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DESIGN CONSIDERATIONS AND CALCULATIONS FOR A Li^6 SEMICONDUCTOR SANDWICH FAST NEUTRON SPECTROMETER EXPERIMENT

by

R.A. RYDIN

1966

Joint Nuclear Research Center
Ispra Establishment — Italy

Chemistry Department
Nuclear Chemistry

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Conclusions are: 1) the background response does not appear to limit the use of the spectrometer in a fission type spectrum although it may prove troublesome for other spectra; 2) the background response is large enough to require background subtraction; 3) Loss of efficiency at higher energies due to discrimination of thermal neutron events is not large and can be corrected for.

A circuit arrangement, using fast electronics to minimize gamma ray pileup effects, low level discriminators to eliminate thermal neutron response if desired, and a fast gate to minimize true pulse pileup in the microsecond part of the electronic chain, is recommended.

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A. Introduction

In a number of recent papers concerning the use of Li^6 sandwich semiconductor spectrometers,[1] design criteria based on experimental observations have been discussed. Some of the usual recommendations are:

1) A dummy detector or a detector with a removable Li^6F layer should be used to evaluate and allow subtraction of the background produced by (n,p) and (n,α) reactions occurring in the silicon of the diodes;
2) The highest low level discriminator setting, which does not discriminate against true events, should be used to minimize detector background response;
3) The minimum depletion layer thickness, consistent with the highest energy triton of interest, should be used to minimize detector background response;
4) Pileup of true events in the microsecond part of the circuit (input to the multichannel analyser) is the most serious electronic limitation;
5) The use of fast (nanosecond) electronic circuitry would tend to reduce or eliminate the gamma ray pileup problem encountered when making reactor measurements.

In this paper, the above recommendations are investigated in order to more fully understand the phenomena involved and to predict the usefulness of this type of device for measuring fission type fast neutron spectra in reactor environments.

Circuitry and detectors are being built which will be used to measure the neutron spectrum from an enriched uranium converter plate shortly to be installed in a beam port of the ISPRA-1 Reactor.

Manuscript received on December 20, 1965.

B.True Coincidence Background Calculation.

A true coincidence background count occurs when a proton or alpha particle, emitted in an (n,p,) or (n,α) reaction in silicon, crosses both diodes and deposits enough energy in each to produce a pulse above a predetermined discriminator level.Since the Q value for these reactions is negative, while that for the Li^6 reaction is positive, a background event can produce a count in the same channel as a true event only when the neutron energy is higher by the difference of both Q values (i.e. for the Si^{28}(n,p) reaction,ΔE= 8.64 MeV.). Of course, if the particle does not lose all of its energy in the two depletion layers then the count will be registered in a lower channel.

Although the neutron flux at higher energies is strongly depleted (fission type spectra), the source volume of silicon compared to that of Li^6F is so large that a comparable number of events can be registered from each reaction in the lower energy channels. Therefore background subtraction becomes necessary.

In order to calculate the background response, the following assumptions were made, (See Figure 1):

1) The detector is a semi-infinite sandwich with the two halves in contact (one-dimensional calculation). Particle ranges are of the order of microns while detectors normally have sizes the order of a centimeter; hence the edge effect is only a small fraction of the total;
2) There are no losses in the dead layer and in the Li^6F layer. For most particle energies of interest, the range lost these layers is only a few percent of the range lost in silicon.
3) Excited levels in the silicon are ignored. These levels tend to shift some background events to lower energies where the counts are less important.
4) The particles are isotropically emitted in the laboratory system. This simplification, while not strictly

true, is not expected to lead to a large error. Angular distribution data are almost non-existent[2].

With these assumptions, the coincidence background rate at any summed particle energy for a given input spectrum can be computed by integrating over the entire possible source volume of silicon. The equation used is the following,

$$E_s) = 2\int dE_n \sum_i \left[\Sigma_i(E_n)\ \phi(E_n) \int_0^{R_{Ti}(E_n)} dx \int_0^{\pi/2} d\theta \ \left(\frac{\sin\theta}{2}\right) p_D(E_s \mid x, \theta, R_{Ti}, DL, DISC)\right] \qquad (1)$$

where: $N(E_s)$ is the coincidence background detection rate at a given summed particle energy, E_s $\left(\frac{\text{number}}{\text{cm}^2\text{-sec-MeV}}\right)$;

$\Sigma_i(E_n)$ is the macroscopic absorption cross section[3] of the ith reaction at energy E_n (cm^{-1});

$\phi(E_n)$ is the differential neutron flux at energy E_n $\left(\frac{\text{neutrons}}{\text{cm}^2\text{-sec-MeV}}\right)$;

x is the depth in silicon where the reaction occurs (cm);

$R_{Ti}(E_n)$ is the range of the particle produced in the ith reaction with a neutron of energy E_n (cm);

θ is the emission angle from the normal to the detector plane;

$\frac{\sin\theta}{2}$ is the isotropic emission probability;

DL is the depletion layer thickness (cm);

DISC is the low level discriminator setting (MeV);

$p_D(E_s \mid x, \theta, R_{Ti}, DL, DISC)$ is the probability of detection of an event given the starting point and direction of the particle, its range, and the depletion layer thickness and discriminator settings. Its value is either 0 or 1, and it serves mainly to shift the recording of an event occurring with a neutron of energy E_n to the channel corresponding to E_s

Referring to Figure 1, the solution procedure is the following:

1) For a given neutron energy, the energy of the particle produced, $E_p \cong (E_n + Q_i)(\frac{1+Msi - Mi}{1 + Msi})$, where Q_i is negative, and the production rate, $\Sigma_i(E_n)\ \phi(E_n)$, are computed;
2) For the particle of energy E_p, the total range in silicon is determined and used to set the upper limit of the x integration, $R_{Ti}(E_n)$;
3) For chosen source distance x and emission angle θ the range in each of the four numbered regions of Figure 1, including the two depletion regions, is computed. These distances are related to R_{Ti}, $x/\cos\theta$ and $DL/\cos\theta$;
4) Using residual ranges, the energies lost in the two depletion layer regions, 2 and 3 of Figure 1, are calculated;
5) If the energies lost in both regions are above the discriminator level, they are added to get the summed particle energy E_s and a $(\frac{\sin\theta}{2})\,dx\,d\theta$ weighted count is placed in the channel corresponding to E_s;
6) The procedure is repeated for all reactions, energies, distances and angles, for the given neutron flux distribution.

For the range-energy calculations, polynomial fits to the proton range data, calculated by ECCLES(4) et al, were used. Alpha particles were treated as equivalent protons of energy $E_p = E_\alpha/4$. It was found, however, that the two expressions given by ECCLES did not quite match in the region of overlap. Therefore, the constant term in the high energy fit was slightly modified to make the curves consistent. The expressions used were, for ($E_p \leq 3.7$ MeV),

$$
\begin{cases}
Y = \ln\,(1000\ E_p) - 7.50 \\
W = 2.2166 + 1.5811\ Y + 0.1101\ Y^2 - 0.0195\ Y^3 - 0.0051\ Y^4 + 0.0015\ Y^5 \\
R_T = \exp\,(W/1.0204) \quad (\mathrm{mg/cm^2})
\end{cases} \tag{2}
$$

and, for ($E_p \geq 3.7$ MeV),

$$
R_T = -4.47 + 3.8224\ E_p + 1.3587\ E_p{}^2 - 0.0071213\ E_p{}^3 (\mathrm{mg/cm^2}) \tag{3}
$$

It was also necessary to calculate energy as a function of residual range. In the low energy region, the expression for the range-energy curve was successfully inverted into an energy-range curve using formulas for reversion of a series[5]. The expression used was, for ($E_p \leq 3.7$ MeV),

$$
\begin{cases}
W = 1.0204\ \ln\,(R_T) - 2.2166 \\
Y = 0.63247\ W - 0.027855\ W^2 + 0.005574\ W^3 - 0.0004411\ W^4 \\
\qquad - 0.00002581\ W^5 \\
E_p = \exp\,(Y + 7.50)\ /1000. \quad (\mathrm{MeV})
\end{cases} \tag{4}
$$

In the high energy region, linear interpolation of a seven point table was found to be sufficiently accurate for the present purpose.

Results of one of the calculations are presented in Figure 2a where the background response spectra due to the $Si^{28}(n,p)$, $Si^{28}(n,\alpha)$ and $Si^{29}(n,\alpha)$ reactions (smoothed cross sections were used) are compared to the ideal true response spectrum from Li^6 ($\sim$400 $\mu g/cm^2$ Li^6F) produced by irradiation in a fission neutron spectrum (resolution effects were ignored). A depletion depth of 60 mg/cm^2 ($\sim$8.5 MeV tritons) and a discriminator setting of 1.6 MeV (which accepts all true Li^6 events) were used in these calculations. The general shape of the background spectrum is due to the cross section variations in the low energy region and to the neutron spectrum variation in the high energy region. Conclusions can be made that, for a fission neutron spectrum, the $Si^{28}(n,p)$ reaction is the only background reaction of importance and that its magnitude is comparable to that of the Li^6 reaction, necessitating careful background subtraction at all energies.

Available experimental spectrometer data,[6] for reactor spectrum neutrons, are shown in Figure 2b. Although the calculation appears to overestimate the relative value of the background contributions, the general agreement in spectral shape between theory and experiment is excellent. Differences may possibly be explained by: 1) Simplicity of the calculational model; 2) Inaccuracies in the physical data used; 3) Numerical inaccuracies due to the discretization of the problem; 4) Physical differences between the experiment and the model: 5) Poor experimental statistics; and 6) Finite resolution effects.

In Figure 3, results of repeating the previous calculation using depletion depths varying from 20 to 100 mg/cm^2 ($\sim$4.3 to 11.5 MeV tritons) are shown for the $Si^{28}(n,p)$ reaction. There are of course, no variations in the (n,α) reaction background curves for depletion layer depth variations in this range.Several comments may be made. At low energies, where the source depth is less than the depletion depth, the energy deposited is independent of depletion depth and all curves are similar. At high energies, where most particles pass through both depletion layers, the main effect is a change in the total energy detected for each particle and hence a shifting of the spectrum to lower energies with decreasing depletion depth. However, the reduction obtained in background is relatively small when the depletion depth is varied over a practical range of interest.

In Figure 4, results of repeating the previous calculation using various low level discriminator settings, 0.6 to 2.0 MeV, are shown for the $Si^{28}(n,p)$ reaction. Here, the main effect is a reduction in the depth at which a particle can originate and still produce a coincidence above the discriminator level. At high energies, this change is a small fraction of the total source depth and therefore all curves are similar. At low energies, the change can be a large fraction of the source depth and greatly reduce the background. In the region of interest, however, the overall effect of discriminator level on background response is not large.

As a general conclusion it can be said that the lowest background response is obtained using the minimum practical depletion depth and the maximum practical discriminator level. However, the improvements are not great enough to allow the background to be ignored. Furthermore, the amount of improvement obtainable does not by itself justify extreme efforts in the setting of either the discriminator level or the depletion depth when measuring fission type neutron spectra.

The background calculations were also performed for the case of an incident Pu-α-Be neutron spectrum(7). This spectrum differs from a fission neutron spectrum in two respects. First it has some relatively large high energy components and, second, there are no neutrons emitted at energies greater than $\sim$10.5 MeV. The results of these calculations are shown in Figure 5a where the effects of the large population of high energy neutrons in the spectrum are shown (large background at low energy) and the effects of both the offset in energy caused by the Q values of the reactions and the cutoff of the neutron spectrum at high energy are illustrated. In particular, the $Si^{28}(n,p)$ background response is much greater than the true Li^6 response in the low neutron energy region but disappears above ~2 MeV, where the (n,α) reactions become important due to the lack of competition with the (n,p) reaction. Available experimental data[6] are shown in Figure 5b. The agreement, except for approximately the same normalization difference noticed in the case of the fission spectrum neutrons, is again excellent.

In conclusion, the high energy part of the spectrum can be measured with almost no background interference but the low energy part of the spectrum can only be accurately obtained using careful background subtraction or greatly increased sensitivity (ie, more Li^6).

C. Non-coincident Singles Background Calculation (Reactions in Silicon)

The singles background spectrum is of interest because it represents a part of the total detector count rate which must be handled by the electronics and rejected by the coincidence circuitry. The calculation is almost identical to that performed for the true coincidence background spectrum, the main differences being:

1) The upper limit on the Θ integration is changed in order to accept particles which proceed away from the interface as well as toward it;
2) The upper integration limit on the particle source depth, x, is changed in order to accept all reactions which can produce a count in the depletion layer of a diode, even those which have no chance of producing a coincidence;
3) All events which make a valid coincidence are excluded;
4) All particles which deposit less than an arbitrary "noise" energy in a diode are ignored.

In practice, the above requirements are fulfilled by repeating the original calculation from Θ equals 0 to $\pi/2$ twice, first using an x integration limit of $R_{Ti} + DL$ and considering the possibility of singles counts and coincidence in the other diode, and second, using an x integration limit of DL and ignoring the other diode.

Results of this calculation are shown in Figure 6 for a depletion thickness of 60 mg/cm^2 and a low level discriminator setting of 1.6 MeV. In particular, it can be noted that the singles rate in the low energy region is approximately an order of magnitude greater than the coincidence background rate, due partly to the greater source volume available and partly to the low coincidence probability. In the high energy region, where the source volumes are more nearly equal and where coincidences are much more likely, the two rates are the same order of magnitude. Note also that the singles rate in the second diode, produced by reactions occurring in the first, is very small compared to the internally produced singles rate. This occurs because the source is smaller and particles which do cross into the second diode are likely to produce a coincidence.

D. Detection Efficiency Calculation-Use of a Low Level Discriminator to Eliminate Thermal Neutron Events.

Since the thermal neutron cross section of the Li^6 reaction is almost four orders of magnitude greater than the fast neutron cross section, the thermal neutron reaction rate may actually be four or five orders of magnitude greater than the fast neutron reaction rate when the detector is used in a thermal reactor. Unfortunately, thermal neutron reactions produce valid coincidences and hence these pulses are analysed together with the pulses from the fast neutron reactions. If the multichannel analyser is capable of sorting, for example, 10^4 counts per second without pileup, then less than 1 count per second would actually belong to the fast spectrum and a long counting time would be necessary to obtain a fast spectrum with reasonable statistics. Furthermore, chance coincidences could produce distortions in the measured spectrum.

One partial solution is to surround the detector with a thermal neutron absorber such as cadmium or boron. A factor of up to 10^3 reduction of thermal neutrons can be achieved, which reduces the ratio of detected thermal to fast events to the order of 10 to 100. Of course, it is not always possible to use absorbers in a reactor without disturbing the quantity which is to be measured.

A second partial solution is to electronically discriminate against all thermal neutron caused events and prevent them from being analysed. If the discrimination and gating is performed in the fast part of the electronic circuitry, then the acceptable fast neutron count rate without distortion is limited mainly by the possibility of chance coincidences which depend upon the coincidence resolving time and the total event rate at the coincidence input.

A combination of the above solutions would appear to give the instrument the greatest flexibility. Under these conditions, matching of the detector to the experiment would be simplified and a spectrum could be obtained in a reasonable length of time.

A calculation was performed to determine the maximum and minimum triton and alpha particle energies emitted in the $Li^6(n,\alpha)T$ reaction as a function of neutron energy[8]. These maximum and minimum values are plotted in Figure 7. It can be seen that the minimum energy particles are emitted in reactions with neutrons having energies greater than thermal energy and that any attempt to discriminate all of the thermal neutron events would result in a loss of events at higher energy. A discriminator setting of 2.1 MeV would eliminate all of the thermal neutron produced pulses but a high pulse rate at the input to the coincidence circuit would still result, since all the thermal neutron produced triton pulses would pass, leading to a possible high chance coincidence rate. Setting the discriminator at 2.8 MeV, to eliminate all thermal neutron produced triton pulses, would result in a spectrometer sensitive only to neutrons of energies greater than ~0.9 MeV.

The relative detection efficiency of a semiconductor sandwich spectrometer, irradiated with an arbitrary angular neutron flux distribution, can be calculated using the following formulation[9],

$$\epsilon_R(E) = \int_\alpha d\alpha \int_\theta d\theta \quad p_\alpha(\alpha) \quad p_\theta(\theta,E) \quad p_D(E|\alpha,\theta) \qquad (5)$$

where: $\epsilon_R(E)$ is the relative detection efficiency including angular effects only;

$p_\alpha(\alpha)$ is the probability that a neutron, which strikes the detector, enters at an angle α from the detector axis;

$p_\theta(\theta,E)$ is the probability that the triton is emitted at an angle θ from the direction of the incident neutron as a function of energy (includes differential cross section and kinematics effects);

$p_D(E|\alpha,\theta)$ is the conditional probability, given by geometrical considerations, that a neutron which enters the detector at an angle α from the axis and which produces a triton at angle θ from the neutron direction, will result in a valid coincidence.

The effect of the low level discriminator can be calculated by slightly modifying the conditional probability term to also exclude from detection all events which result in a triton or alpha particle with energy below the discriminator level. This amounts to replacing the conditional probability term in Equation 5 by $P_D(E|\alpha,\theta,\text{DISC})$.

The relative detection efficiency has previously been calculated for a sandwich spectrometer in a flux of neutrons from a disk source[(9)]. The detection efficiency with and without discriminator is given in Figure 8 assuming isotropic differential cross sections and in Figure 9 using available differential cross section data. From these results it can be concluded that the use of a discriminator should not materially affect the accuracy with which the final spectrum is determined. Further, it should be possible to experimentally measure the effect of a change in discriminator level and to compare this to the calculated value. It must be pointed out that it would be of great value to have better data on the differential angular cross section of the $Li^6(n,\alpha)T$ reaction[(2)].

For completeness, a comparison of the $Si^{28}(n,p)$ coincidence background response and the true spectrometer response to a fission neutron spectrum, with the discriminator set at 2.1 MeV, is shown in Figure 10. It can be seen that the use of the discriminator in this manner does not materially affect the background problem.

E. Gamma Ray Pileup - The Use of Fast Electronics

The major problem encountered in using semiconductor fast neutron spectrometers in reactors is their sensitivity to gamma radiation. The pileup of gamma produced pulses can in many cases completely destroy the ability of a spectrometer to detect neutrons by masking the neutron produced pulses(1). One solution to this problem involves an elaborate scheme to completely shield the diodes from external radiations(10). Unfortunately the device can only be used for extracted neutron beams. A second solution involves the use of fast electronic circuitry.

It is a well known fact that pulse pileup effects can be minimized by the use of narrow pulse widths. In preliminary experiments with our detectors, cathode followers, line shapers and amplifiers, we have been easily able to obtain pulse widths of 10 - 15 nanoseconds with about 15 feet of cable between the detectors and amplifier.

A single semiconductor probe, using a fast electronics system built by H. Katzenstein(11) (15 nsec pulse width), has previously been tested by the author at the M. I.T. Reactor(12). This probe was capable of detecting particles from the $Li^6(n,\alpha)T$ and $B^{10}(n,\alpha)Li^7$ reactions with thermal neutrons in the presence of a reactor and capture gamma background of ~3000 r/hr. The probe was also capable of measuring an undistorted Am^{241} alpha spectrum in the presence of $\sim 10^5$ r/hr of Co^{60} gamma rays from the Cobalt Irradiator at the Massachusetts General Hospital(12).

In a recent paper, Nygaard(13) reported that a Li^6 semiconductor sandwich spectrometer, with a fast electronics system (~10 ns), had operated in a gamma flux of 1.6×10^4 r/hr with no apparent γ ray pulse pileup effects. However, pileup of thermal neutron produced pulses, in the slow circuits to the multichannel analyser, caused some difficulty. In this experiment, the thermal neutron flux was 10^8 n/cm^2-sec and the fast flux was only twice as large.

It is concluded that the use of a properly designed electronics system should permit useful operation of the Li^6 semiconductor sandwich spectrometer in reasonably high gamma ray and thermal neutron fluxes. A neutron spectrometer employing fast electronic circuitry is being developed for use at this laboratory. The system, a simplified block diagram of which is shown in Figure 11, shall be used to measure the neutron spectrum from an enriched uranium converter disk shortly to be installed in beam port 12CH1 of the ISPRA-1 Reactor.

Acknowledgement

The author wishes to thank Prof.G.Bertolini for suggesting this problem.

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PATH OF A CHARGED PARTICLE EMITTED
AT DEPTH X IN A DIODE OF A
SEMICONDUCTOR SANDWICH SPECTROMETER

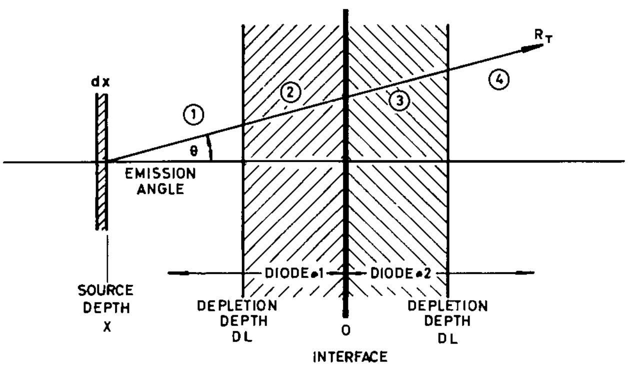


Fig. 1

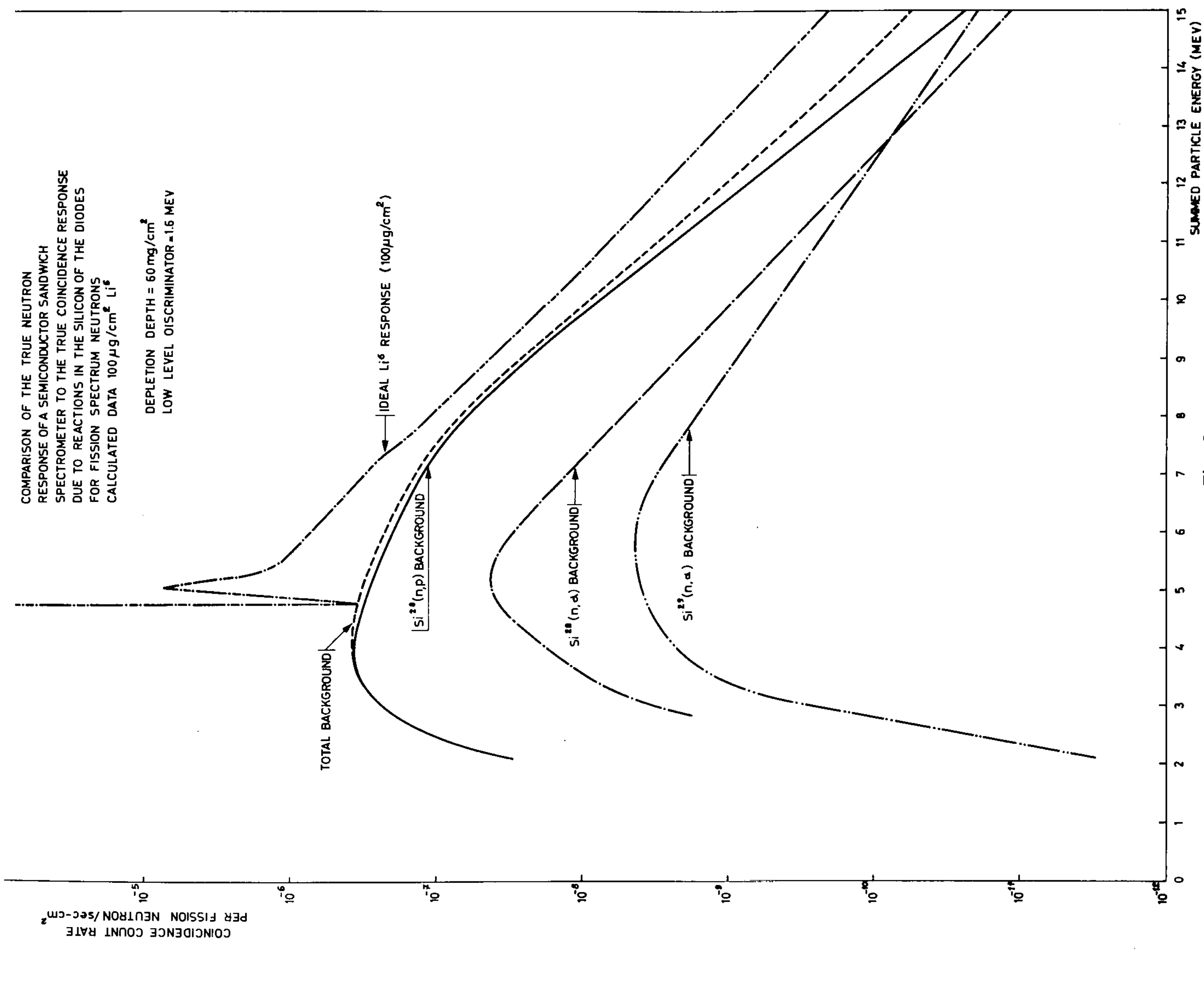


Fig. 2a

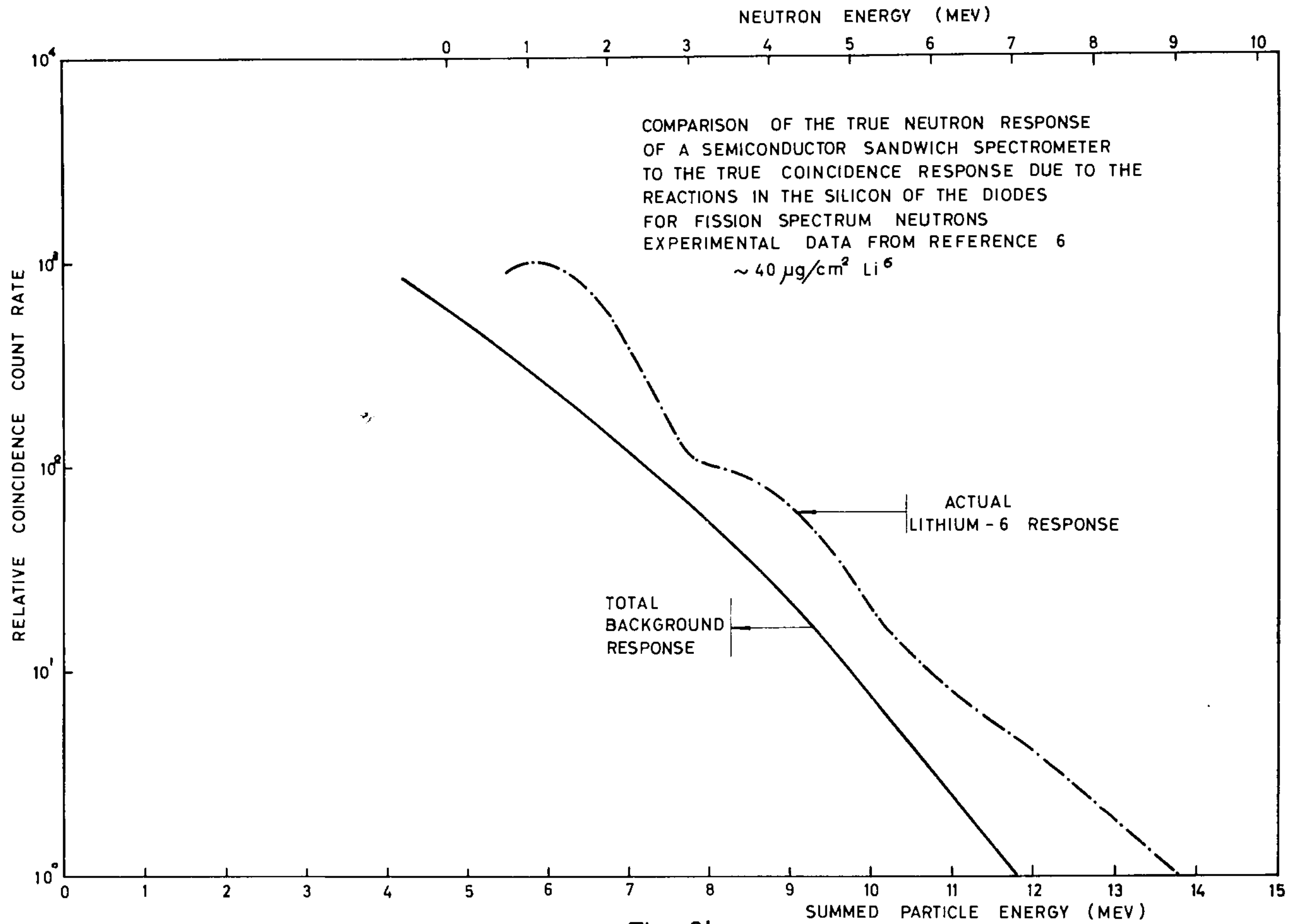

NEUTRON ENERGY (MEV)
COMPARISON OF THE TRUE NEUTRON RESPONSE
OF A SEMICONDUCTOR SANDWICH SPECTROMETER
TO THE TRUE COINCIDENCE RESPONSE DUE TO THE
REACTIONS IN THE SILICON OF THE DIODES
FOR FISSION SPECTRUM NEUTRONS
EXPERIMENTAL DATA FROM REFERENCE 6
~ 40 μg/cm² Li⁶
ACTUAL
LITHIUM - 6 RESPONSE
TOTAL
BACKGROUND
RESPONSE
RELATIVE COINCIDENCE COUNT RATE
SUMMED PARTICLE ENERGY (MEV)

Fig. 2b

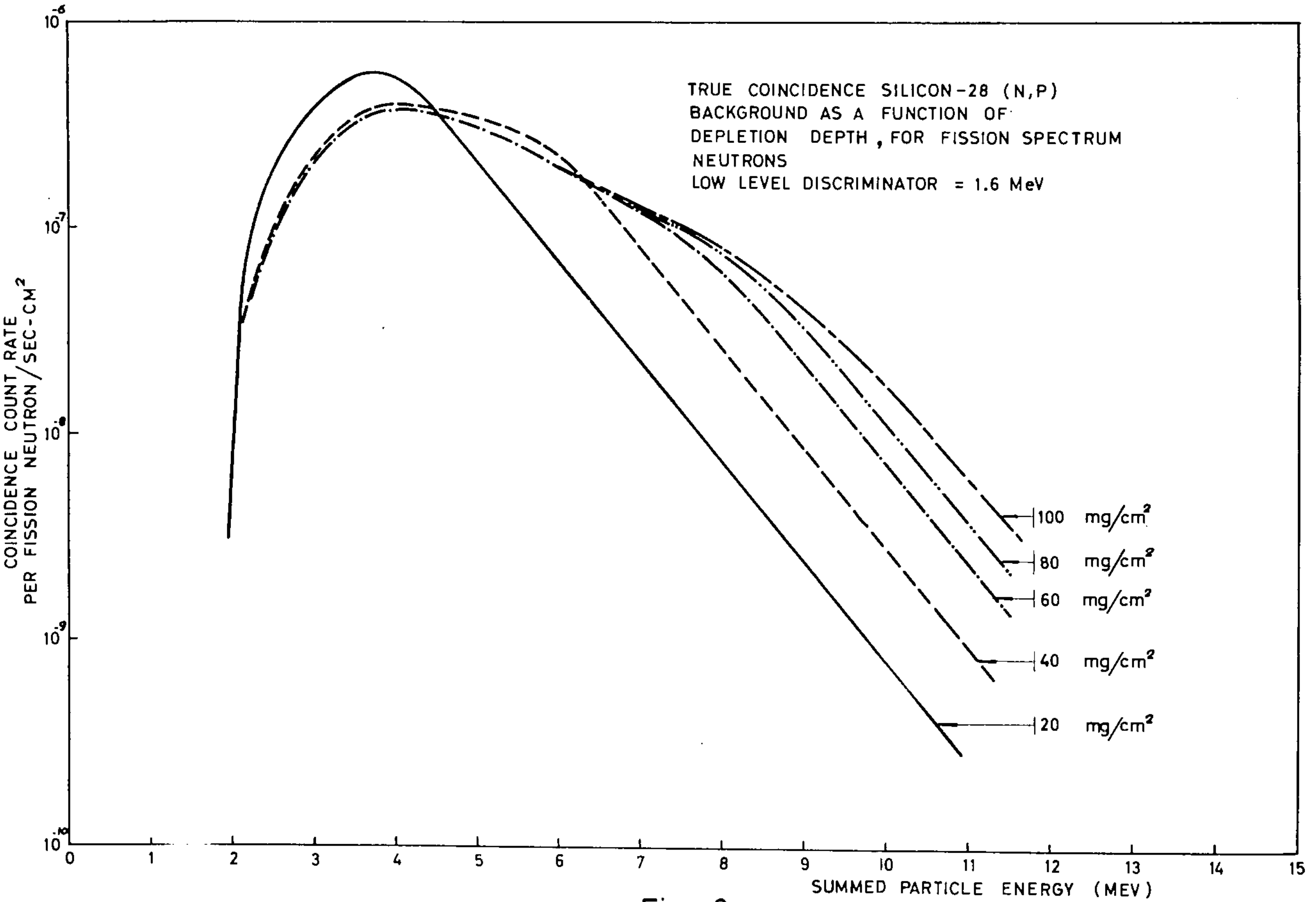

TRUE COINCIDENCE SILICON-28 (N,P)
BACKGROUND AS A FUNCTION OF
DEPLETION DEPTH, FOR FISSION SPECTRUM
NEUTRONS
LOW LEVEL DISCRIMINATOR = 1.6 MeV
100 mg/cm²
80 mg/cm²
60 mg/cm²
40 mg/cm²
20 mg/cm²
COINCIDENCE COUNT RATE
PER FISSION NEUTRON/SEC-CM²
SUMMED PARTICLE ENERGY (MEV)

Fig. 3

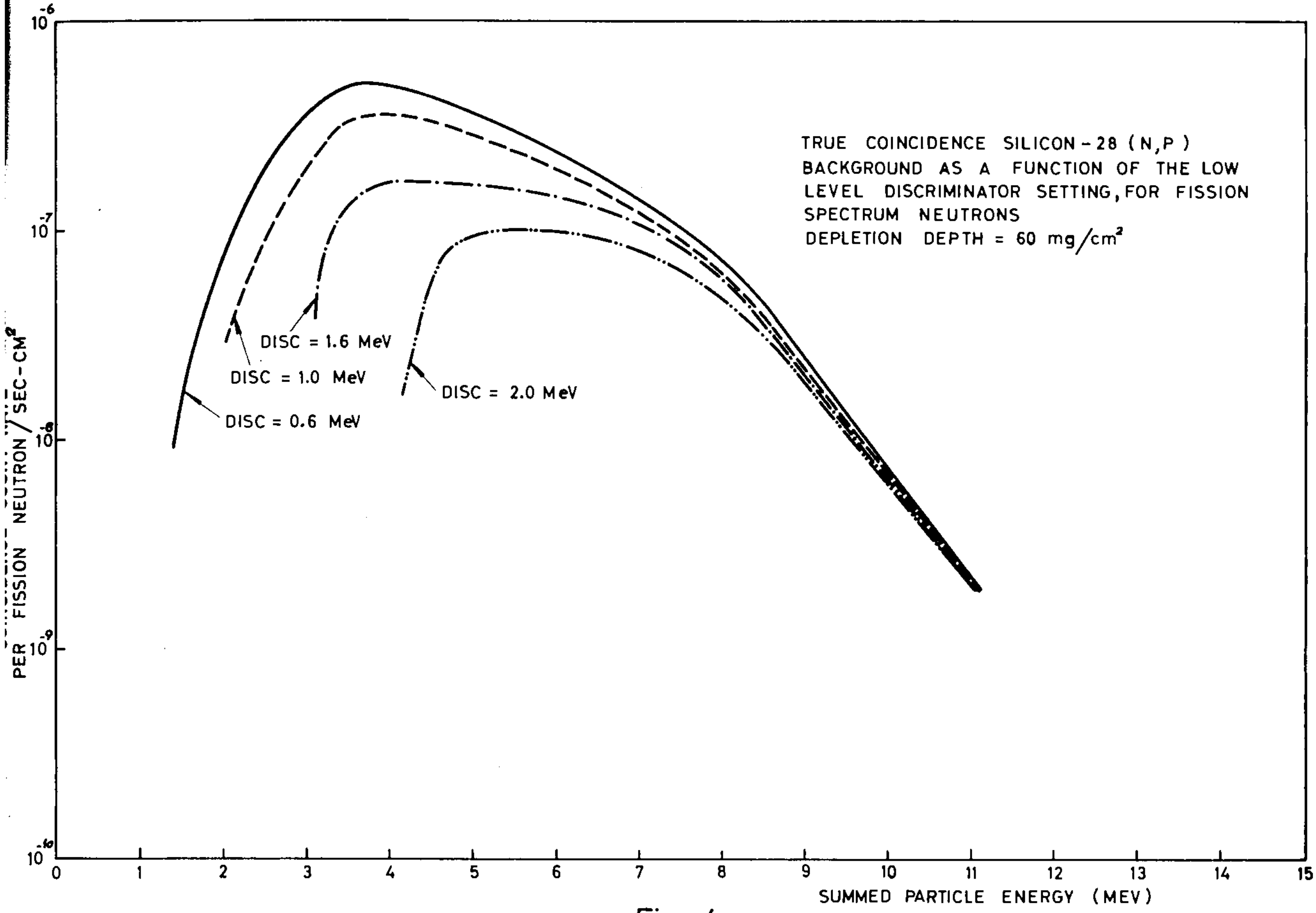

TRUE COINCIDENCE SILICON-28 (N,P) BACKGROUND AS A FUNCTION OF THE LOW LEVEL DISCRIMINATOR SETTING, FOR FISSION SPECTRUM NEUTRONS
DEPLETION DEPTH = 60 mg/cm²
DISC = 1.6 MeV
DISC = 1.0 MeV
DISC = 2.0 MeV
DISC = 0.6 MeV
PER FISSION NEUTRON / SEC-CM²
SUMMED PARTICLE ENERGY (MEV)

Fig. 4

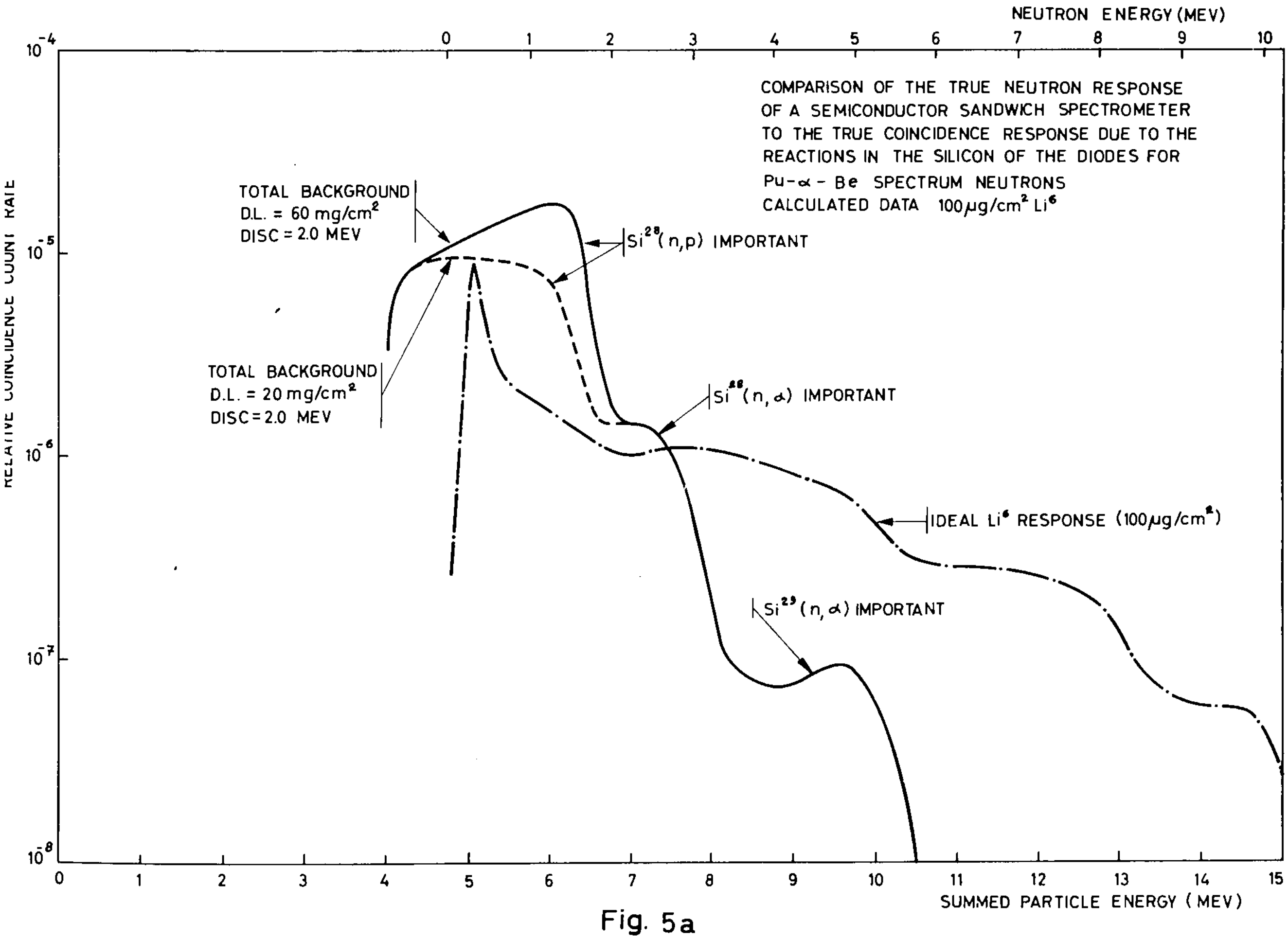
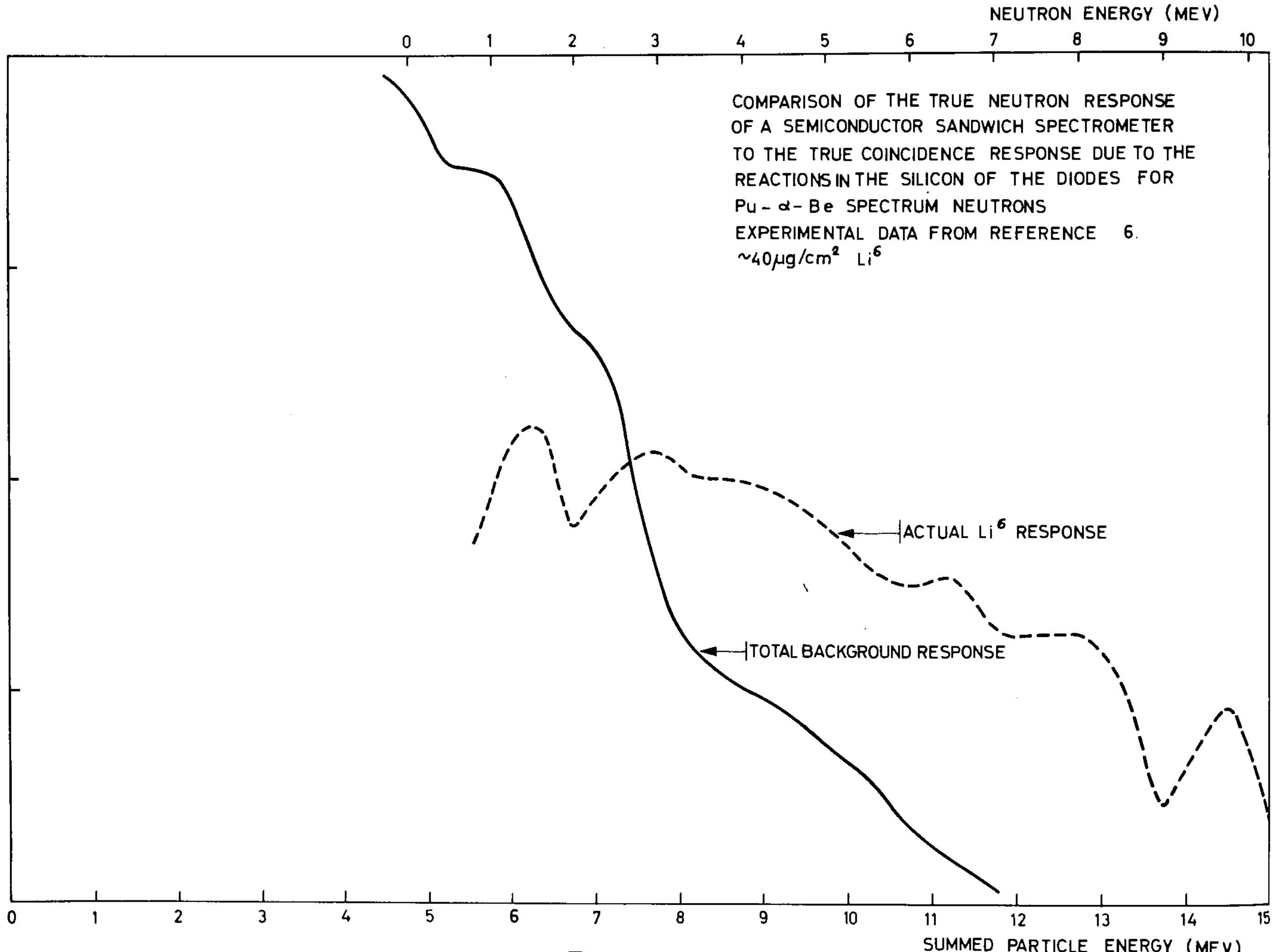
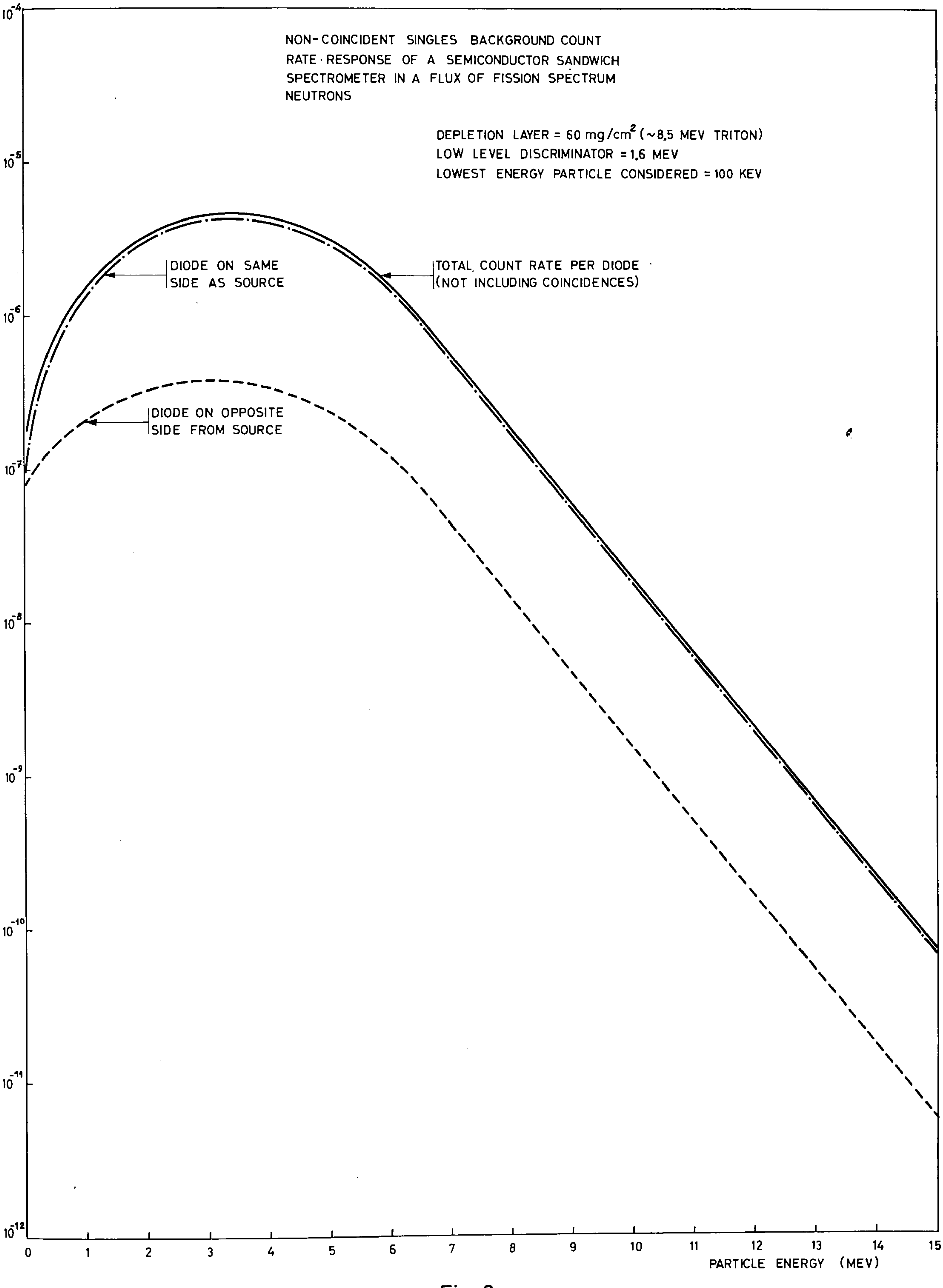

NEUTRON ENERGY (MEV)
COMPARISON OF THE TRUE NEUTRON RESPONSE OF A SEMICONDUCTOR SANDWICH SPECTROMETER TO THE TRUE COINCIDENCE RESPONSE DUE TO THE REACTIONS IN THE SILICON OF THE DIODES FOR Pu-α-Be SPECTRUM NEUTRONS
CALCULATED DATA 100μg/cm² Li⁶
TOTAL BACKGROUND D.L. = 60 mg/cm² DISC = 2.0 MEV
Si²⁸(n,p) IMPORTANT
TOTAL BACKGROUND D.L. = 20 mg/cm² DISC = 2.0 MEV
Si²⁸(n,α) IMPORTANT
IDEAL Li⁶ RESPONSE (100μg/cm²)
Si²⁹(n,α) IMPORTANT
RELATIVE COINCIDENCE COUNT RATE
SUMMED PARTICLE ENERGY (MEV)

Fig. 5a



NEUTRON ENERGY (MEV)
0 1 2 3 4 5 6 7 8 9 10
COMPARISON OF THE TRUE NEUTRON RESPONSE OF A SEMICONDUCTOR SANDWICH SPECTROMETER TO THE TRUE COINCIDENCE RESPONSE DUE TO THE REACTIONS IN THE SILICON OF THE DIODES FOR Pu-α-Be SPECTRUM NEUTRONS
EXPERIMENTAL DATA FROM REFERENCE 6.
~40μg/cm² Li⁶
ACTUAL Li⁶ RESPONSE
TOTAL BACKGROUND RESPONSE
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
SUMMED PARTICLE ENERGY (MEV)

Fig. 5b



NON-COINCIDENT SINGLES BACKGROUND COUNT RATE · RESPONSE OF A SEMICONDUCTOR SANDWICH SPECTROMETER IN A FLUX OF FISSION SPECTRUM NEUTRONS
DEPLETION LAYER = 60 mg/cm² (~8.5 MEV TRITON)
LOW LEVEL DISCRIMINATOR = 1.6 MEV
LOWEST ENERGY PARTICLE CONSIDERED = 100 KEV
DIODE ON SAME SIDE AS SOURCE
TOTAL COUNT RATE PER DIODE (NOT INCLUDING COINCIDENCES)
DIODE ON OPPOSITE SIDE FROM SOURCE
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
PARTICLE ENERGY (MEV)

Fig. 6

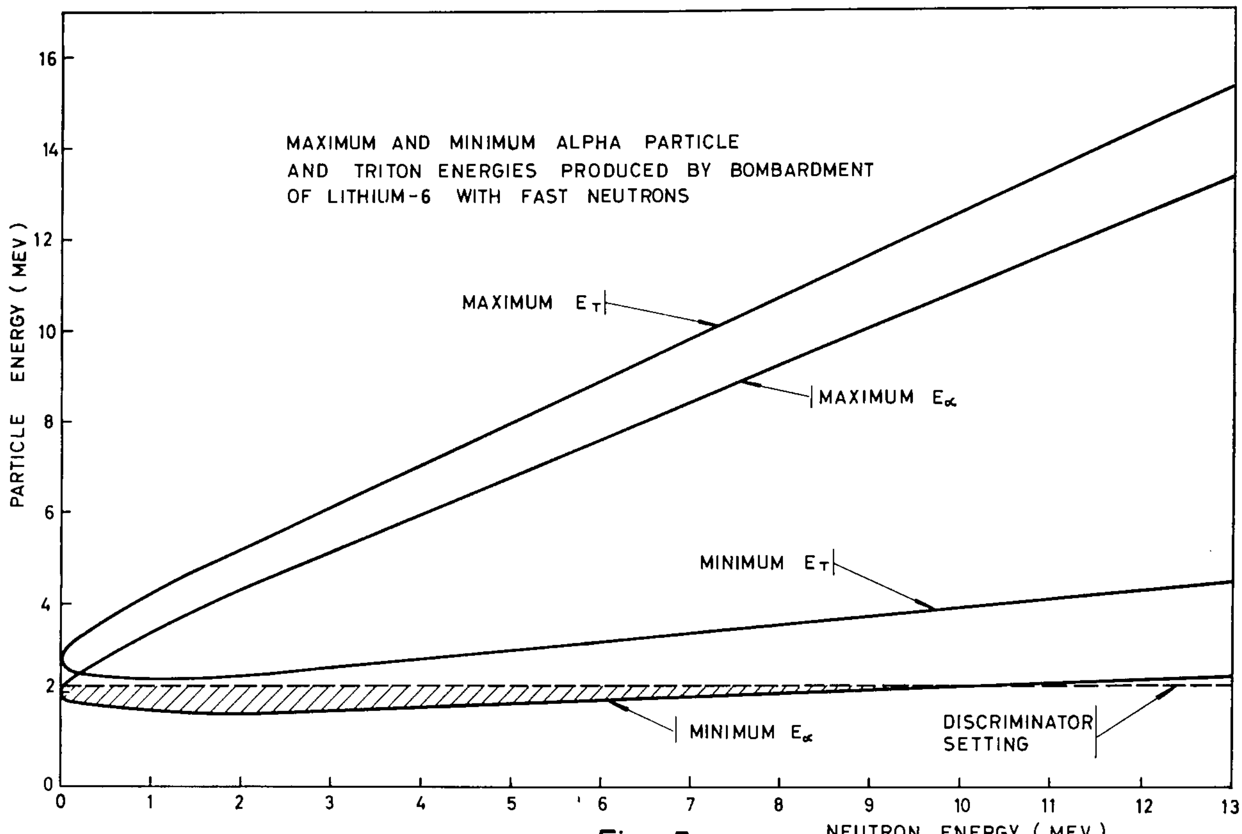

MAXIMUM AND MINIMUM ALPHA PARTICLE
AND TRITON ENERGIES PRODUCED BY BOMBARDMENT
OF LITHIUM-6 WITH FAST NEUTRONS
PARTICLE ENERGY (MEV)
MAXIMUM E_T
MAXIMUM E_α
MINIMUM E_T
MINIMUM E_α
DISCRIMINATOR
SETTING
NEUTRON ENERGY (MEV)

Fig. 7

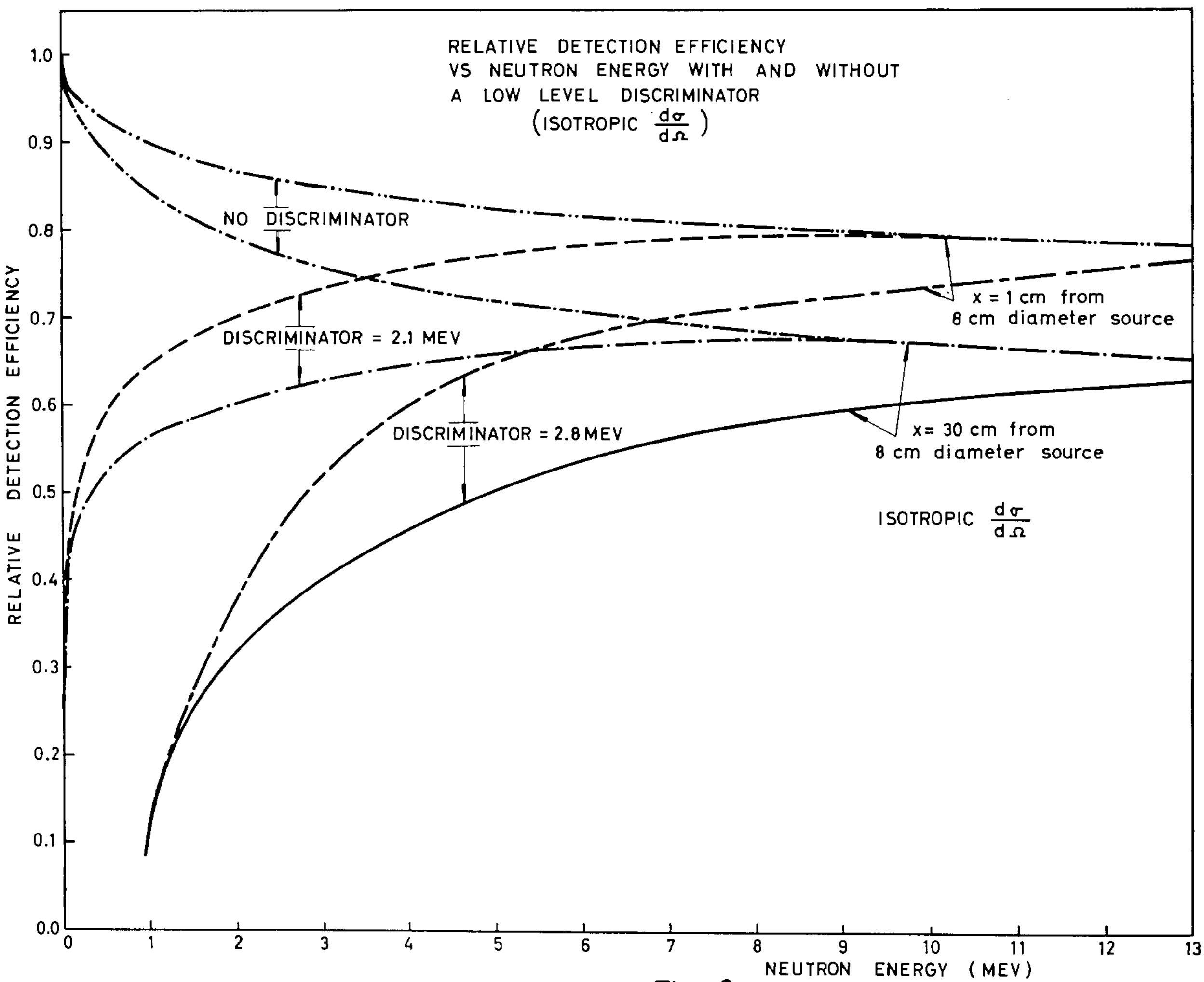
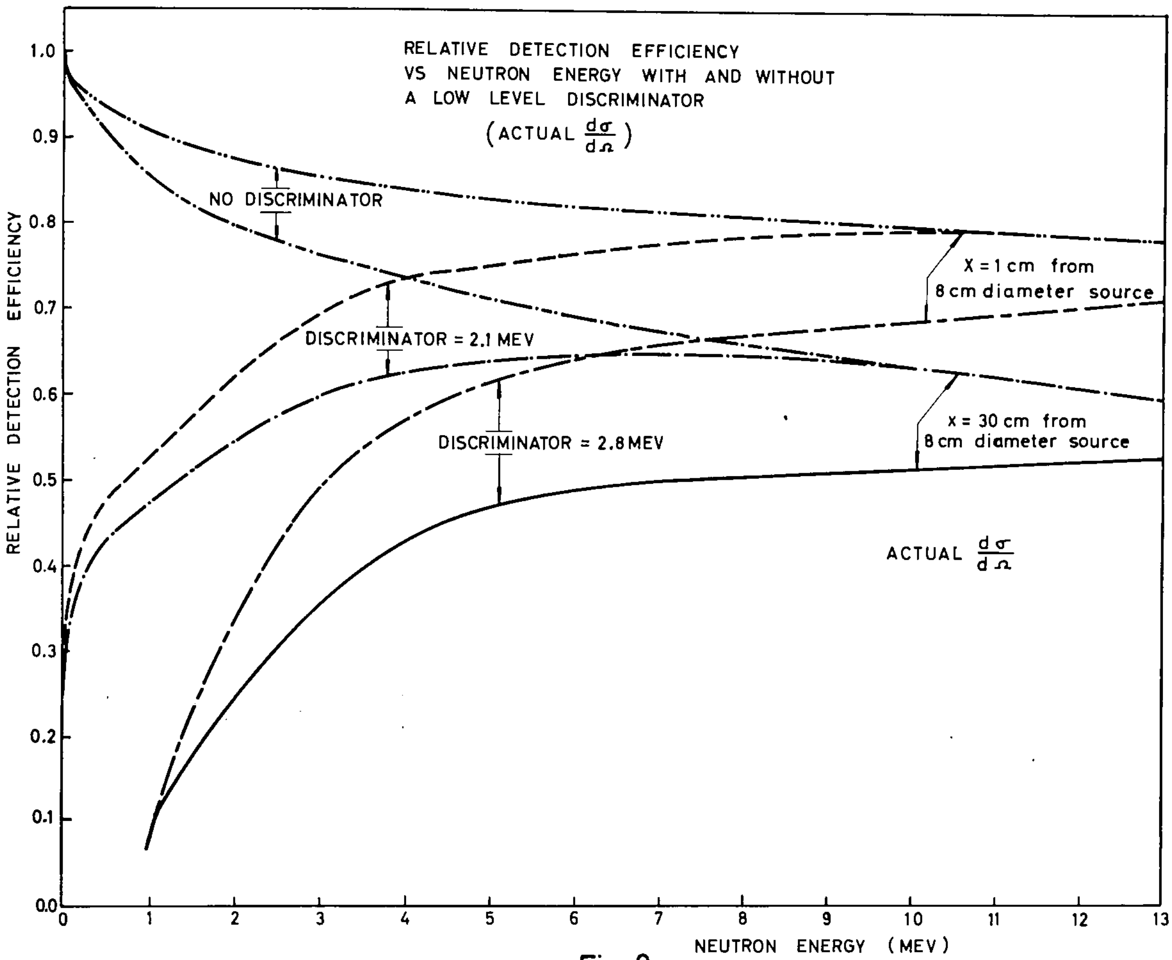
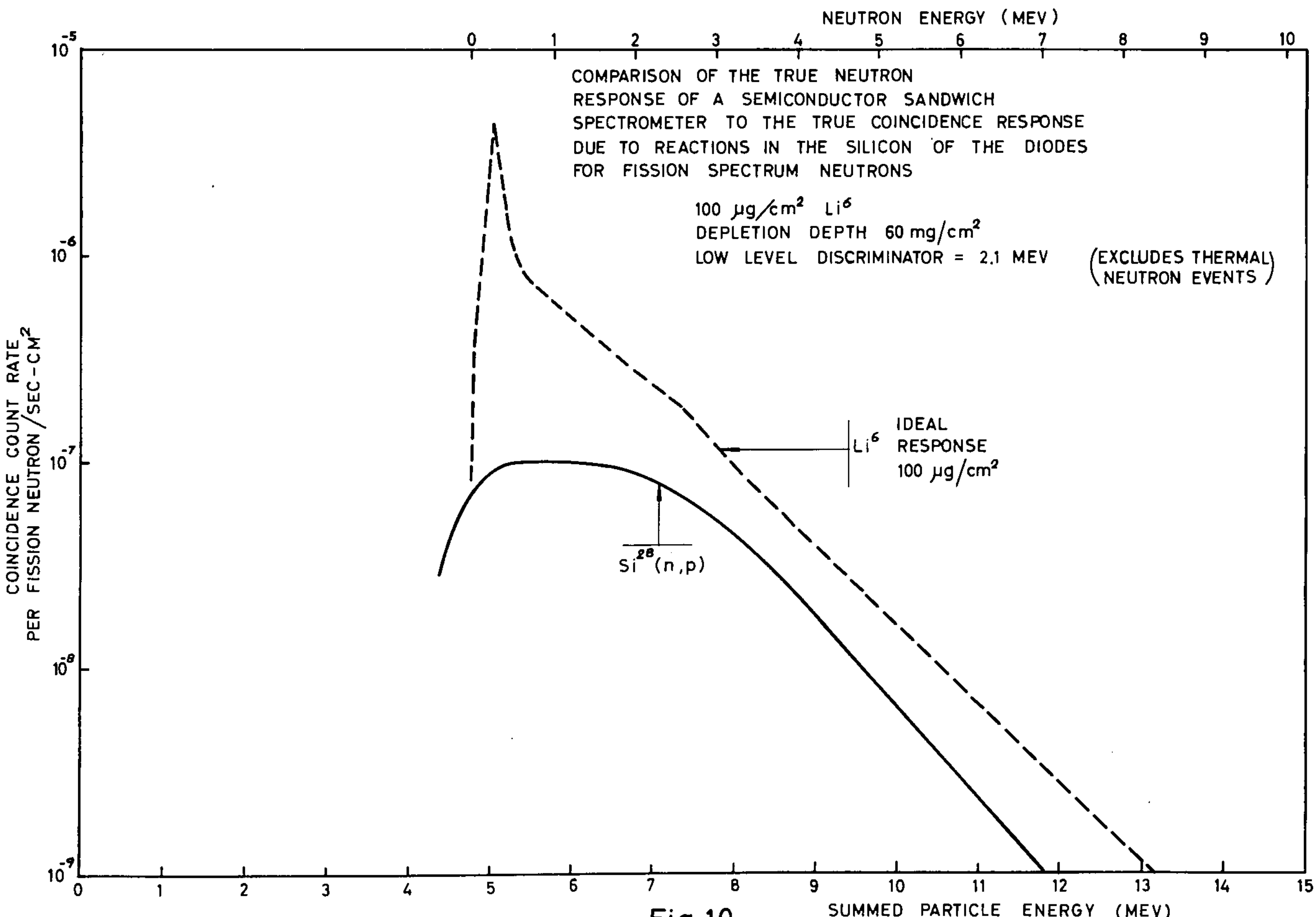

RELATIVE DETECTION EFFICIENCY
VS NEUTRON ENERGY WITH AND WITHOUT
A LOW LEVEL DISCRIMINATOR
(ISOTROPIC $\frac{d\sigma}{d\Omega}$)
NO DISCRIMINATOR
DISCRIMINATOR = 2.1 MEV
DISCRIMINATOR = 2.8 MEV
x = 1 cm from
8 cm diameter source
x= 30 cm from
8 cm diameter source
ISOTROPIC $\frac{d\sigma}{d\Omega}$
RELATIVE DETECTION EFFICIENCY
NEUTRON ENERGY (MEV)

Fig. 8



RELATIVE DETECTION EFFICIENCY
VS NEUTRON ENERGY WITH AND WITHOUT
A LOW LEVEL DISCRIMINATOR
(ACTUAL $\frac{d\sigma}{d\Omega}$)
NO DISCRIMINATOR
DISCRIMINATOR = 2.1 MEV
DISCRIMINATOR = 2.8 MEV
X = 1 cm from
8 cm diameter source
x = 30 cm from
8 cm diameter source
ACTUAL $\frac{d\sigma}{d\Omega}$
RELATIVE DETECTION EFFICIENCY
NEUTRON ENERGY (MEV)

Fig. 9



NEUTRON ENERGY (MEV)
COMPARISON OF THE TRUE NEUTRON
RESPONSE OF A SEMICONDUCTOR SANDWICH
SPECTROMETER TO THE TRUE COINCIDENCE RESPONSE
DUE TO REACTIONS IN THE SILICON OF THE DIODES
FOR FISSION SPECTRUM NEUTRONS
100 $\mu g/cm^2$ Li^6
DEPLETION DEPTH 60 mg/cm^2
LOW LEVEL DISCRIMINATOR = 2.1 MEV
(EXCLUDES THERMAL NEUTRON EVENTS)
Li^6 IDEAL RESPONSE 100 $\mu g/cm^2$
$Si^{28}(n,p)$
COINCIDENCE COUNT RATE PER FISSION NEUTRON/SEC-CM^2
SUMMED PARTICLE ENERGY (MEV)

Fig.10

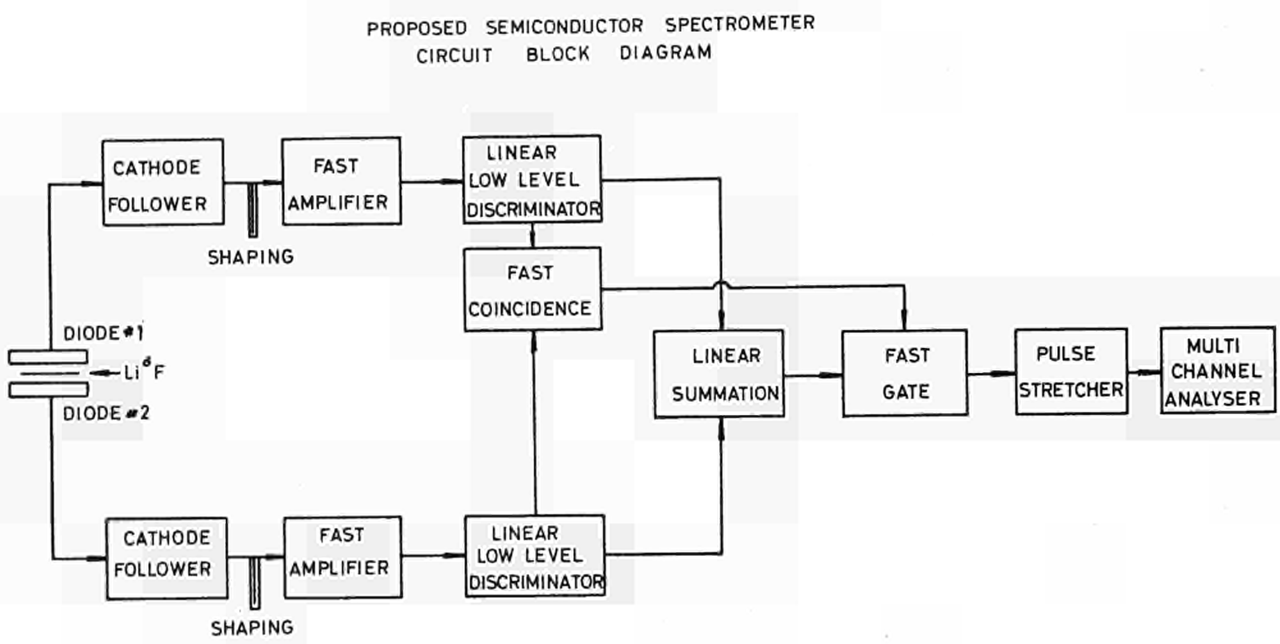

PROPOSED SEMICONDUCTOR SPECTROMETER
CIRCUIT BLOCK DIAGRAM
CATHODE FOLLOWER
FAST AMPLIFIER
LINEAR LOW LEVEL DISCRIMINATOR
SHAPING
FAST COINCIDENCE
DIODE #1
Li^6F
DIODE #2
LINEAR SUMMATION
FAST GATE
PULSE STRETCHER
MULTI CHANNEL ANALYSER
CATHODE FOLLOWER
FAST AMPLIFIER
LINEAR LOW LEVEL DISCRIMINATOR
SHAPING

Fig. 11

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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