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UNITED ARAB REPUBLIC
ATOMIC ENERGY ESTABLISHMENT
REACTOR & NEUTRON PHYSICS DEPARTMENT

CALIBRATION OF A THREE-CRYSTAL-NaI-PAIR-SPECTROMETER

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C O N T E N T S

A B S T R A C T

This work presents the calibration of a scintillation-pair-spectrometer. It is intended to yield energies and intensities of neutron capture gamma rays as precisely as possible. It is found possible to determine experimentally the relative peak-to-total for a pair crystal spectrometer.

1. INTRODUCTION

The three-crystal scintillation pair spectrometer has been described elsewhere* so that only a brief mention will be made here.

A beam of gamma-rays is incident on what is called the "center crystal" which in the present experiment is NaI(Tl) (1.75"Øx2"L). In order to select the pair events from the photoelectric and Compton events, two large NaI(Tl) (3"Øx3"L) crystals are placed on either side of the center crystal so that all three are in line. The annihilation of a positron accompanying a pair event in the center crystal gives two 0.511-MeV quanta going out in opposit directions which can then be detected in the side crystals. A coincidence circuit selects those events in which a pulse in the center crystal is observed simultaneously with two 0.511-MeV coincident pulses in the side crystals. A pulse-height analysis of the center crystal pulses shows peaks due to the difference in energies between the energy of the incident gamma-radiation and the energy (1.022 MeV) expended in the pair production.

This type of spectrometer suffers from a large low energy background [1-5] which was attributed to multiple scattering and double Compton effect. To eleminate this background, a single pulse height analyser was employed on each of the side crystals, so as to admit only the photopeak of the 0.511 MeV distribution. This technique was very successful in reducing the background [6].

The proceeding work deals with the calibration of a three-crystal scintillation pair spectrometer when capture gamma rays were produced in a target placed in an external beam of thermal neutrons from the UA-RR-1 research reactor.

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* Hassan, A.M. and Abu-Zeid, H.M. "Construction of three-Crystal-pair-Spectrometer" U.A.R.A.E.E./Rep.-100 (1970).

A scheme of the experimental geometry is shown in (Fig. 1). The sample under investigation was placed at a point on the axis of the collimator surrounded by boroncarbide (B^{10}) with the exception of the front and back faces which were left free for the passage of the neutrons. Care was taken to adjust the shielding such that the neutron beam would not hit any material except the sample. Pair spectra were obtained (Fig. 2) as described elsewhere**.

2. PAIR SPECTRAL LINE

The line shape in a pair crystal spectrometer consists of a normal distribution (Gaussian) peak and a continuous distribution tail. This tail is due to the escape of the pair electrons and Bremsstrahlung photons [7] from the central crystal. The energy of the tail extends from the energy of the peak downwards.

In case of samples placed in an external beam of thermal neutrons from the reactor, the gamma ray source subtends a big solid angle with the center crystal and the gamma-rays fall allover the front face of the center crystal. So it is impossible to stop the escape electrons [6] from the side of the center crystal. Also the escape of soft bremsstrahlung from the side of the center crystal reaches a maximum amount compared with collimated gamma-rays. As a results of that, the low energy tail is more pronounced than in the case of collimated gamma-rays incident on the center crystals.

In general, the pair spectrum peaks are superimposed on a smooth rising continuum composed of the low-energy tails which extend as weak continuous background to rather low energies, as seen from (Fig. 2).

** Hassan, A.M. and Abu-Zeid, H.M. "Thermal Neutron Capture Gamma-Rays in Iron" (to be published).

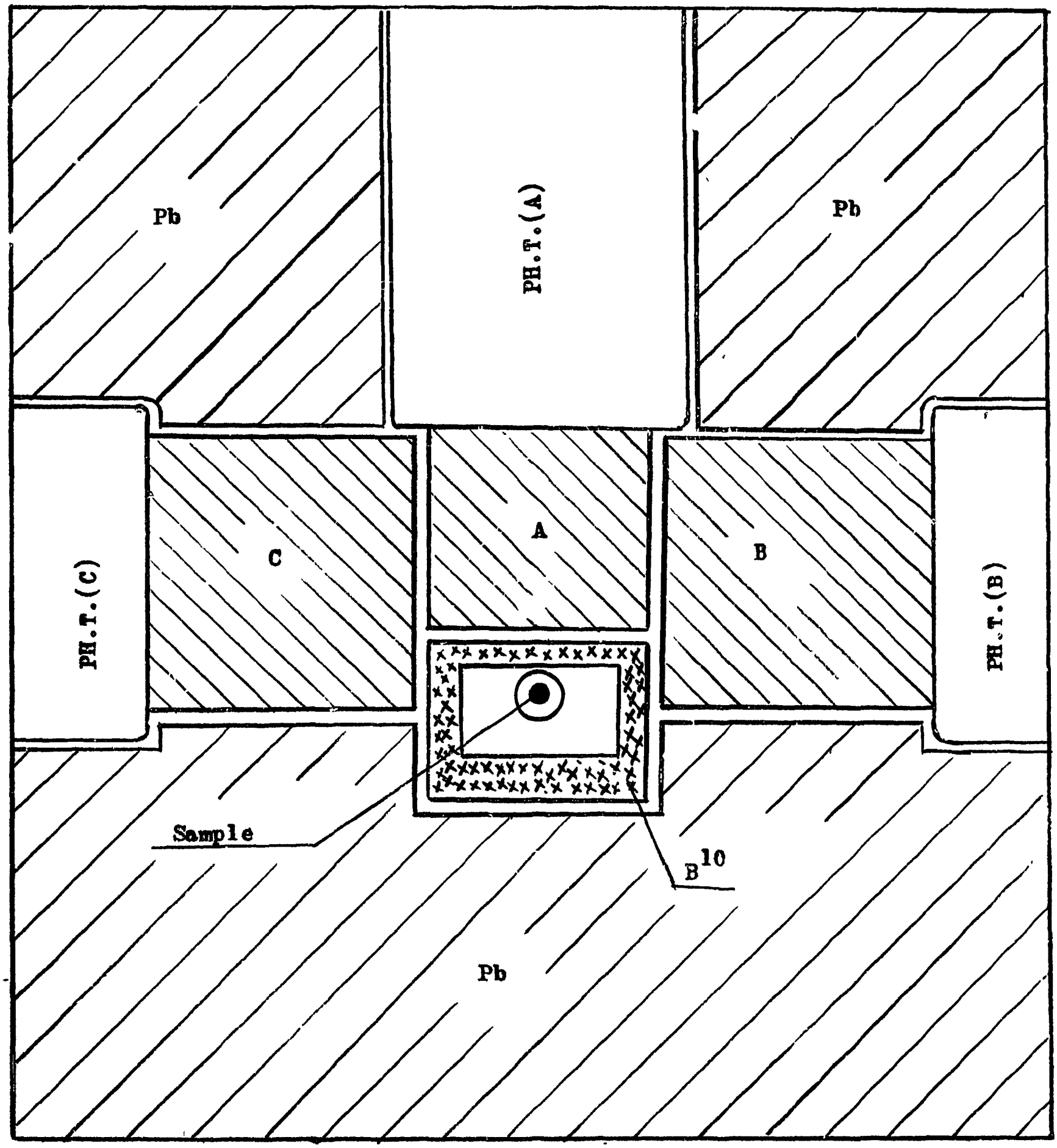

Fig. (1): Arrangement of Crystals in a Pair-Crystal-Spectrometer.

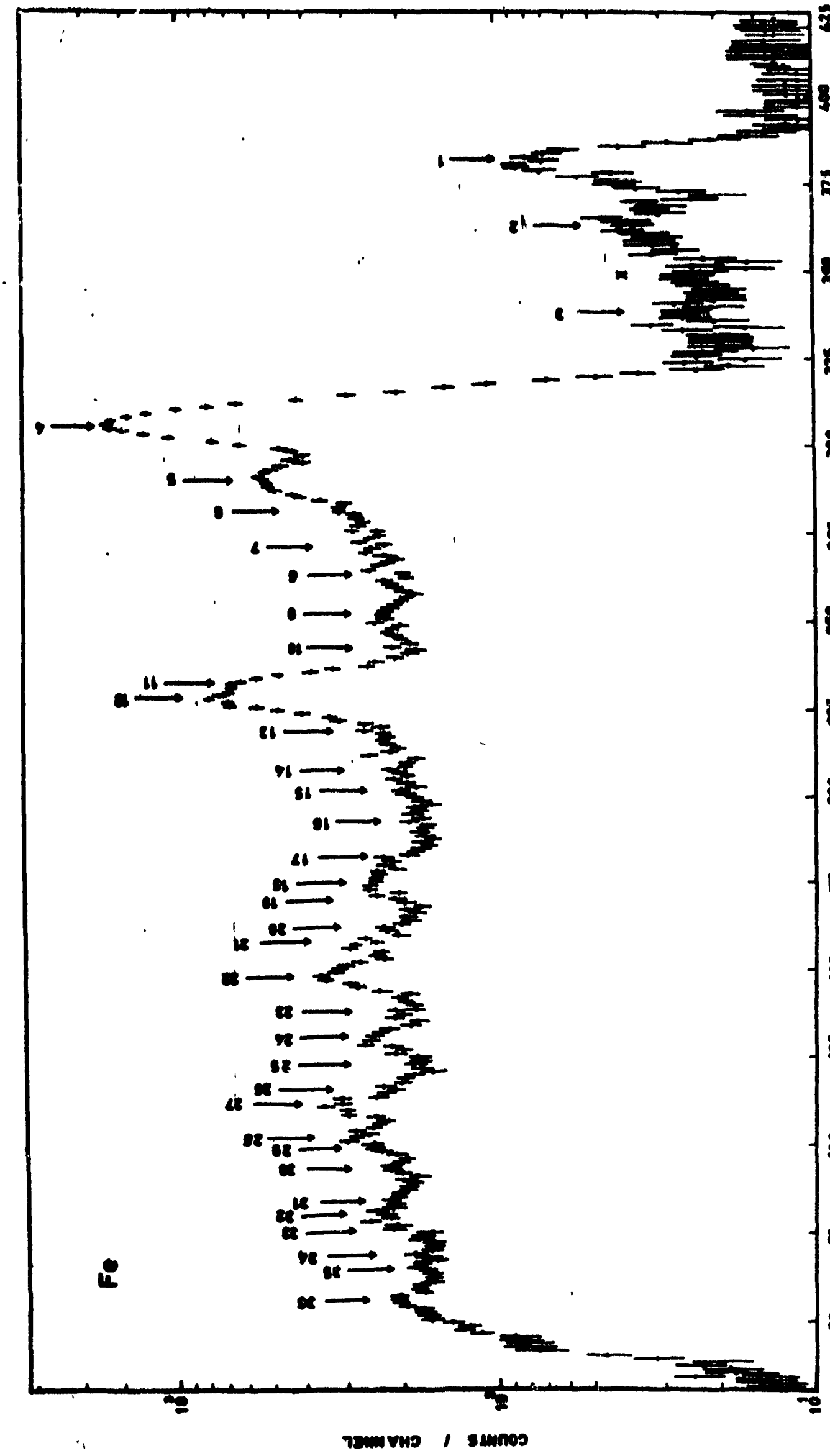

Fig. (2) PAIR SPECTROMETER SPECTRUM OF CAPTURE GAMMA RAYS FROM A NATURAL IRON SAMPLE (UNCORRECTED)

3. ENERGY CALIBRATION

Energy Calibration of the pair spectrometer involves assignment of the gamma ray energy in MeV to the pulse height scale of the multichannel analyser used with the spectrometer.

The relation between the incident gamma-ray energy E and the kinetic energy of the pair electrons E_p which is detected by the pair spectrometer is given by :

$$E_p = (E - 1.022)\ \text{MeV} \qquad (1)$$

An almost linear relationship exists between the incident gamma ray energy E and the pulse height detected by the multichannel analyser of the pair spectrometer which is inturn proportional to the channel number of the pair-peak maximum N. In order to determine the last relationship, the neutron capture gamma ray spectrum of Fe was detected with the pair crystal spectrometer from a sample of natural iron (25.3 g) which was irradiated in the external neutron beam from the UA-RD-1 research reactor. This spectrum is shown in (Fig. 2). By using the results of Adyasevich et al. [8], the energies of Fe gamma-ray lines represented in table I are all quite well known. Using these values for energy calibration, the best fit of a straight line for the relation between E and N is given by :

$$E = (0.02169 \pm 0.0001)\ N + (0.98776 \pm 0.04347) \qquad (2)$$

The remaining gamma ray energies, as determined from equation 2 agree within experimental error to earlier values and demonstrate the linearity of the system. The error in the energy determination by this method is estimated to be within $\pm$ 20 keV.

Table I

Peak No.	1	4	5	22	24
Energy MeV [8]	9.295	7.636	7.273	4.220	3.844

4. ENERGY RESOLUTION

By plotting the relation between $\frac{\Delta E}{E}\%$ and $E^{-\frac{1}{2}}$ where ΔE is the full width at half maximum in MeV and E is the energy of γ-ray peaks selected from the iron spectrum (i.e. E = 9.3, 7.63, 4.2, 3.2, 2.18 MeV) an almost linear relationship exists as shown in (Fig. 3).

This curve can be used for knowing the peak width at half maximum (ΔE) which is necessary for determining the instrumental spectral line which is very important and fundamental to resolve reliably the detected gamma ray spectrum into partial spectra due to separate monoenergetic lines in the true spectrum.

5. DETECTION EFFICIENCY

The detection efficiency of the pair spectrometer S(E) is equal to the probability of making a pair in the center crystal D(E) times the probability of detecting both the annihilation quanta in the photo peaks of the side crystals F(E). The first factor D(E) depends on the pair production cross-section, depth of the crystal and the distance of the source along the extended cylindrical axis from the near face of the detector. The second factor F(E) depends on the position within the center crystal where the pair is created, the geometry and position of the center crystal relative to the side crystals, the selected window widths of the side single channels and

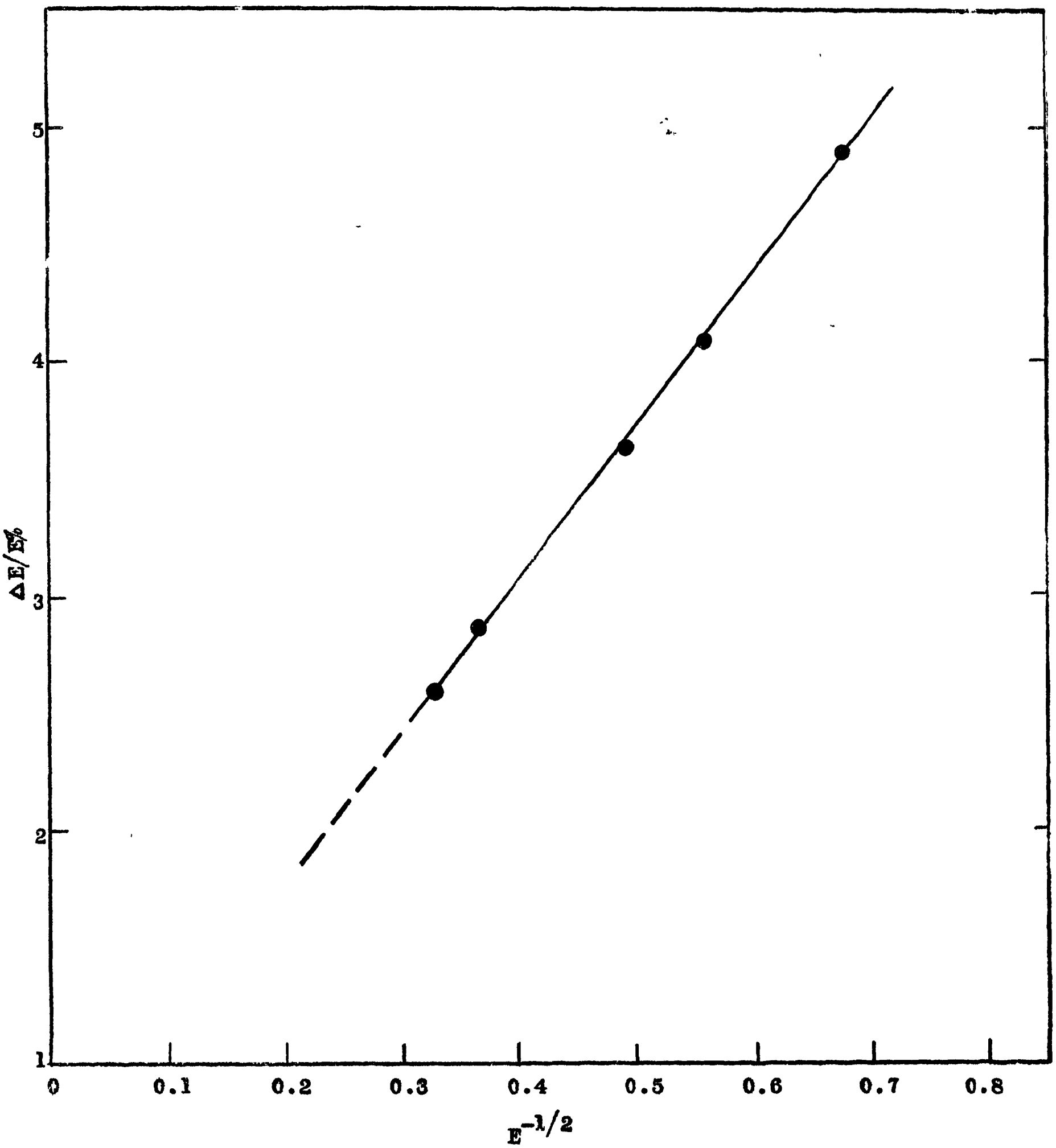

Fig. (3): $\Delta E/E\%$ vs $E^{-1/2}$ for the Pair-Crystal-Spectrometer.

the dimentions of the crystals used in the spectrometer i.e.

$$S(E) = N_p / (N_o W_1 W_2) = D(E)F(E) \qquad (3)$$

and the absolute detection efficiency is given by

$$S_a(E) = N_p / (N_e W_1 W_2) = D_a(E)F(E) \qquad (4)$$

where

N_p is the number of pair counts detected per unit time.

N_o is the number of monoenergetic γ-rays incident on the center crystal per unit time.

N_e is the number of monoenergetic γ-rays emitted per unit time from the source.

W_1 is a correction factor for the absorption in the gamma ray source.

W_2 is a correction factor for the absorption in neutron filters and crystal can.

The pair detection efficiency D(E) and the absolute pair detection efficiency $D_a(E)$ of the center crystal are determined by :

$$D(E) = (\mu_p / \mu_t) T(E) \qquad (5)$$

and

$$D_a(E) = (\mu_p / \mu_t) T_a(E) \qquad (6)$$

where

μ_p is the pair linear attenuation coefficient [9] in cm^{-1}.

μ_t is the total linear attenuation coefficient [9] in cm^{-1}.

T(E) is the total, $T_a(E)$ is the total absolute detection efficiency for the source-detector (C.C.) geometry, which are

related by $T_a(E) = (\Omega/4\pi)\ T(E)$, where Ω is the solid angle subtended by the detector at the source.

Computed values of $T_a(E)$ were tabulated [10-12] for different cylindrical radiation detectors. Theoretically F(E) can be represented by :

$$F(E) = R_1 R_2 R_3 C \qquad (7)$$

where

R_1 is the probability that the positron is annihilated within the center crystal.

R_2 is the probability that both annihilation quanta of one positron are not absorbed in the center crystal.

R_3 is the probability of the total absorption of both annihilation quanta in the side crystals.

C is a correction factor depending mainly on the window width of the side single channels.

R_1, R_2, R_3 and C were treated [13] for a collimated narrow beam of gamma rays incident on the center crystal. With such geometry F(E) was found to a good approximation constant [6,13].

As a pair positron loses energy in the center crystal, there is a small probability that it will annihilate in flight. In this case the quanta are not of 0.511 MeV energy and are not oppositely directed and hence most of such positrons are not detected.

A correction [6] of the detection efficiency $D_a(E)$ for the annihilation of positions in motion has been taken into consideration. The corrected detection efficiency $D_{ac}(E)$ is determined for a point-source along the extended heights h from its near face. (Fig. 4) shows $D_{ac}(E)$ as function of the energy E of incident gamma-rays.

In many cases it is more convenient to be able to relate N_p to the number of events in the pair peak which are detected per unit time A(E). Therefore N_p would be given by :

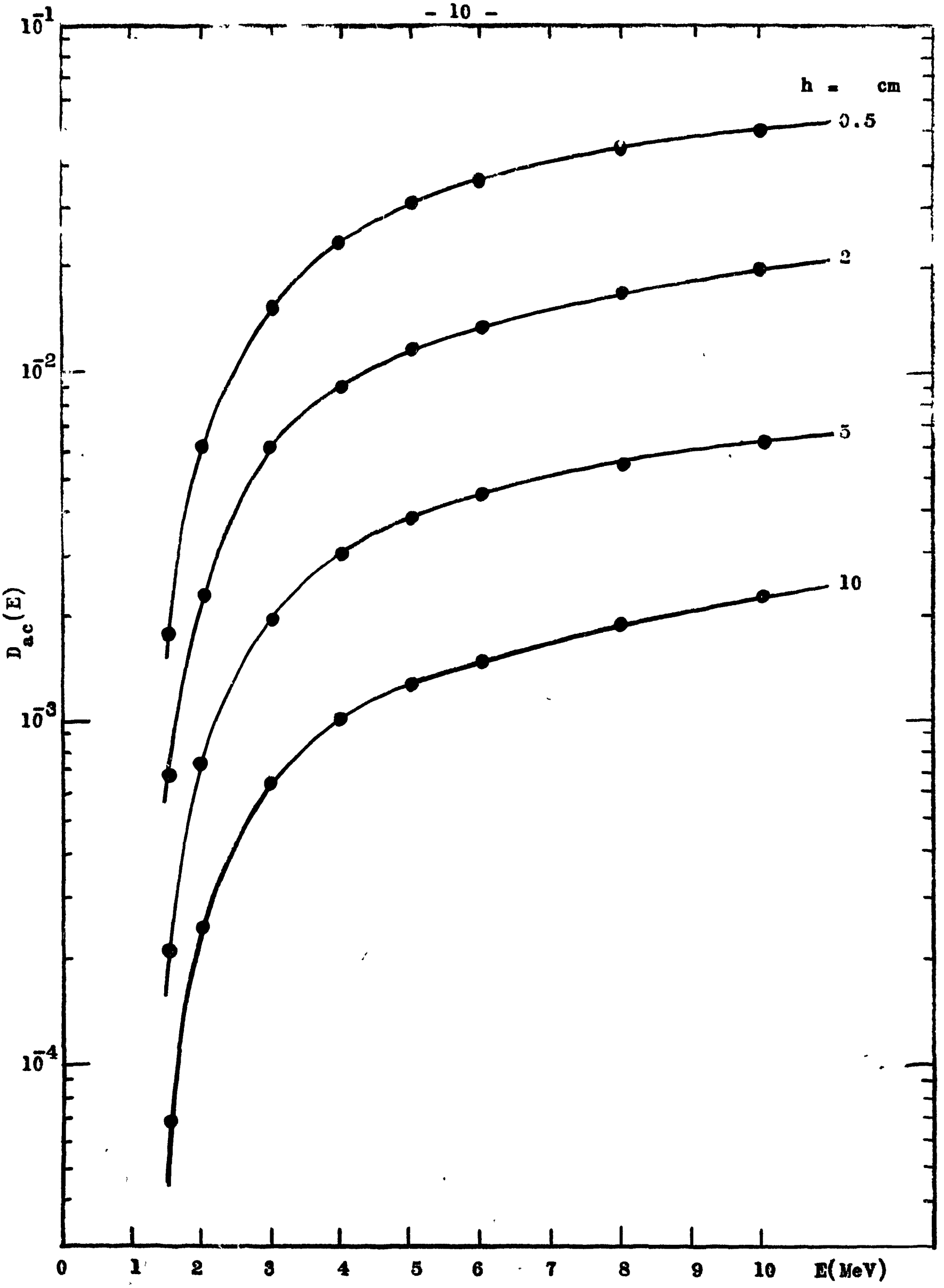

Fig. (4): Corrected Detection Efficiency $D_{ac}(E)$ in NaI(Tl)-Center-Crystal for a Point-Source Along the Extended Heights h from its near f

$$N_p(E) = A(E) / P(E) \qquad (8)$$

where

P(E) is the peak-to-total ratio which has to be either calculated or measured.

In the external beam arrangement a compact geometry was used, as seen from (Fig. 1). In this case it is rather difficult to calculate P(E), without using a computer. Anyhow, for relative intensity measurement, one needs the relative peak-to-total $P(E)/P(E_r)$ which can be evaluated experimentally, as will be seen later.

6. SELF-ABSORPTION

Let the radionuclides which emit the gamma-rays be uniformly distributed in a source of length l, which has a uniform rectangular cross-section normal to l and parallel to the C.C. front face.

If the source emits more than one energy $\sum_i E_i$ and is also long enough, the different energies will be absorbed by different amounts within the source itself, so that the fraction of photons of i-th energy by the source will depend on the length of the source, so long as the detector is far from the source and the gamma-rays reaching this detector could be considered as a parallel beam. Correction for this can be made with the following formula, which gives, the ratio of the number of photons of any one energy N' emitted from the end of the source to those which would be emitted if there were no self absorption N_o.

$$W_l = \frac{N'}{N_o} = \frac{1 - e^{-\mu l}}{\mu l} \qquad (9)$$

where

l is the length of the source and

μ is the total attenuation coefficient (cm^{-1}).

(Fig. 5a) shows W_1 as function of μl.

Self-absorption within a source in the form of a cylinder of radius r and height h, for radiation emerging normal to its axis is given [14], for $r^2/a^2 \ll 1$, by

$$W_1 = N'/N_o = 1 - \frac{8}{3\pi}\mu r + \frac{1}{2}\mu^2 r^2 \qquad (10)$$

where

a is the distance of the source along the extended axis of the cylindrical C.C.

If $\mu r \leq 0.12$, as occurs in many practical cases, then eq. (10) can be represented within 0.2 per cent by

$$W_1 = N'/N_o \simeq \exp - (8\mu r/3\pi) \qquad (11)$$

The plot of the calculated values for W_1 from eq. (11) is represented in (Fig. 5b) which can be used to a very good approximation for any gamma-ray energy $E \geq 1$ MeV and any sample material of different radii attaining the same experimental arrangement.

7. GAMMA-RAY TRANSMISSION THROUGH NEUTRON FILTER AND CENTER CRYSTAL CANNING

In order to determine the fraction of gamma-rays absorbed or scattered inside the boron carbide neutron filter (B^{10}) and the aluminum canning of the center crystal, consider the following formula. Assuming N' γ -rays per unit time are emitted from the sample and N. the number per unit time reaching the front face of the center crystal, we have :

$$W_2 = N/N' = \exp - (0.3\mu_{B_4C} + 0.06\mu_{Al}) \qquad (12)$$

where

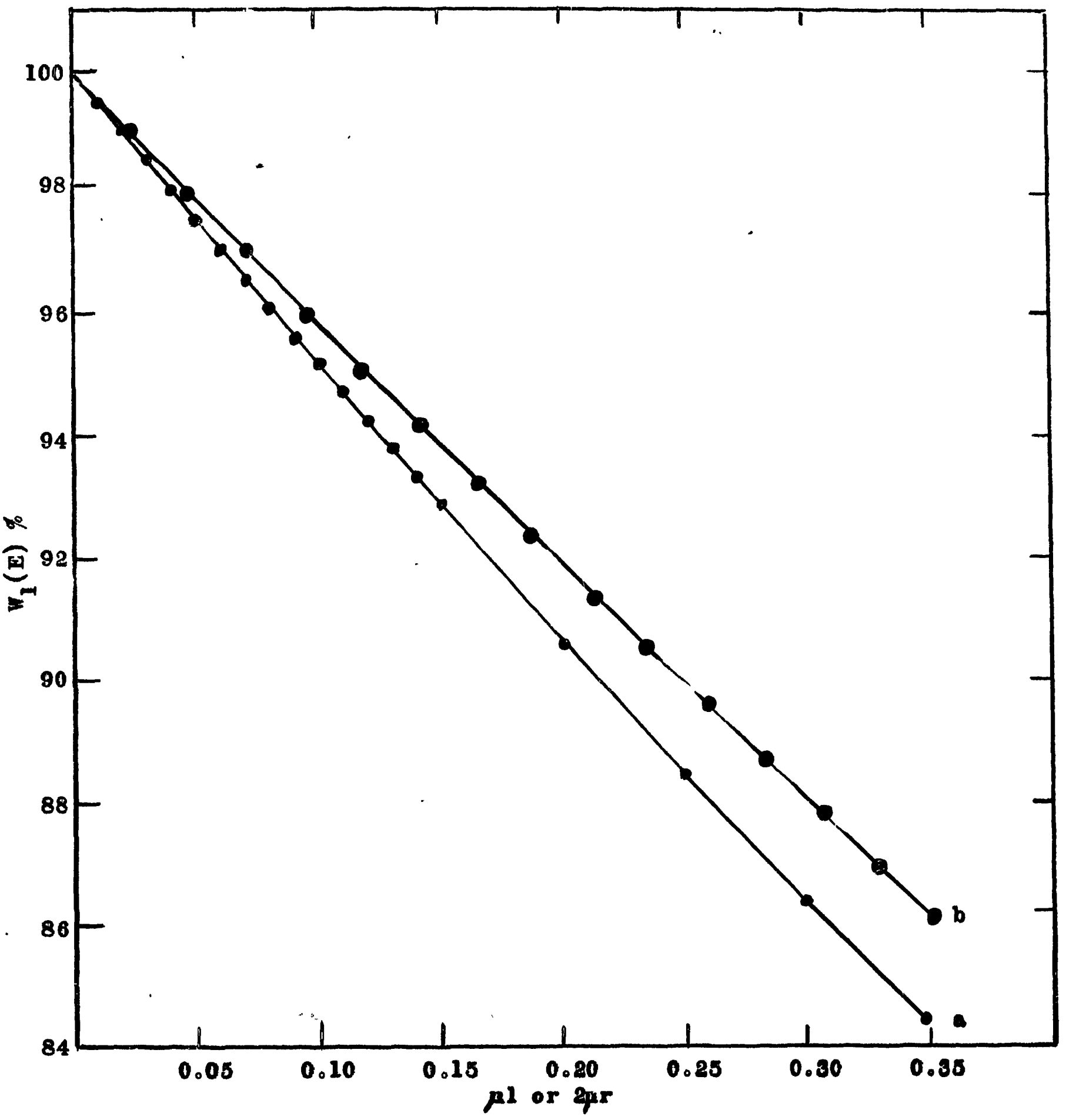

Fig. (5): Gamma-ray Self-Absorption Within (1) Rectangular Source of Length l (2) Cylindrical Source of Radius r.

0.3 cm is the thickness of the (B_4C) neutron filter placed between the sample under investigation and C.C.

0.06 cm is the thickness of the C.C. aluminum canning.

μ_{B_4C} and μ_{Al} are the total linear attenuation coefficient in B_4C and Al respectively.

The results of calculation is shown in (Fig. 6).

8. GAMMA-RAY RELATIVE INTENSITY

The relative intensities I(E) of gamma-rays producing the pair spectrum are determined by the following formula :

$$I(E) = \frac{A(E)}{A(E_r)} \frac{S(E_r)}{S(E)} \frac{P(E_r)}{P(E)} \frac{W_1(E_r)}{W_1(E)} \frac{W_2(E_r)}{W_2(E)} \qquad (13)$$

where

$A(E)/A(E_r)$ is the ratio of the pair peak counting rates.

$S(E)/S(E_r) \simeq D(E)/D(E_r)$ = ratio of corrected detection efficiency of the spectrometer (Fig. 4).

$P(E)/P(E_r)$ is the relative peak-to-total ratio, which is given in the next part.

$W_1(E)/W_1(E_r)$ is the ratio of the transmission coefficient in the sample measured (Fig. 5).

$W_2(E)/W_2(E_r)$ is the ratio of the transmission coefficient in neutron filter B_4C and aluminum cover of the C.C. (Fig. 6).

E_r is the energy of the reference gamma-ray line with which all other spectrum lines are compared.

In many experiments it is impossible to use point sources of radiation, extended sources being necessary because of low specific

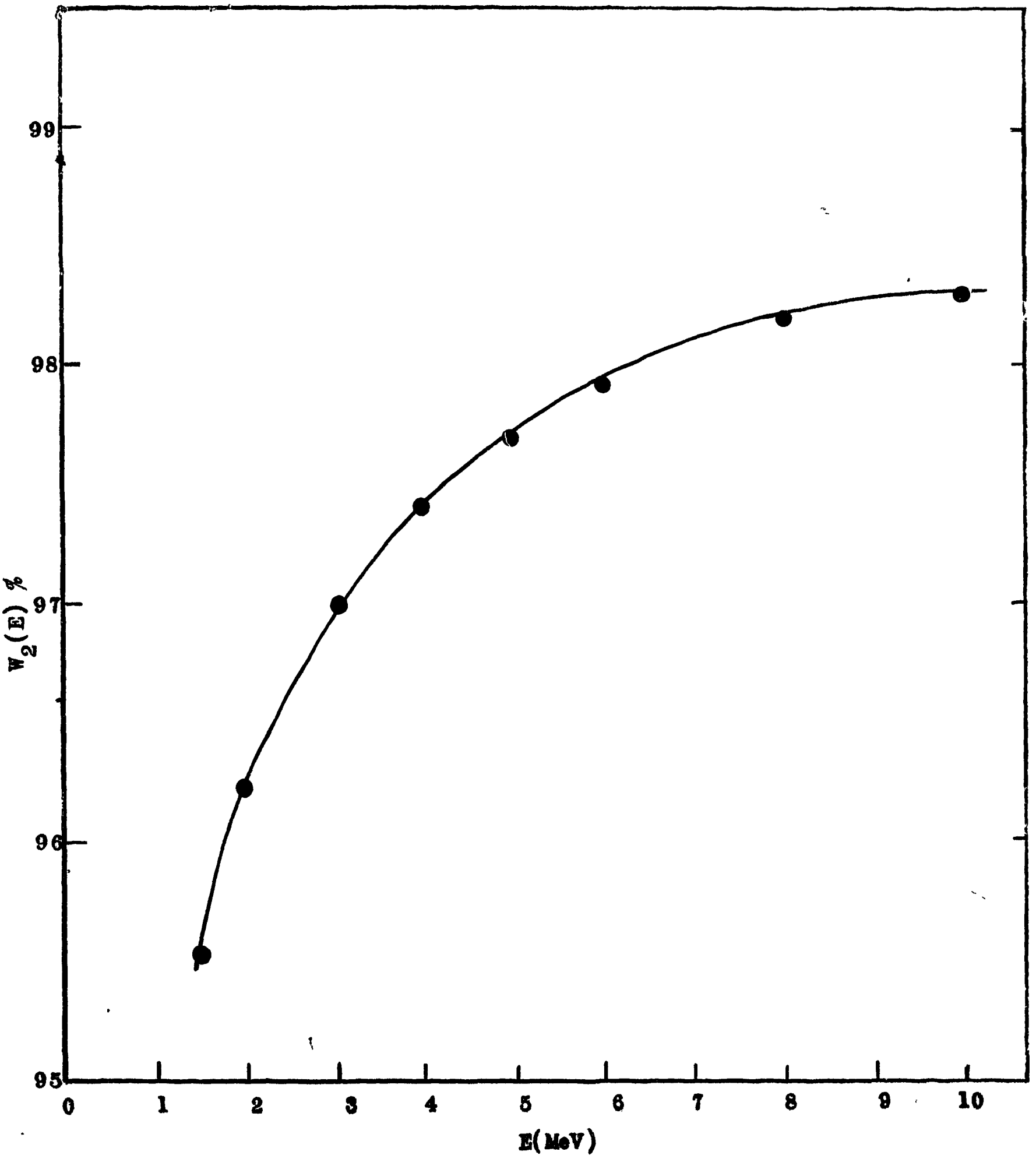

Fig. (6): Correction Factor for Gamma-ray Absorption in Neutron Filter and Center Crystal Canning.

activities. It was therefore felt necessary to investigate the effect of non zero source dimensions on the relative detection efficiency given by :

$$D_a(E)/D_a(E_r) = \varrho(E)\ \mu_p(E).\mu_t(E_r)\ /\ \mu_p(E_r).\mu_t(E) \qquad (14)$$

where

$$\varrho(E) = T_a(E)/T_a(E_r)$$

The correction factors K_D and K_L for disc and line sources respectively are represented by :

$$K_D(E) = \varrho_D(E)/\varrho_p(E) \qquad \text{and} \qquad (15)$$

$$K_L(E) = \varrho_L(E)/\varrho_p(E) \qquad (16)$$

where

ϱ_D is the relative absolute detection efficiency for disc sources.

ϱ_L is the relative absolute detection efficiency for line sources.

ϱ_p is the relative absolute detection efficiency for point sources.

Calculations of K_D and K_L have been made*** when increasing the source diameter D or length L(D=L=0.25d; 0.5d; 0.75d; 0.999; where d=center crystal diameter = 1.75") for various values of the source-detector separation h(h=0.001; 1; 3; 5; 10 cm) as well as for different gamma ray energies (from 1.1 to 10 MeV). As is to be expected the percentage deviation from a point source is negligible. In its optimum value it is within 0.1 per cent.

The application of eq.(13) for determining the relative intensity of the capture gamma-rays from natural iron** showed good agreement with the results taken by magnetic compton [8,15] and pair [16] spectrometers. For well resolved lines from the sample the relative intensities were accurate to within ~15%.

*** See Acknowledgement.

9. RELATIVE PEAK-TO-TOTAL

In order to determine the relative peak-to-total in a pair crystal spectrometer, the continuous background spectrum for natural iron spectrum (Fig. 2) was outlined by drawing the smooth curve passing by the minimum points of smallest value in the spectrum. Each of these points was selected such that its distance from the next peak was greater than the peak half width.

So we had neglected summing effect from the neighbouring peak. Peaks represented in table II has been selected and the area of each was measured and corrected for the detection efficiency, annihilation in flight [6], self absorption of sample, and gamma absorption in neutron filters and crystal cover. As a rough approximation F(E) of eqs. (3 and 4) was considered constant [6,13].

Table II

Peak No.	1	4	5	11	22	26	38
E MeV	9.30	7.63	7.28	6.04	4.20	3.51	2.65
P/P_r	1	1.29	1.44	1.55	1.94	2.35	2.39

If A'(E) be the corrected area of the gamma ray peak of which the energy is E and P(E) is the peak-to-total ratio, we get the number of gamma quanta in the gamma ray line equal to $\frac{A'(E)}{P(E)}$.

The corresponding intensity of the gamma ray line of energy E relative to that of energy E_r is given by

$$I(E) = \frac{A'(E) \cdot P(E_r)}{A'(E_r) \cdot P(E)} \qquad (17)$$

from which we get :

$$\frac{P(E)}{P(E_r)} = \frac{A'(E)}{A'(E_r)} \Big/ I(E) \qquad (18)$$

Using the calculated intensities for the γ-ray lines of natural iron by Adyasivich [8] we determine by eq. (18) the relative peak-to-total

$$\frac{P(E)}{P(E_r)} = \frac{P(E)}{P(9.30\ \text{MeV})}$$

for the pair spectrometer spectrum from the natural iron sample placed in the external neutron beam.

In (Fig. 7) the $\frac{P(E)}{P(9.30\ \text{MeV})}$ is plotted via the line energy E.

The curve shown in (Fig. 7) can be used to determine the relative peak-to-total refered to any reference line of energy say E_x by the relation

$$\frac{P(E)}{P(E_r)} \Big/ \frac{P(E_x)}{P(E_r)} = \frac{P(E)}{P(E_x)} \qquad (19).$$

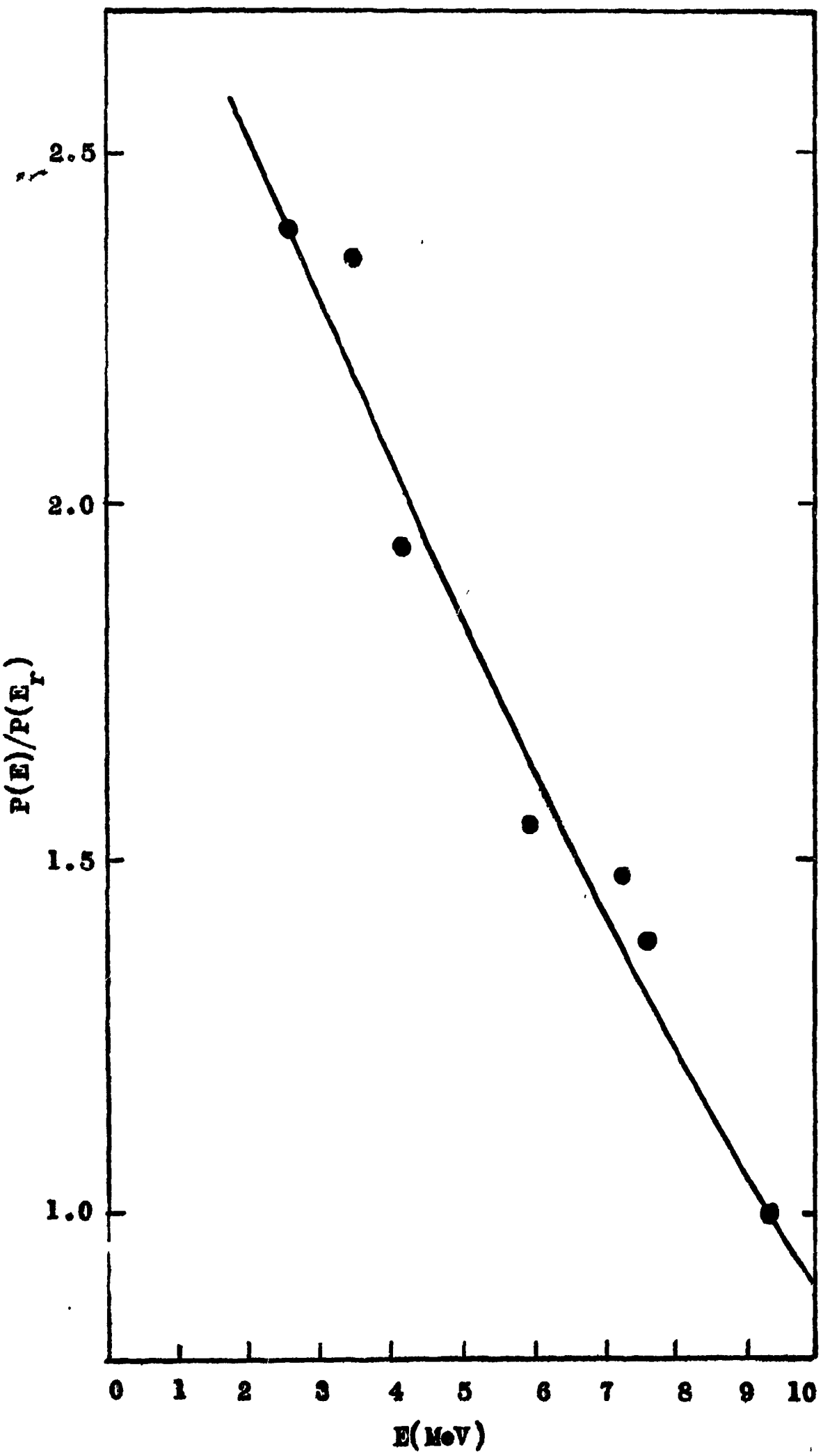

Fig. (7): $P(E)/P(E_r)$ vs E(MeV) for Gamma-ray Lines from Pair Spectrometer Spectrum (E_r = 9.30 MeV).

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