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NEUTRAL PION PHOTOPRODUCTION ON NUCLEI NEAR THRESHOLD

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1. Introduction

Historically, the first π^0 photoproduction near threshold measurements on nuclei were performed twenty-five years ago. With almost the same experimental procedure we are using presently, data on nuclei ranging from deuterium to lead were collected until 1965. For the last ten years there has been no significant development in the field. The renewal of interest in the subject, attested by the present session of our meeting, comes primarily because of the advent of a new generation of linear electron accelerators providing significantly higher photon fluxes with a larger duty-cycle. This improved capability allows both better accuracy in the measurements and the exploration of the very near-threshold region which could not be reached by our predecessors because of the nearly vanishing cross sections.

In discussing the frame of interpretation of the experiments I shall try to explain the essential motivations of this investigation and show that one can learn about basic pion photoproduction on nucleons, photoproduction mechanism in nuclei and nuclear matter distribution. The main difficulty will obviously be to disentangle the contribution of these different factors by studying a set of judiciously chosen nuclei. Next, I shall sketch the experimental procedure utilized and discuss the difficult problem of the absolute calibration of the measurements. I shall conclude by showing data on deuterium taken at the Saclay linac which will illustrate these points. Preliminary data will be presented by my colleagues of Bates on complex nuclei, and by Eric Vincent of Saclay on ^{3}He and

^{4}He. This will give you an overall view of the most recent developments in the field and an insight of the possibilities and limitations of these experiments.

2. Discussion of the interpretation frame

The theoretical framework used to study pion photoproduction is the distorted wave impulse approximation. The effects of the various nucleons in the nucleus are assumed to be additive and an effective elementary amplitude of the process on the nucleon is used. The pion wave is distorted by its interaction with the nucleus ; this distortion is usually moderate because of the weakness of the pion nucleus interaction at low energy. To the extent that the pion momentum is small, the pion wave function will be constant inside the nucleus and we will probe the transition form factor of the nuclear initial and final states at momentum transfer m_π.

2.1. *Neutral pion production on the nucleons*

The photoproduction amplitude on a free nucleon is calculated using the operator :

$$O_\pi = \vec{K}\,\vec{\sigma} + L$$

In the vicinity of threshold the quantities $\vec{K}$ and L can be accounted for using the two multipolar amplitudes E_{0+} and M_{1+} which are both real in this energy region. The dipole E_{0+} is almost constant with energy whereas M_{1+} which dominates the Δ (1236) resonance region varies like qk, the product of the pion momentum by the photon momentum in the center of mass system ; O_π can be expressed in terms of E_{0+} and M_{1+} 1)

$$O_\pi = \left[E_{0+}\,\hat{\varepsilon} + M_{1+}\,\hat{\varepsilon}(\hat{q}.\hat{k}) - M_{1+}\,\hat{k}(\hat{\varepsilon}.\hat{q})\right].\vec{\sigma} + 2M_{1+}\,\hat{q}.\left[\hat{k}\times\hat{\varepsilon}\right]$$

$\hat{\varepsilon}$ is the photon polarization.

The differential cross section on the nucleon reads :

$$\frac{d\sigma}{d\Omega} = \frac{q}{k}\left\{E_{0+}{}^2 + 2E_{0+}\,M_{1+}\cos\theta + M_{1+}{}^2\left(\cos^2\theta + \frac{5}{2}\sin^2\theta\right)\right\},$$

and the integrated cross section

$$\sigma = 4\pi\frac{q}{k}\left[E_{0+}{}^2 + 2M_{1+}{}^2\right]$$

From the experimental values of the multipoles E_{0+} of Table 1 on can see that the proton and neutron photoproduction cross sections at threshold are comparable and two orders of magnitude smaller that the charged pion photoproduction ones. In the energy region we investigate, the nucleonic π° cross sections are typically a few tenths of a microbarn.

Threshold photoproduction of π° is a topic interesting on its own right. $E_{0+}(p\pi^\circ)$ and $E_{0+}(n\pi^\circ)$ are important parameters of s-wave pion physics, however they are experimentally known with a very poor accuracy. Values of neutral pion channels E_{0+} can discriminate between theoretical models which agree on charged pion channels. The experimental value of $E_{0+}(p\pi^\circ)$ for instance rules out the pseudo scalar Born approximation results (see Table 1).

The determination of the threshold value

$$E_{0+}(p\pi^\circ) = (-0.0018 \pm 0.0006)\, m_\pi^{-1}$$

is coming from the analysis of two measurements by Govorkov et al.[2] who investigated the energy dependence of the 90° center of mass cross section in the range 160-200 MeV using a conventional experimental set-up. To illustrate the poor accuracy of these measurements let us notice that this value proceeds from the combination of the two following parameter determinations extracted from the experiment : 0.06 ± 0.06 and 0.09 ± 0.08.

The Govorkov value agrees with the analysis by Mullensiefen of the Hitzeroth[3] experiment performed with nuclear emulsions to detect the recoil protons inside a hydrogen gas target. It is also in good agreement with the multipole analysis in the Δ(1236) region by Noelle[4] which yields $E_{0+}(p\pi^\circ) = -0.0019$.

Depending on the type of analysis the M_{1+} multipole varies from $M_{1+}(\pi^\circ p) = 0.008\ qk/m_\pi^2$ to $M_{1+}(\pi^\circ p) = 0.010\ qk/m_\pi^2$ (see Ref.2).

We notice that in contrast with charged pion production where E_{0+} dominates even at 200 MeV photon energy, in the case of neutral pion production the M_{1+} contribution to the total cross section is equal to the E_{0+} one, 2 MeV above threshold. From this constation, it follows that non spinflip terms are important very close from threshold.

At this point, one must observe that no absolute measurement closer than 13 MeV from threshold has been performed so far on the reaction :

$$\gamma + p \rightarrow \pi^0 + p \quad (1) \quad E_{\gamma\ \mathrm{threshold}} = 144.67\ \mathrm{MeV.}$$

This remark has an importance in view of the singularity which is expected in the cross section of (1) at the inception of the competing reaction

$$\gamma + p \rightarrow \pi^+ + n \quad (2) \quad E_{\gamma\ \mathrm{threshold}} = 151.44\ \mathrm{MeV.}$$

This effect has been theoretically investigated by Baldin et al.$^{5)}$ who conclude to a maximum 20 % addition to the multipole $E_{0+}(p\pi^0)$ value. A more recent calculation by Laget$^{6)}$ confirms this estimation (see Fig. 1).

The effect would enhance the cross section close from threshold by as much as 50 % as compared to the prediction based on the quoted values of the multipoles. Let us stress that the mentionned calculations based on the unitarity relations for the S matrix and a q dependence at threshold of reaction (2), do not deal with the dynamical properties of the pion nucleon system in an energy region where the isotopic multiplet masse differences are important.

The implications of this peculiar circumstance for our measurements will be discussed later.

Needless to say, direct experimental observation of reaction:

$$\gamma + n \rightarrow \pi^0 + n \qquad (3)$$

is impossible. However, using invariance properties in isospin space of strong interactions - isoscalar - and electromagnetic interactions - isoscalar + third component isovector -, multipolar amplitudes of the four photoproduction channels can be expressed in terms of three independant amplitudes. The knowledge of the three other channels multipoles allows determination of the reaction (3) multipoles by the relation

$$\mathcal{M}(n\pi^0) = \mathcal{M}(p\pi^0) - [\mathcal{M}(n\pi^+) + \mathcal{M}(p\pi^-)]/\sqrt{2}. \qquad (4)$$

Unfortunately the value$^{7)}$

$$E_{0+}(n\pi^\circ) = (0.0003 \pm 0.0009)m_\pi^{-1}$$

deduced using (4) is affected by a large uncertainty which stems equally from the poorly known $E_{0+}(p\pi^\circ)$ and from the absolute uncertainty of $E_{0+}(p\pi^-)$ which is seven times larger than that of $E_0(n\pi^+)$. As for $M_{1+}(n\pi^\circ)$, all estimations agree and yield approximately $M_{1+}(n\pi^\circ) \simeq 0.9\ M_{1+}(p\pi^\circ)$.

It appeared to the Saclay group$^{3)}$ that an improvement of our knowledge of the nucleonic amplitudes was possible by studying π° photoproduction very near threshold on the lightest nuclei : d and ^{3}He.

Indeed, at threshold, in the plane wave impulse approximation and assuming frozen nucleons, elastic π° photoproduction cross sections on these two nuclei are such that :

$$\sigma_d \sim |E_{0+}(p\pi^\circ) + E_{0+}(n\pi^\circ)|^2$$

$$\sigma_{^3He} \sim |E_{0+}(n\pi^\circ)|^2$$

Comparison with the hydrogen would at least put some constraints on $E_{0+}(n\pi^\circ)$.

2.2. *The nuclear process*

Using the nucleonic amplitudes and assuming a plane wave pion the nuclear matrix element for a transition between nuclear states ψ_i and ψ_f will be

$$< \psi_f \ | \sum_{i=1}^{A} (\vec{K}\,\vec{\sigma}_i + L)\ e^{i(\vec{k}-\vec{q})\vec{r}_i} | \psi_i >$$

The spin independent term contributions of all nucleons will add coherently, whereas only a few nucleons can contribute in the spin dependent production. Except for light non zero spin nuclei, even in the vicinity of threshold, the coherent photoproduction will dominate. For instance, the elastic coherent π° photoproduction cross section will read :

$$\frac{d\sigma}{d\Omega} = \frac{q}{k} \frac{(1+m_\pi/M)^2}{(1+m_\pi/M_A)^2}\ 2|Z\ M_{1+}(\pi^\circ p) + N\ M_{1+}(\pi^\circ)|^2\ F^2(t)\ \sin^2\theta$$

F(t) is the matter body form factor (form factor of the nucleons positions) at transfer $t = (k-q)^2$, since neutrons as well as protons contribute almost equally to the process. Neutral pion photoproduction on complex nuclei can then be considered as a tool for investigating matter density of the nucleus and hopefully neutron density by using the electron scattering charge density information.

So far we have neglected the pion nucleus interaction ; we shall now try to understand how it will affect the results.

2.3. *The pion nulceus interaction*

At low energy the pion nucleon interaction is very weak, especially for neutral pions, as shown by the scattering lengths $a(\pi,\pi)$ displayed in Table II ; they are of the order of 0.1 fm two orders of magnitude smaller than the nucleon nucleon ones.

The emitted π° can be described by a distorted wave calculated using an optical potential in a Schrödinger equation. However since we have been using effective nucleonic amplitudes, the correct procedure consists in calculating the pion multiple scattering series, because the interaction of the pion with the nucleon on which it was produced, is already contained in the photoproduction amplitude. This remark is particularly important in the case of very light nuclei (as witnessed by π^+ photoproduction results on d and ^{3}He). Anyway, distortion of the π° wave inside the nucleus is expected to be moderate in the threshold region.

However the coupling of the various nucleon π photoproduction and π scattering channels will induce a very special feature, first pointed out by Koch and Woloshyn9), for the E_{o+} non coherent part of the amplitude. Because $E_{o+}(\pi^\circ)$ are lower than $E_{o+}(\pi^\pm)$ by more than one order of magnitude, the two step process charged pion photoproduction and virtual charge exchange will compete with the direct process (see Fig. 2). Since non coherent production can principally be observed in very light nuclei, we will be sensitive to the process, in the nuclei from which we were expecting to learn about $E_{o+}(n\pi^\circ)$.

To evaluate, in first approximation, this effect at threshold, we will use a very simple model10) which gives reasonable predictions of the π^-d and π^- ^{3}He scattering lenths deduced from the experimental energy shifts of pionic d and ^{3}He. In this model, the nucleons are taken as fixed scatterers and the pion in the intermediate state considered as free ; the nuclear wave functions are pure S states. The rescattering amplitude

$$A_r = \langle \psi_f | \sum_{ij} a(\pi^{\mp}, \pi^0)(j) \frac{1}{|\vec{r}_i - \vec{r}_j|} e^{ik\vec{r}_i} E^{\pi^{\mp}}_{0+}(i) | \psi_i \rangle$$

which describes s wave photoproduction on nucleon i and charge exchange scattering on nucleon j, simplifies in

$$A_r = \langle \phi_f | \left| \frac{1}{\vec{r}_i - \vec{r}_j} \right| e^{i\vec{k}\vec{r}_i} | \phi_i \rangle \langle S_f \, T_f | \sum_{ij} a(j) \, E_{0+}(i) | S_i \, T_i \rangle$$

ϕ are radial wave functions S and T spin and isospin of the nuclear states.

The first term in the A_r expression will be noted $\langle \frac{1}{r} \rangle_k$.

For elastic π^0, photoproduction on deuterium, using Reid soft core deuteron s wave function we find

$$\langle \frac{1}{r} \rangle_{m_\pi} = 0.52 \text{ fm}^{-1} \; (0.74 \; m_\pi).$$

At this point we should note that the quantity $\langle \frac{1}{r} \rangle_{m_\pi}$ is very dependent of the central density of the nucleus ; the use of a non realistic wave function is dangerous because it enhances the rescattering effect . For instance $\langle \frac{1}{r} \rangle_{m_\pi}$ Hulthen = 0.65 fm^{-1}.

$$A = [E_{0+}(p\pi^0) + E_{0+}(n\pi^0)] - (1 + m_\pi/M) \langle \frac{1}{r} \rangle_{m_\pi} a(\pi^-, \pi^0) [E_{0+}(p\pi^-) - E_{0+}(n\pi^-)]$$

$$= (-0.0016 \pm 0.0014) - (0.0060).$$

The rescattering amplitude is at least two times larger than the direct amplitude.

For ^{3}He elastic π^0 photoproduction, the rescattering term happens to have exactly the same expression than for deuterium. The quantity $<\frac{1}{r}>_{m_\pi}$ has been deduced starting from the value of the ^{3}H Coulomb energy for the S.S.C. Lavergne and Gignoux[11] wave function.

$$<\frac{1}{r}>_{m_\pi} = 0.44\ \text{fm}^{-1}.$$

The direct amplitude is $E_{0+}(n\pi^{\circ}) = 0.0003 \pm 0.0009$
and the rescattering one $A_r = -\ 0.0054.$

Second order scattering can be neglected because it intro duces an additional factor
$a(\pi,\pi) \times <\frac{1}{r}>_{m_\pi}$ which is typically 1/10.

More refined calculations on deuterium[12,13] and ^{3}He[14] taking into account the complete photoproduction elementary nucleonic amplitudes and the Fermi motion of the nucleons have been developed. However these estimations still suffer from ambiguities and uncertainties related to the off shell behaviour of the elementary amplitudes. Anyhow the importance of the rescattering term makes of these reactions a very sensitive testing ground for the photoproduction mechanism description ; this aspect is important for instance in view of the precise calculation required for the much smaller rescattering effets met in π^{+} photoproduction[15]. In Fig. 3 and 4 the various predicted cross sections for d and ^{3}He are displayed.

Pion rescattering in light complex nuclear targets has been investigated by J. Vergados and R.M. Woloshyn[16] and found to dominate the coherent production very near threshold for non zero spin targets ; in the case of ^{3}He they find ∿ 20 % increase in the cross section at all energies from threshold up to 8 MeV above threshold.

3. The experimental procedure

Experimental procedure has barely changed since the first measurements performed in the early fifties. The photon source is bremsstrahlung. The photon flux is monitored by a quantameter. Near threshold, the knowledge of the absolute energy scale is crucial ; it can be established through the study of the π^{+} photoproduction on the proton which yields the threshold energy of the process (151.44 MeV) with a ± 30 keV accuracy.18)

The two gammas from the pion decay are converted and subsequently detected in two counter telescopes placed symmetrically about the photon beam direction. The angle between the two telescopes is varied with the π° energy to account for the decay kinematics. The rotation of the plane of the two detectors, with respect to an axis perpendicular to the photon beam allows the investigation of the π° angular distribution. The angular resolution obtained in this way improves with increasing π° energy. The π° detection efficiency is usually estimated by a Monte Carlo simulation taking into account exact kinematics, detector geometry, π° decay gammas conversion and propagation in the telescopes.

Below-threshold measurements give the background level related to electromagnetic reactions (large angle pairs,...). Even for high Z nuclei, there is no sizable contribution to the π° yield in the threshold region, from the Primakoff effect17) (production of a π° through the interaction of the photon with the Coulomb field of the nucleus).

The π° yield

$$\mathcal{Y}(E_e) = \int_{E_{th.}}^{E_e} \frac{d\sigma}{d\Omega}\, \varepsilon(E_{\pi^\circ},\theta)\, \frac{dN}{dk}(E,E_e)\, dE$$

is measured as a function of the end point energy E_e of the bremsstrahlung spectrum, and compared to "theoretical" yields obtained by folding theoretical cross sections with the bremsstrahlung spectrum dN/dk and the Monte Carlo calculated efficiency ε.

Absolute normalization of the yield is a major problem ; it requires the calibration of the π° detector and the knowledge of the normalized photon spectrum per unit quantameter. Hydrogen which cross section is inaccurately known can not play the calibration role it had in π^+ threshold photoproduction studies.18)

There are some plans in Saclay in order to improve the present situation

- We contemplate calibrating our detection system with the 2.9 MeV π° of stopped π^- charge exchange capture in hydrogen, using the Saclay Linac pion facility. Pion charge exchange branching ratio in hydrogen is deduced from the Panofsky ratio19) to be 0.61 ± 0.01 ; the main uncertainty in the efficiency measurement will stem from the determination of the number of stopped pions in the target which can be estimated with an accuracy better than 10 %.

- Taking advantage of our monochromatic annihilation photon beam, we can consider, even with the current operating conditions (50 nA average e^+ current corresponding to ∿ 10 photons per sec. at 150 MeV), the measurement of the π° photoproduction on the proton, 3 MeV above threshold (expected cross section 0.5 μb) with an overall accuracy of 10 %. A larger positron intensity would be desirable to bring into light, through the measurement of the forward differential cross section ($d\sigma/d\Omega\ (0^\circ) \sim |M_{1+} + E_{0+}|^2$) the predicted cusp behaviour induced by the π^+ channel.

4. Experimental data

4.1. *Photoproduction of π° on very light nuclei (d, ^3He, ^4He)*

In 1953 in an early attempt to measure the ratio of the cross sections from deuterium and hydrogen at threshold, C. André20) concluded that for ∿ 10 MeV π°, $\sigma_d/\sigma_p = 4.2 \pm 1.3$.

There were no other data in the threshold region before the Saclay experiment21). In the latter experiment we studied the energy range up to 8 MeV above threshold. The π° detection system (two telescopes at 90° from the beam direction) was devised in order to be sensitive to the total cross section ; the Monte Carlo claculated efficiency vs. π° energy is displayed in Fig. 5.

The measured yields for deuterium and hydrogen are shown in Fig. 6. They are compared to two theoretical estimations by J. Koch and R. Woloshyn12) (KW) and by P. Bosted and J.M. Laget13) (BL). Complete photoproduction operators and rescattering amplitudes are used in both papers which differ only by the choice of the deuterium wave function : BL use a parametrization of Reid soft core, whereas KW utilize a Hulthen wave function.

In order to produce "theoretical" yield curves, we have folded the hydrogen predicted cross section with the Monte Carlo calculated efficiency and the bremsstrahlung shape for the different values of the photon spectrum end point energy selected in the experiment. By fitting these values to the experimental hydrogen yields we deduced a normalization factor for the π° detection efficiency which was then used to construct the deuterium theoretical yield curve.

As explained in the discussion on rescattering, the agreement of the experimental data with KW theory is probably fortuitous since the Hulthen wave function enhances artificially the rescattering amplitude.

No definite conclusion other than the importance of the rescattering process can be drawn from the inspection of the only deuterium data. Preliminary results of recent experiments on ^{3}He and ^{4}He will be presented by E. Vincent,26) together with a detailed yield curve on hydrogen. The complete set of data on the four nuclei has not yet been analyzed as a whole. A first attempt, is to try to understand the four nuclei in the frame of an impulse approximation approach including the very simple model of rescattering developed in 2.3, and leaving the nucleon multipoles as free parameters to be adjusted on the data.

4.2. *Coherent π° photoproduction*

Extensive measurements of π° photoproduction differential cross section on various complex nuclei targets were performed by Schrack et al.22) at 166 MeV and by Govorkov et al.2) at 180 MeV bremsstrahlung end-point energy. A generally good agreement with coherent elastic photoproduction theory is observed for nuclei $A < 40$ (see Fig. 7). Mean-square radii of nuclear matter distribution were extracted from the data in good agreement with those obtained from other experiments. Inelastic processes and failure of Born approximation were invoked to explain the discrepancies observed for backward production on high A nuclei. More detailed investigation of the nucleonic density distribution would require taking into account pion distorsion and improving the experimental accuracy. In their recent measurements under taken at Bates, J.L. Milder et al.27) minimize the non elastic contributions by choosing to investigate the very near-threshold region. When confronted to the Vergados and

Woloshyn[16] calculations which treat completely the pion-nucleus interaction, their results can bring useful information.

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Table I

The experimental and theoretical values of the dipole pion photoproduction amplitudes E_{0+} in units $10^{-3}\ m_\pi^{-1}$

Channel	Experiment a)	Born PV b)	Born PS c)	Current d) algebra
$\gamma p \to n\pi^+$	28.6 ± 0.14	28.	28.1	29.0
$\gamma n \to p\pi^-$	-31.5 ± 1.0	-32.2	-31.7	-33.2
$\gamma p \to p\pi^0$	-1.8 ± 0.6	-2.5	- 8.1	- 2.4
$\gamma n \to n\pi^0$	0.3 ± 0.9	0.4	5.6	0.3

a) from Ref.7) b) from Ref.13) c) from Ref.23)
d) from Ref24).

Table II

The pion nucleon scattering lengths in units $10^{-3}\ m_\pi^{-1}$

Channel	Scattering length a)
$\pi^0 N \to \pi^0 N$	-4. ± 3.
$\pi^- p \to \pi^- p$	83. ± 3.
$\pi^- n \to \pi^- n$	-92. ± 2.
$\pi^- p \to \pi^0 n$	-124.± 3.

a) from Ref.25)

Figure captions

Fig. 1 The proton π° photoproduction cross section. The dotted line corresponds to the multipole amplitudes $E_{o+}=-0.0025$ and $M_{1+} = 0.008\ qk/m_\pi^2$. The solid line includes the cusp effect produced by the coupling with the π^+n channel as predicted by J.M. Laget.5)

Fig. 2 The direct and the rescattering processes in π° photoproduction on deuterium.

Fig. 3 The π° photoproduction reduced cross section on deuterium as a function of the excess energy above threshold. The light lines represent the direct term contribution only ; the heavy lines include the rescattering term. Solid lines correspond to Ref.13), dashed-dotted lines to Ref.12) and the dotted lines to the simple impulse approximation with frozen nucleons model discussed in the text. All estimates use approximately the same proton cross section ($E_{o+}=-0.0025$ $M_{1+} = 0.008\ qk/m_\pi^2$.

Fig. 4 The π° photoproduction reduced cross section on ^3He. Labeled as Fig. 3. Solid lines Ref.14)

Fig. 5 Efficiency of the detection telescope, used in the deuterium Saclay experiment21), as a function of the π° energy.

Fig. 6 The π° photoproduction on deuterium from Ref21). The measured photoproduction yields as a function of the Bremsstrahlung end point energy E_e are compared to theoretical estimates for deuterium without rescattering (short dashes Ref.12) and long dashes Ref.13))and including rescattering (dash-dots Ref.12) and solid line Ref.13)). These two theoretical estimates use the same proton cross section ; the corresponding yield has been adjusted to the hydrogen data. Arrows indicate the threshold energies. The yields are given in microbarn for equivalent quantum.

Fig. 7 The π° photoproduction on carbon and copper from Ref.22). Experimental data and best shape fit of the data by a Monte Carlo synthesis. The ordinate is the relative yield and the abscissa the cosine of the colatitude angle of the counter system with respect to the incident photon beam. The end point energy of the bremsstrahlung spectrum was 166 MeV.

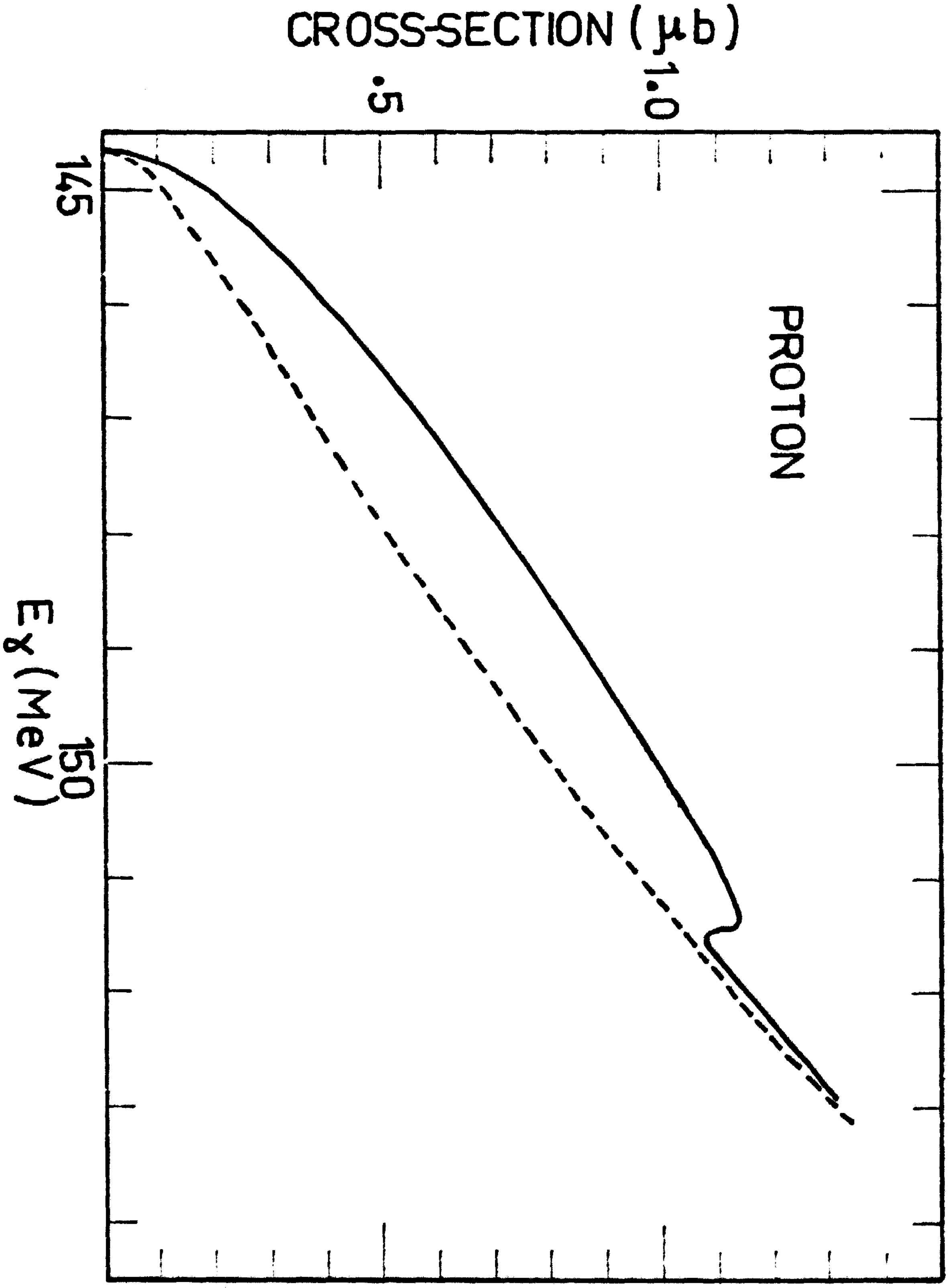
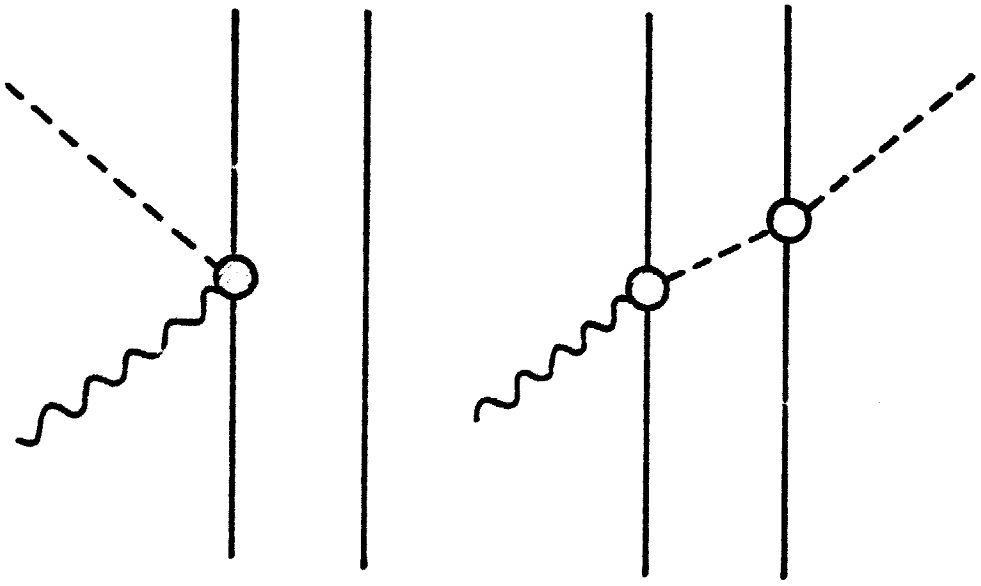


Fig. 1



direct rescattering

Fig. 2

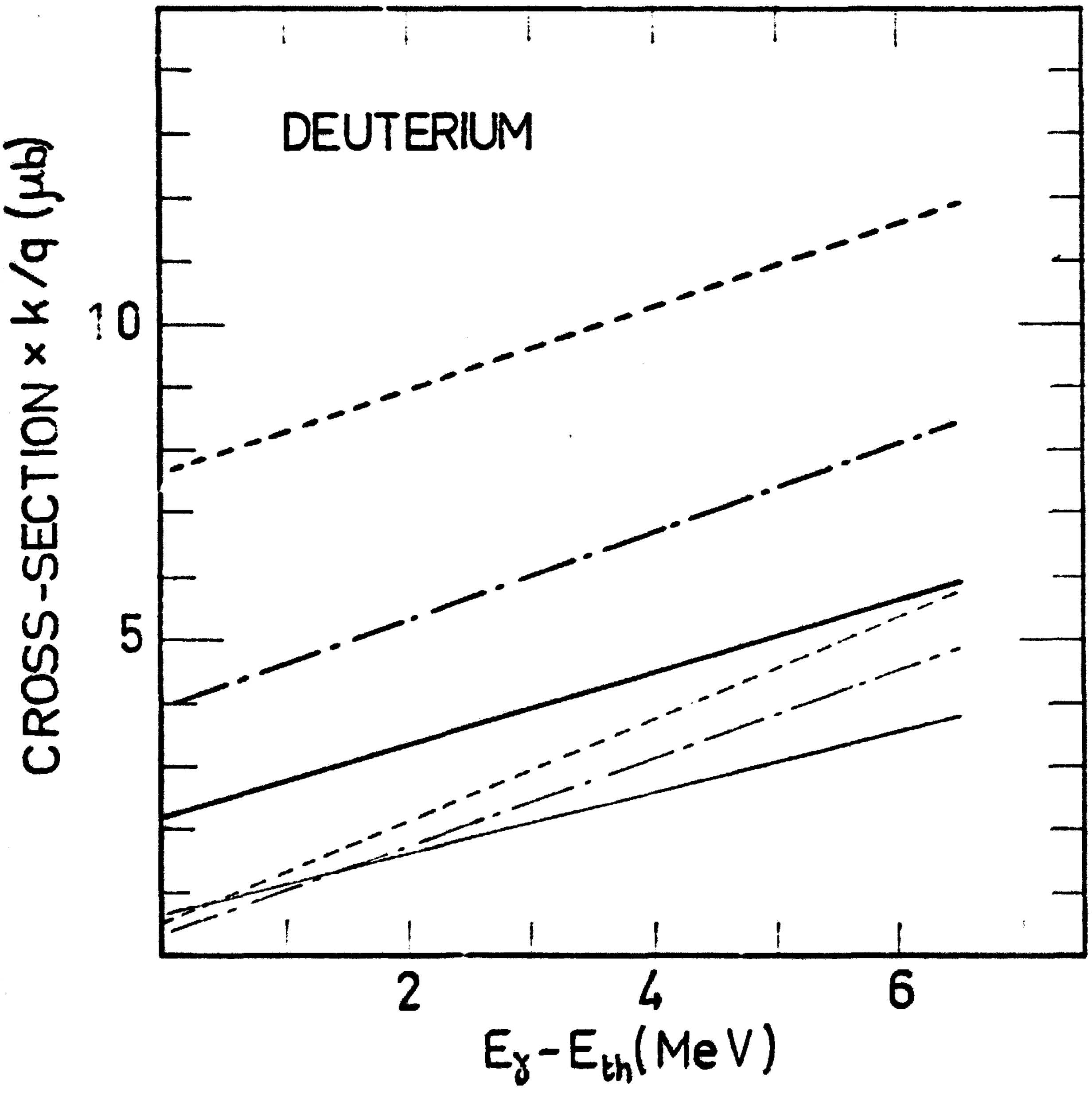


Fig. 3

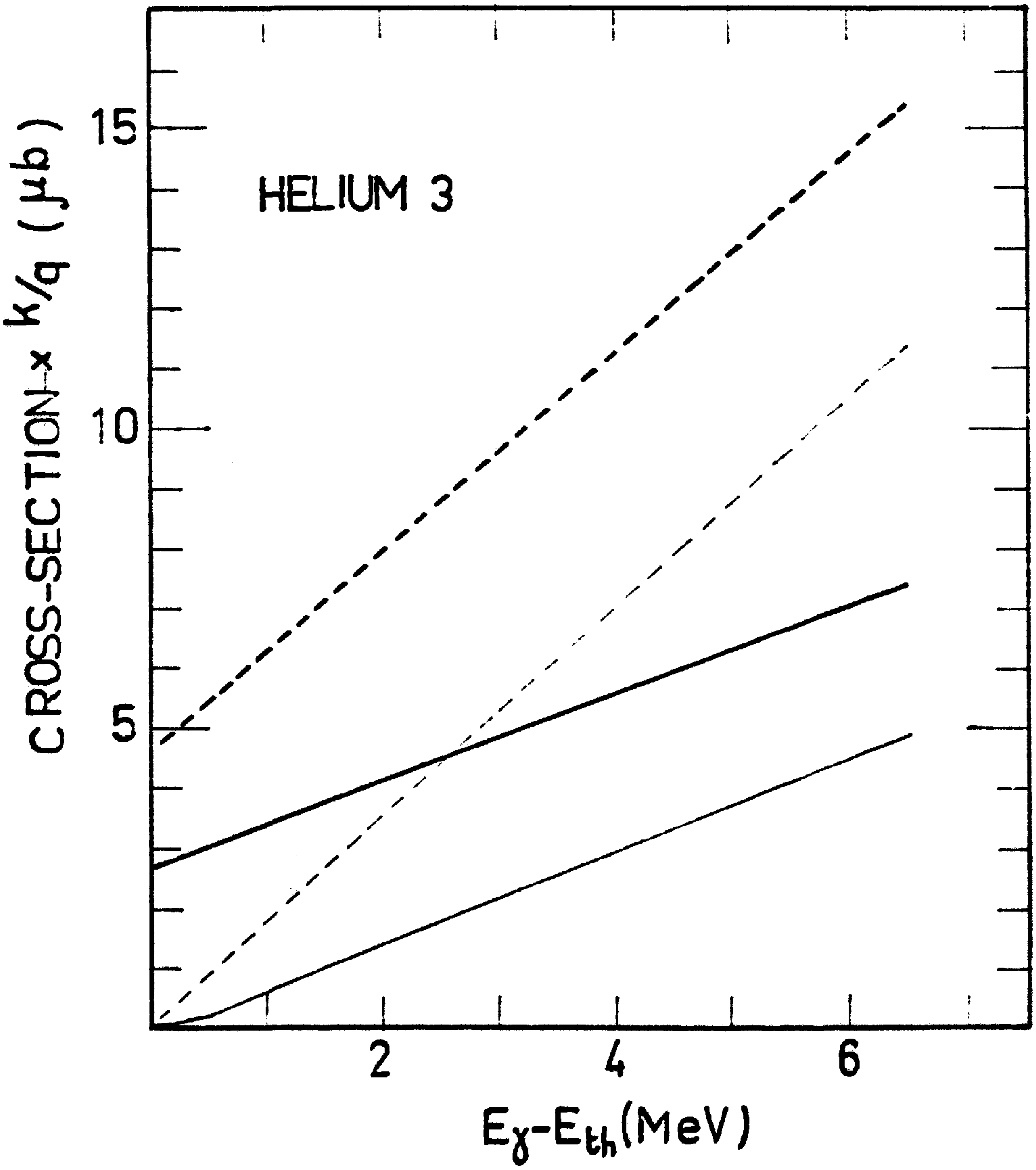


Fig. 4

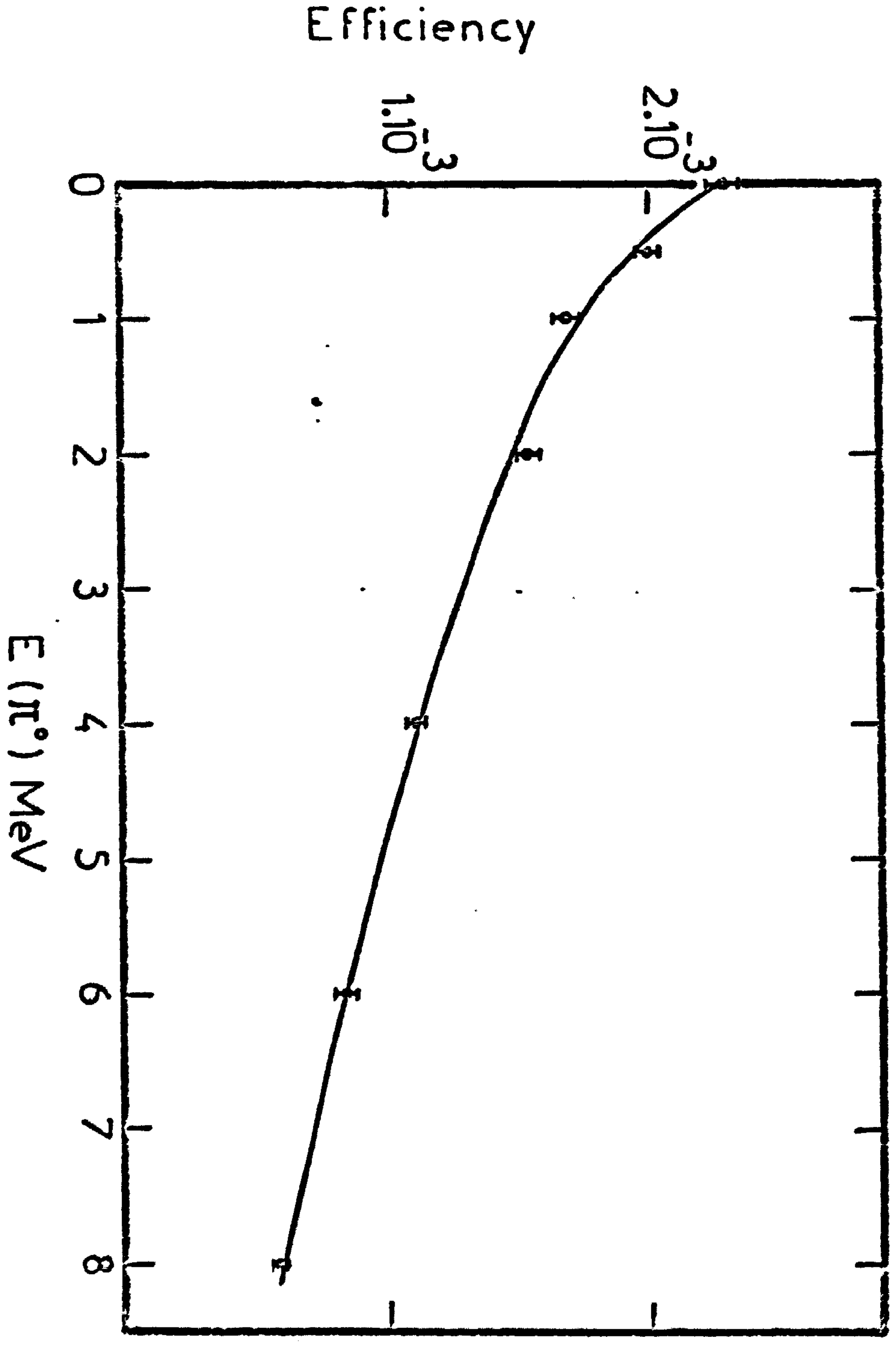


fig. 5

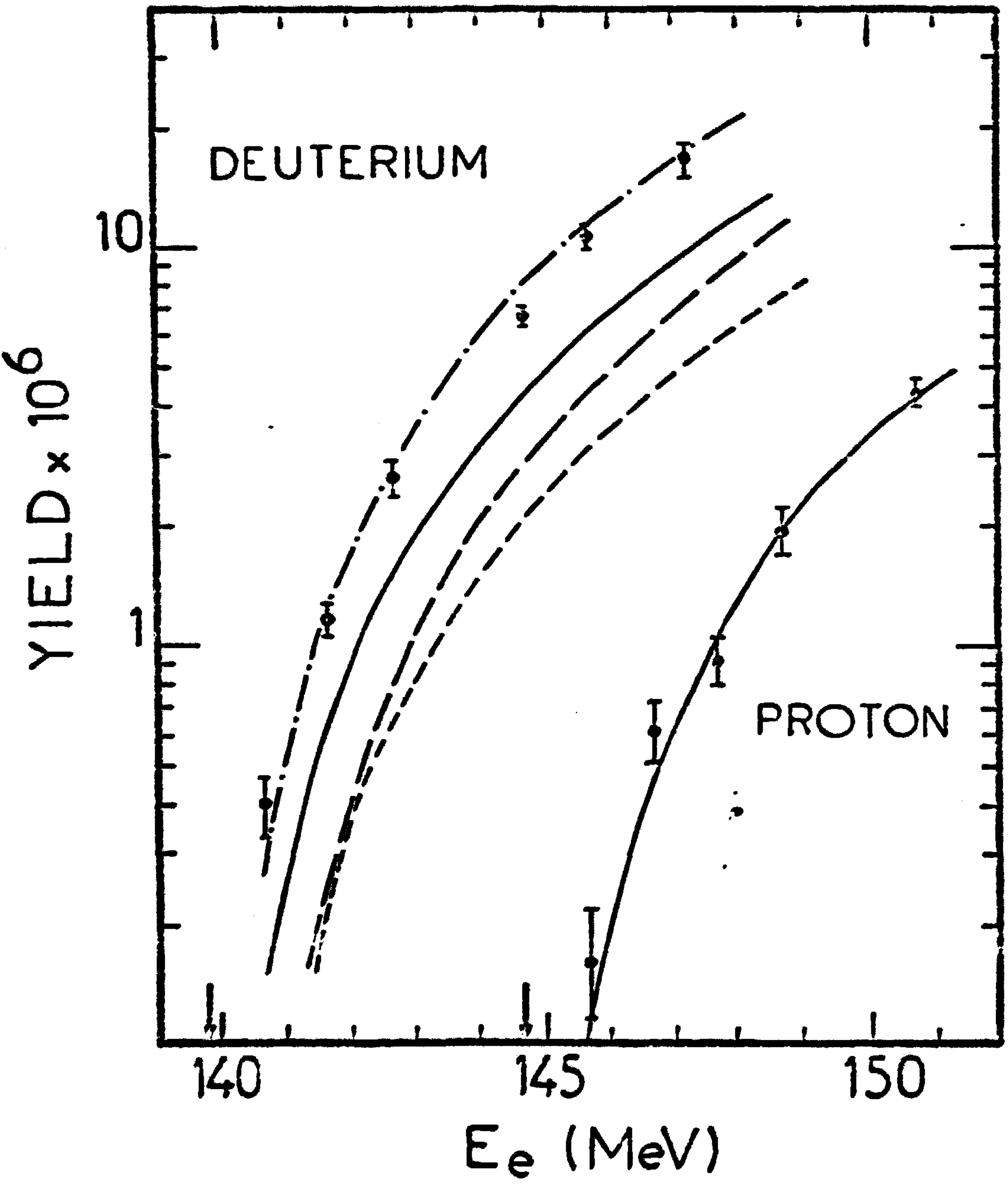


Fig. 6

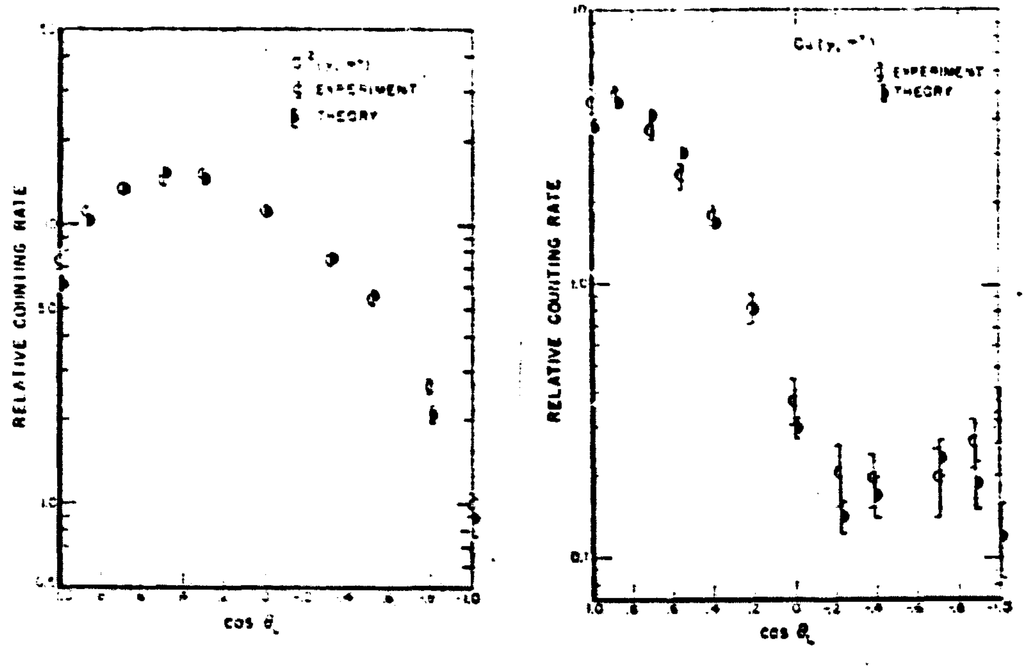


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Fig. 7