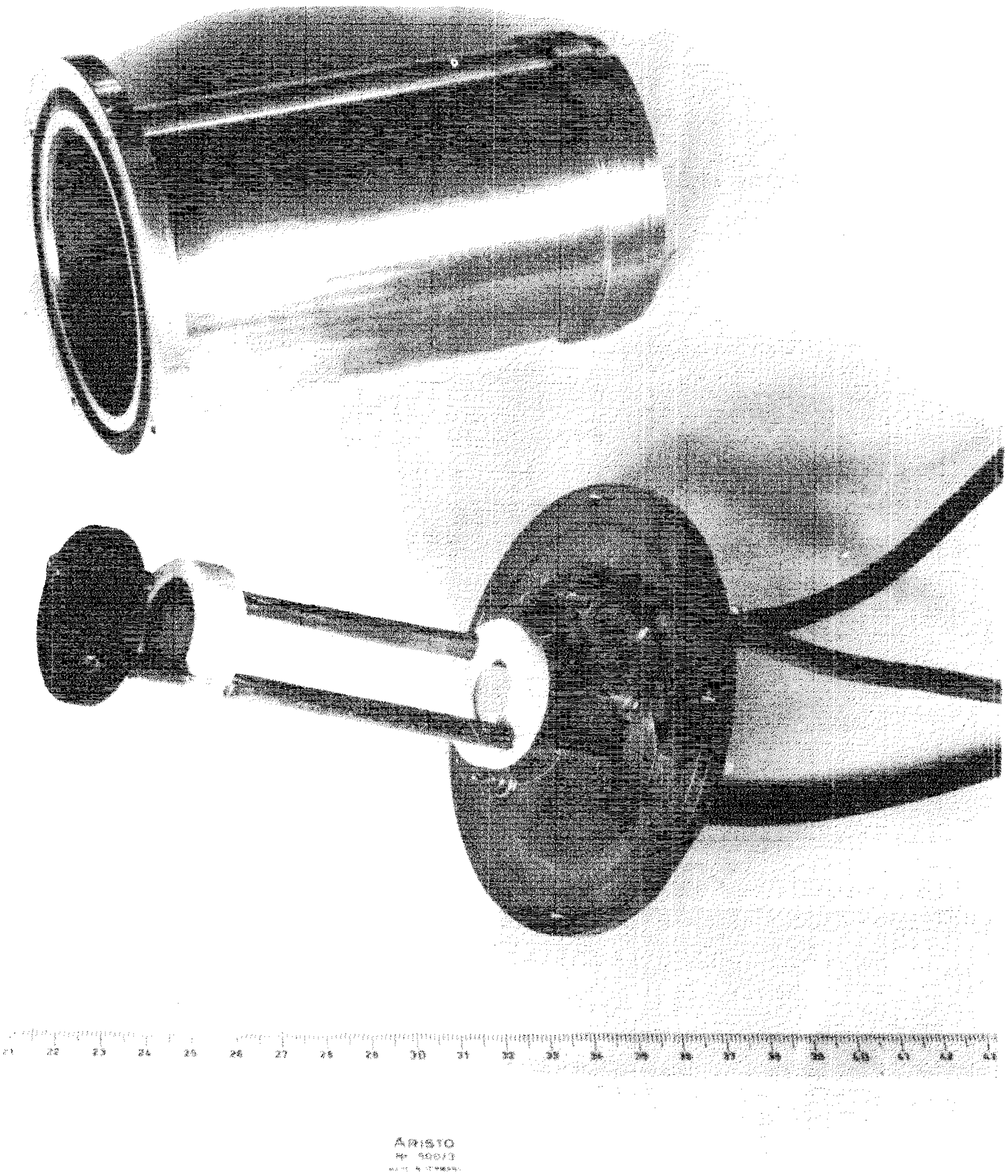
Fig.5 Background proton and deuteron spectra for Telescope II, with both thin counters 25 microns thick. 100 counts correspond to a cross-section of 4 mb/sterad for a target of 10 mg/cm^2 having atomic mass 30.

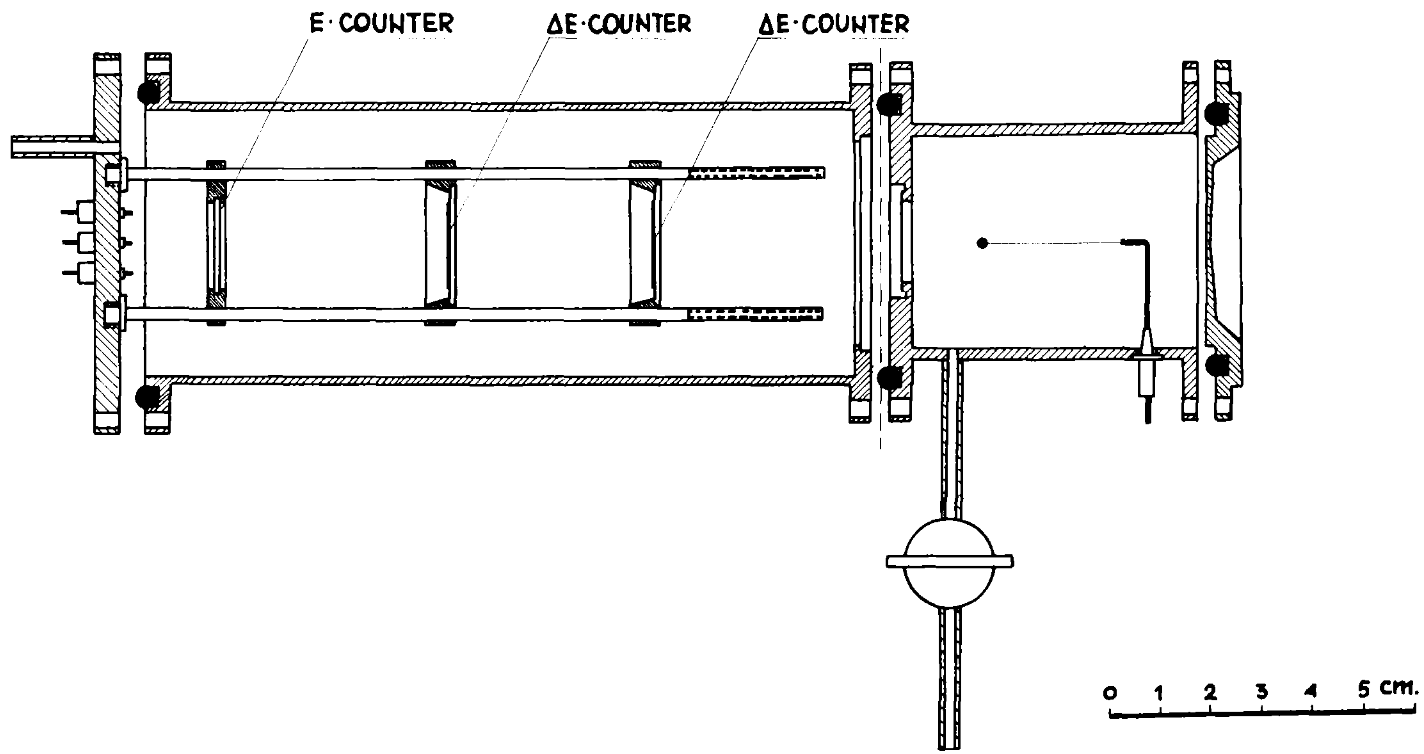
Fig.6 The alpha particle spectrum at 0^o for the $Pr^{141}(n,alpha)La^{138}$ reaction (16)

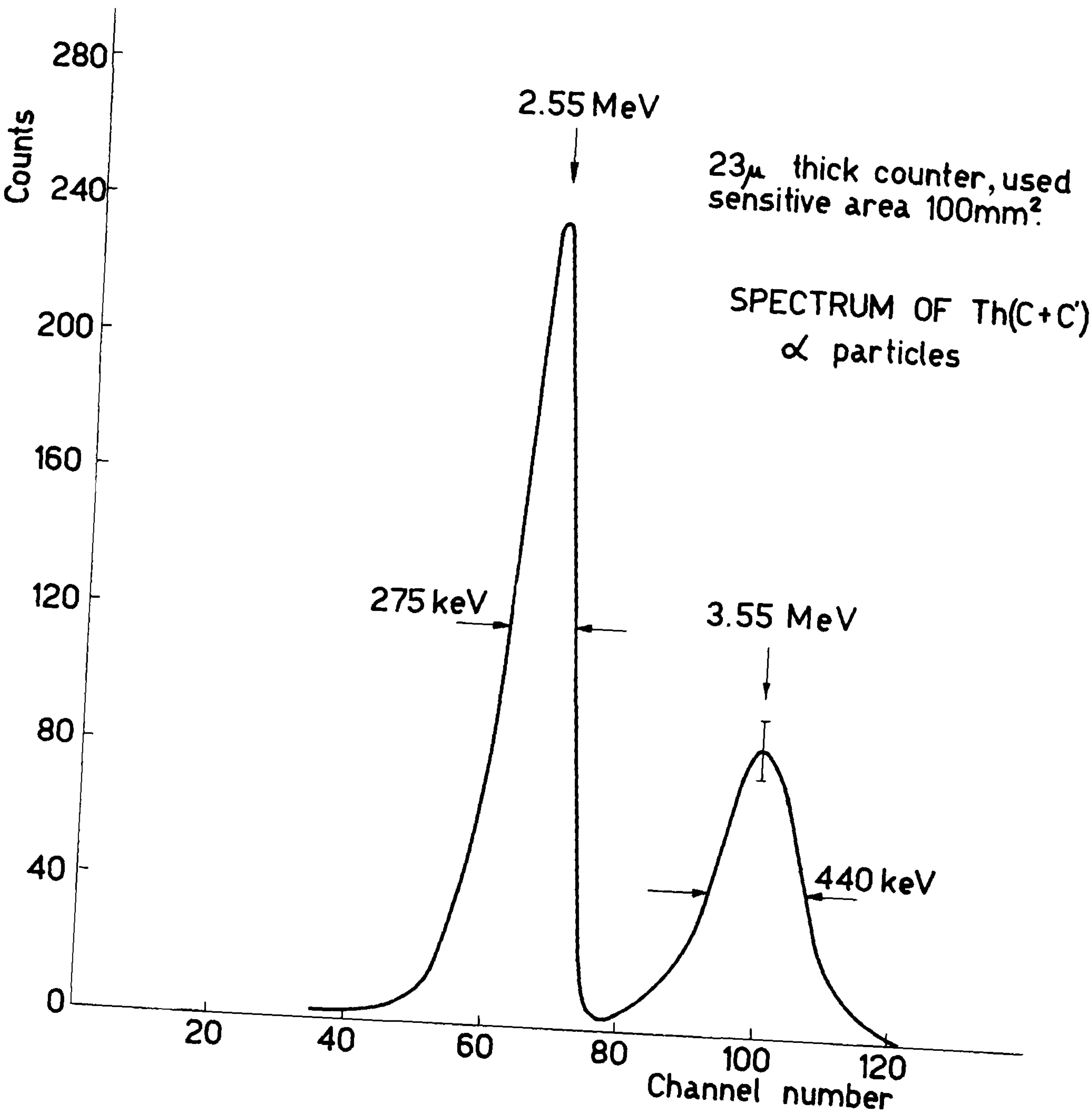
Fig.7 Resolution of the thin counter for 12.7 MeV deuterons and 10.7 MeV tritons.

Fig.8 Energy loss distributions for 8 MeV protons and deuterons obtained in the tritium break-up experiment (15).

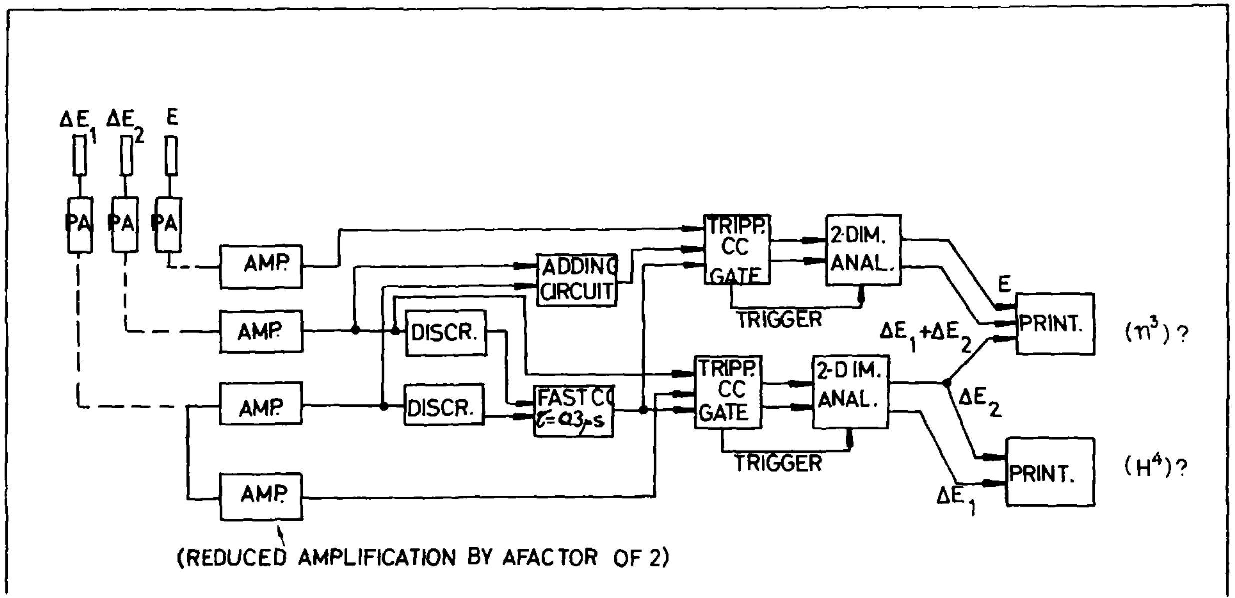
Fig.9 Spectrum of 10.3 MeV tritons and 12.4 MeV deuterons from elastic scattering of 14.4 MeV neutrons.


ARISTO

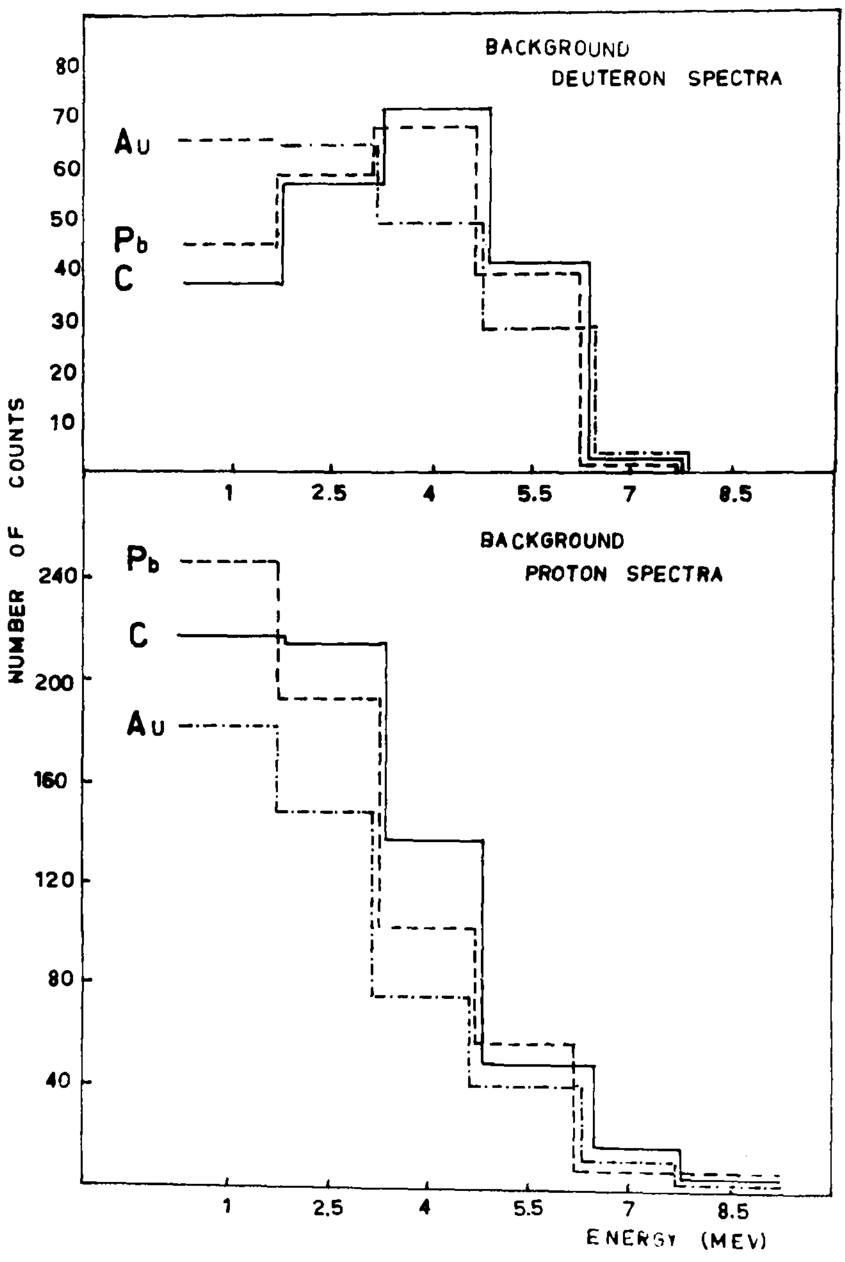

E·COUNTER
ΔE·COUNTER
ΔE·COUNTER
0 1 2 3 4 5 cm.

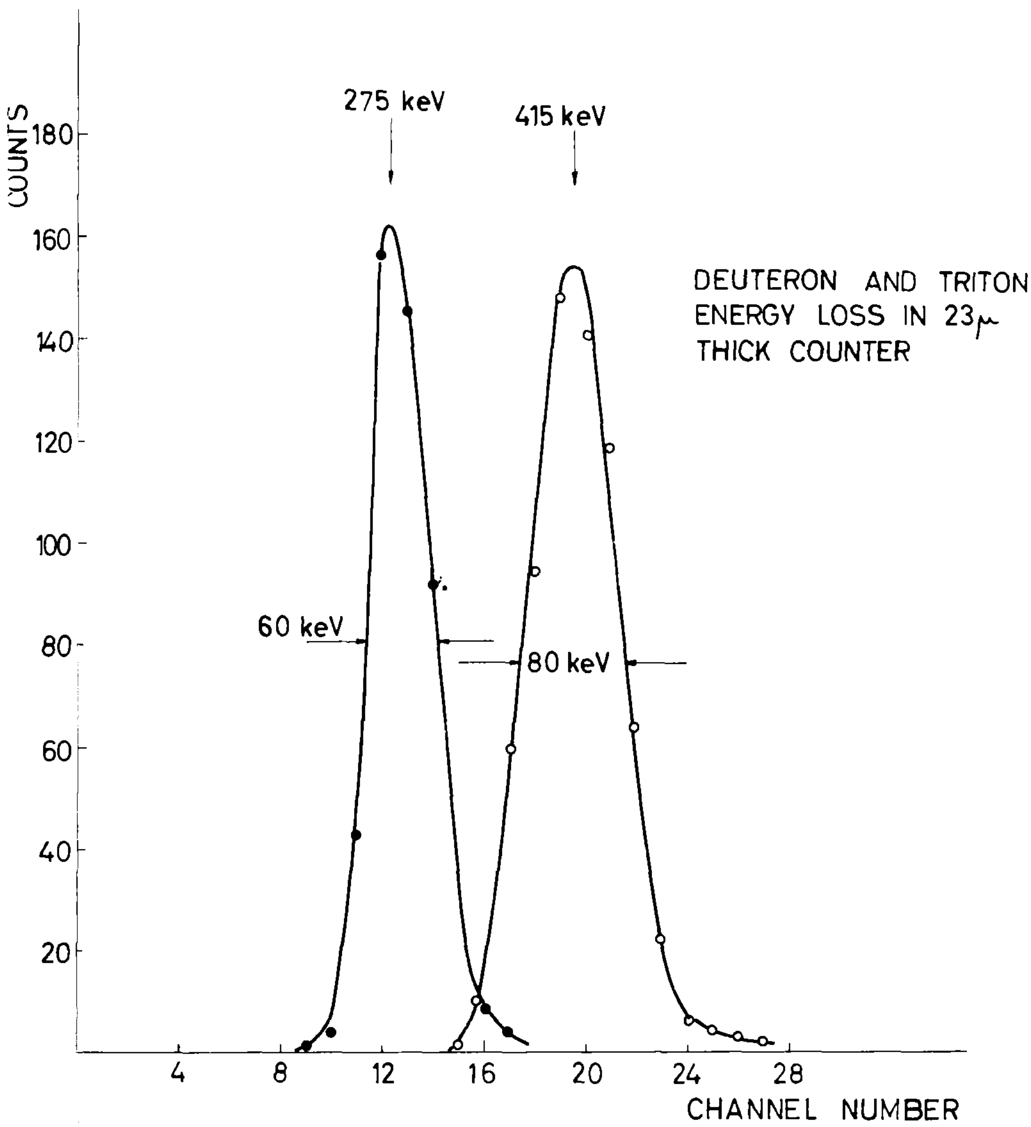


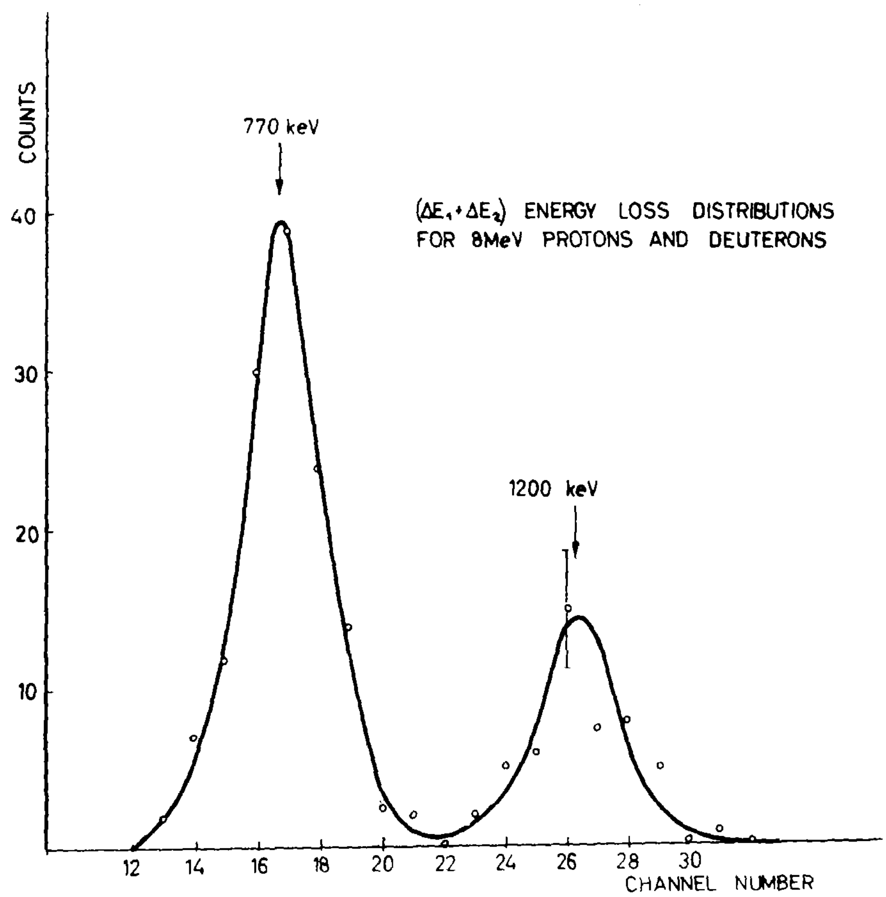
Counts
280
240
200
160
120
80
40
0
20
40
60
80
100
120
Channel number
2.55 MeV
275 keV
3.55 MeV
440 keV
23μ thick counter, used sensitive area 100mm².
SPECTRUM OF Th(C+C')
α particles



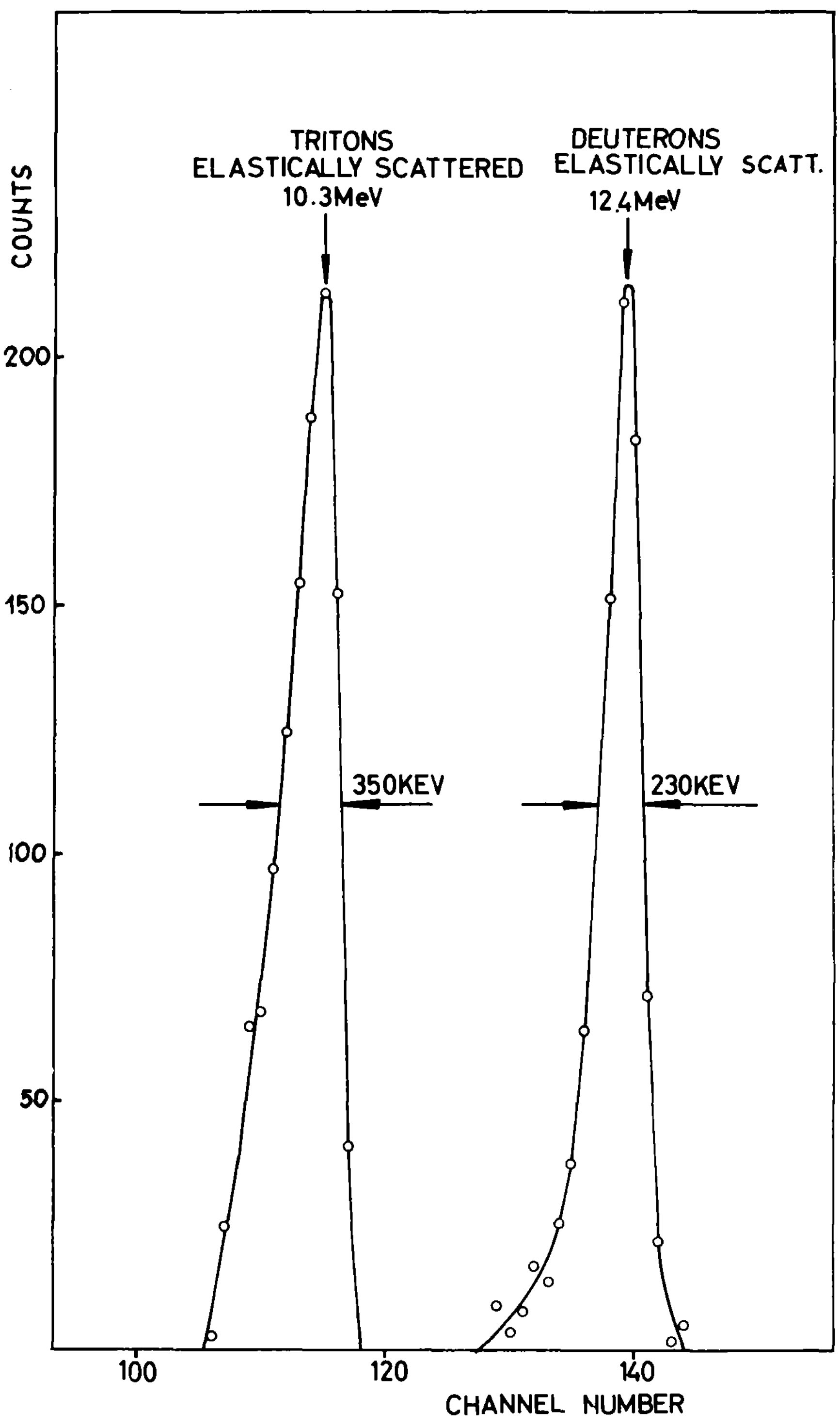
ΔE1
ΔE2
E
PA
PA
PA
AMP.
AMP.
AMP.
AMP.
ADDING CIRCUIT
DISCR.
DISCR.
FAST CC τ=0.3 μs
TRIPP. CC GATE
TRIPP. CC GATE
2-DIM. ANAL.
2-DIM. ANAL.
TRIGGER
TRIGGER
E
ΔE1+ΔE2
ΔE2
ΔE1
PRINT.
PRINT.
(n³)?
(H⁴)?
(REDUCED AMPLIFICATION BY AFACTOR OF 2)


BACKGROUND
DEUTERON SPECTRA
Au
Pb
C
80
70
60
50
40
30
20
10
NUMBER OF COUNTS
1
2.5
4
5.5
7
8.5
BACKGROUND
PROTON SPECTRA
Pb
C
Au
240
200
160
120
80
40
1
2.5
4
5.5
7
8.5
ENERGY (MEV)


COUNTS
180
160
140
120
100
80
60
40
20
4
8
12
16
20
24
28
CHANNEL NUMBER
275 keV
415 keV
DEUTERON AND TRITON
ENERGY LOSS IN 23μ
THICK COUNTER
60 keV
80 keV



COUNTS
770 keV
1200 keV
(ΔE₁+ΔE₂) ENERGY LOSS DISTRIBUTIONS
FOR 8MeV PROTONS AND DEUTERONS
40
30
20
10
12
14
16
18
20
22
24
26
28
30
CHANNEL NUMBER



COUNTS
TRITONS
ELASTICALLY SCATTERED
10.3MeV
DEUTERONS
ELASTICALLY SCATT.
12.4MeV
350KEV
230KEV
200
150
100
50
100
120
140
CHANNEL NUMBER