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DETECTION OF FISSION FRAGMENTS USING THICK SAMPLES IN CONTACT WITH SOLID STATE NUCLEAR TRACK DETECTORS*

by

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Whenever use is made of thick samples in contact with solid state nuclear track detectors for determination of fission yields, one of the fundamental problems is the evaluation of the effective number of target nuclei which contributes to the fraction of the number of fission events that will be recorded. Besides the peculiarities of the fission case under study (induced or spontaneous fission of heavy nuclei, induced fission of intermediate-mass nuclei,etc), several quantities must be also considered such as the range of fission fragments in both the sample and detector materials, the registration threshold, and the limit angle of incidence for fragment detection. The evaluation of the effective number of target nuclei which contributes to recorded events is based on the evaluation of the effective thickness of the sample. In the present work, a method of evaluating effective thicknesses of thick samples has been developed for binary fission modes, and a cross section formula which takes into account all the necessary corrections due to fragment attenuation effects by a thick target has been deduced for calculating fission yields in induced-fission experiments.

Key-words: Fission fragments; Thick samples; Track detectors; Induced fission; Medium-weight elements.

1. Introduction

In 1981 we had the opportunity of beginning a systematic study on photofission of intermediate-mass nuclei using bremsstrahlung photons from the 2.5-GeV Electron Synchrotron of the Bonn University (Germany) [1-3]. Samples of natural Al, Ti, Co, Zr, Nb, Ag, In, and Ta were available in the form of thick metal foils as targets, and CR-39* plates and makrofol† polycarbonate sheets have been used as solid state nuclear track detectors for fission fragments of these elements. Results of photofission cross section measurements obtained in these experiments have been reported elsewhere [4-6]. In order to obtain the photofission yields whenever thick samples are used in contact with solid state track detectors we need to develop a method which gives the number of target nuclei of the sample which actually contributes to fission events recorded. The method developed by us is the subject of this paper.

2. Preliminary considerations

The number of target nuclei which contributes to the fraction of fission events recorded on the detector is a fundamental quantity to determine the reaction yield (cross section, σ) which, in the induced fission case, is obtained by the relationship

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*Allyl diglycol carbonate polymer by American Acrylics and Plastics, Inc. (Stratford, Conn., USA).

†Makrofol N, Auftrag 90002 (0.7 Kg) by Bayer AG (Germany).

$$\sigma = \frac{N_e}{N_a Q \varepsilon} \tag{1}$$

where N_e is the number of fission events (fission fragment tracks) recorded per unit area, N_a is the effective number of target nuclei of the thick sample per unit area, Q is the number of photons (or particles) incident perpendicularly on the target-detector stacks per unit area, and ε is the efficiency factor which takes into account both track registration and identification (observation) efficiencies. Formula (1) is applicable whenever target samples and detectors are arranged during irradiation as shown schematically in Fig. 1-a. N_a is related to the effective thickness of the target sample, x_{ef}, by

$$N_a = \frac{\rho N_0}{M} x_{ef} , \tag{2}$$

where ρ is the density of the sample (g/cm^3), N_0 is Avogadro's number, and M is the atomic weight (g). To simplify the calculation, we have introduced the following basic assumptions:

i) the target sample is homogeneous and uniform, and nuclear fragments are emitted isotropically from any point inside the sample;

ii) the registration threshold of track detectors and the resolution power of the optical system for observation of tracks require a minimal etched track length in the detector, r_m, in order to make possible observation of tracks;

iii) latent tracks are revealed by etching for fragments entering the detector at angles greater than the critical angle of track etching, ϕ_c (measured from the detector surface); it is assumed ϕ_c constant, i.e., independent of the energy-loss--rate of fragments at the detector surface;

iv) since the kinetic energy of fission fragments is low ($\lesssim$ 0.5 MeV/u), the rate of energy-loss (due essentially to ionization) in both the target and detector materials is described by simple relationships of the form [7,8]

$$-\frac{dE}{dy} = \xi_a E^\alpha \quad , \quad -\frac{dE}{dy} = \xi_d E^\alpha \quad , \tag{3}$$

where E is the fragment kinetic energy, and ξ_a , ξ_d , and α are constants (the subscripts a and d denote, respectively, the target and detector materials). The constant α ($0 < \alpha < 1$) may be considered as much as the same for both media, and $\xi_a > \xi_d$. As a consequence, the residual ranges will be given by

$$R_a(E) = \frac{E^{1-\alpha}}{\xi_a(1-\alpha)} \quad , \quad R_d(E) = \frac{E^{1-\alpha}}{\xi_d(1-\alpha)} \quad . \tag{4}$$

3. Effective thickness and cross section for identical fragments

Let us assume first that the emitted fragments are identical (symmetric fission mode), i.e., they have equal charge, mass and initial kinetic energy. Consider a nuclear fragment which moves towards the detector with an initial kinetic energy E_0 from a point-origin inside the sample whose position is given by the vertical distance x from the target-detector interface (Fig.1-b).

First, the fragment travels a distance a inside the sample, reaching the interface with an energy $E < E_0$, and then it penetrates the detector where it travels a path-length r before coming to rest. Let $a_0 = R_a(E_0)$ and $r_0 = R_d(E_0)$ be the full residual ranges, respectively, in the sample and detector. If ϕ denotes the dip angle, from eqs. (4) and Fig. 1-b we have

$$x = a_0(1 - \frac{r}{r_0}) \sin\phi \quad , \quad dx = - \frac{a_0}{r_0} \sin\phi dr \quad . \tag{5}$$

The number of fragments emitted towards the detector with a dip angle between ϕ and $\phi+d\phi$, i.e., within the solid angle $2\pi\cos\phi d\phi$, is that number of fragments which is produced from a sample layer of thickness

$$d^2x = \frac{a_0}{r_0} \sin\phi\cos\phi d\phi dr \quad . \tag{6}$$

To obtain the equivalent thickness Δx of the target sample which contributes to tracks recorded per unit area it suffices to integrate eq. (6) between the limits allowed for ϕ and r. We have

$$\Delta x = \frac{a_0}{r_0} \int_{r_m}^{r_0} \int_{\phi_c}^{\pi/2} \sin\phi\cos\phi d\phi dr = \frac{a_0}{2} (1 - \frac{r_m}{r_0}) \cos^2\phi_c \quad . \tag{7}$$

Therefore, the reaction cross section (reaction yield) will be given by

$$\sigma = \frac{N_e}{Q \frac{\rho N_0}{M} \frac{a_0}{2} (1 - \frac{r_m}{r_0}) \cos^2\phi_c} \tag{8}$$

In this equation we identify and interpret the different quantities as follows (cf. eqs. (1) and (2)): $x_{ef} = \frac{a_0}{2}$ is the effective thickness of the thick target, $\varepsilon_0 = 1 - r_m/r_0$ is the efficiency factor related to observation of tracks, and $\varepsilon_d = \cos^2\phi_c$ is the detection efficiency. This latter should be compared to $\varepsilon_d' = 1 - \sin\phi_c$, which is the detection efficiency for thin targets in contact with track detectors [9]. The combined efficiency is, therefore, $\varepsilon = \varepsilon_0 \varepsilon_d$. Since r_m can be as small as $\sim 3\mu$m, and r_0 varies in the range 7-10 μm for the cases of photon-induced fission of intermediate-mass nuclei studied [4,5], ε_0 may result to be 60-70%. For the same fission cases, an average value $\phi_c \simeq 15^{\circ}$ has been estimated, so that $\varepsilon_d \approx 93\%$, and the total efficiency may amount to some 55-65%. It is remarked that, under the specified assumptions, the effective thickness of a thick target equals to half of the full residual range of fragments in that target material.

The expected track-length distribution of tracks recorded on the detector can be obtained in the following way. Suppose we have ν fissions per unit volume produced in the target sample. The number of tracks recorded per unit area due to fragments from a target layer of thickness dx and within a solid angle $d\Omega = 2\pi\cos\phi d\phi$ is given by

$$\frac{d^2N}{d\Omega dx} = \frac{\nu}{2\pi} \quad . \tag{9}$$

Taking into account the result expressed by eq. (5), and after integration with respect to ϕ, one obtains

$$\frac{dN}{dr} = \frac{1}{2}\, \nu\, \frac{a_0}{r_0} \cos^2\phi_c \quad . \tag{10}$$

Such result will be useful in the study of detection of fission fragments from different fission modes, as we shall see in the next sections.

4. Effective thickness and cross section for a distribution of fission fragments

Let us consider the general situation of a distribution of fission fragments generated by the interaction of the incoming photon (or particle) beam with the target sample. Each group of identical fragments will be defined by their full residual ranges a_0 and r_0, respectively, in the sample and in the detector materials. Let n be the number of fragments of any type emitted per unit volume and isotropically from points inside a thick target in 2π-geometry. The differences in charge, mass, and kinetic energy of fragments produce a track-range distribution in the sample and a track-length distribution in the detector. It is expected that the maximum track-length distribution (the r_0 distribution) of tracks of a given group of fragments follows a gaussian-type distribution, i.e.,

$$\frac{dN}{dr_0} = \frac{n}{s\sqrt{2\pi}} \exp\left[-\frac{(r_0-\bar{r}_0)^2}{2s^2}\right] , \qquad (11)$$

where $\bar{r}_0$ is the mean value, and s is the standard deviation. Such a distribution is shown in Fig. 2-a for $n = 1000$, $\bar{r}_0 = 8\mu m$, and $s = 2\mu m$. The number of fragments defined by eq. (11) follows, in turn, a track-length distribution as that given by eq. (10). Accordingly, the number of tracks expected to be recorded per unit area whose track-length is between r and r+dr due to fragments whose maximum track-length in the detector is between r_0 and r_0+dr_0 will be given by

$$\frac{d^2N}{drdr_0} = \frac{1}{2}\frac{a_0}{r_0}\cos^2\phi_c \frac{n}{s\sqrt{2\pi}} \exp\left[-\frac{(r_0-\bar{r}_0)^2}{2s^2}\right] . \quad (12)$$

In order to construct this distribution it is necessary to know how the quantities a_0 and r_0 are related to each other and which are the values of ϕ_c for the different groups of fragments. The ratio $\xi = \xi_a/\xi_d = r_0/a_0$ is expected not to vary so significantly with the nature of fragments and, therefore, it will be assumed ξ constant for all groups of fragments and set equal to the ratio $\bar{r}_0/\bar{a}_0$ of the most frequent group of fragments. Although ϕ_c should vary with the type of fragment, it will also be assumed ϕ_c constant and equal to the average value $\bar{\phi}_c$ for the most frequent group of fragments. In this way, eq. (12) transforms to

$$\frac{d^2N}{drdr_0} = \frac{\cos^2\bar{\phi}_c}{2\xi} \cdot \frac{n}{s\sqrt{2\pi}} \exp\left[-\frac{(r_0-\bar{r}_0)^2}{2s^2}\right] . \quad (13)$$

This distribution is illustrated in Fig. 2-b for $\bar{\phi}_c = 10^\circ$ and $\xi = 2.42$. Finally, to obtain the expected track-length distribution for all nuclear fragments emitted it suffices to integrate (13) with respect to r_0, i.e.,

$$\frac{dN}{dr} = \frac{\cos^2\bar{\phi}_c}{2\xi} \int_{\infty}^{r} \frac{n}{s\sqrt{2\pi}} \exp\left[-\frac{(r_0-\bar{r}_0)^2}{2s^2}\right] dr_0 . \quad (14)$$

This distribution is depicted in Fig. 2-c, which shows the effect of fragment absorption by a thick sample on the etched-track--length distribution. This trend should be compared with that obtained for the case of a thin sample (Fig. 2-a). To obtain the cross section formula and, as a consequence, the effective thickness and efficiency factors as well for the case of a mixture of fragments, it is essential to make an analysis of the track--length distributions which are actually derived from track measurements, and to compare them with the expected track-length distributions.

4.1 *Comparison between observed and expected track-length distributions*

Fig. 3 shows typical examples of observed track-length distributions from some selected irradiation conditions of bremsstrahlung-induced fission experiments of medium-weight target elements at intermediate energies [4]. These distributions can be well represented by Weisskopf-like curves

$$\left.\frac{dN}{dr}\right|_o = f(r) = c(r-r_m)\ \exp\ [-b(r-r_m)] \quad , \qquad (15)$$

where b, c, and r_m are constants, the latter one being the measured threshold etched-track length. Such curves have the following properties:

i) most probable track-length

$$r_{mp} = r_m + 1/b \quad ; \qquad (16)$$

ii) maximum frequency

$$f_{max} = f(r_{mp}) = \frac{c}{eb} \quad ; \tag{17}$$

iii) track-length of the point of inflection

$$r_{in} = r_m + 2/b \quad ; \tag{18}$$

iv) frequency of the point of inflection

$$f_{in} = f(r_{in}) = \frac{2c}{e^2 b} \quad ; \tag{19}$$

v) total number of tracks observed per unit area

$$N_T = \int_{r_m}^{\infty} f(r)\, dr = c/b^2 \quad . \tag{20}$$

If r_m, r_{mp}, and N_T are values taken from an observed track-length distribution, then, from properties i-v above, we can determine the values of parameters b and c as

$$b = 1/(r_{mp}-r_m) \tag{21}$$

$$c = N_T/(r_{mp}-r_m)^2 \quad , \tag{22}$$

so that such an observed track-length distribution turns out to be described by

$$\left.\frac{dN}{dr}\right|_o = \frac{N_T(r-r_m)}{(r_{mp}-r_m)^2} \exp\left[-\frac{r-r_m}{r_{mp}-r_m}\right] \quad . \tag{23}$$

On the other hand, the expected track-length distributions (Eq. 14) have shown to exhibit a trend like the one depicted in Fig. 2-c. As one can see, these distributions are very similar to a Fermi distribution which we have chosen to represent the expected distributions. Accordingly,

$$\left.\frac{dN}{dr}\right|_e = g(r) = \frac{\mathcal{N}}{1+\exp\left(\frac{r-p}{q}\right)} , \tag{24}$$

where $\mathcal{N}$, p, and q are parameters to be determined. In this case,

$$r_{in} = p \quad \text{and} \quad g_{in} = \frac{\mathcal{N}}{2} \tag{25}$$

define the point of inflection of the distribution. The evaluation of parameters $\mathcal{N}$, p , and q has been made by fitting the expected track-length distribution to the observed one in the region of r where both distributions coincide mostly. The remaining differences between each other can then be computed, and such differences are regarded as corrections to be introduced into the observed number of tracks. In this way, from eqs. (18), (21), and (25), we have

$$p = 2r_{mp} - r_m , \tag{26}$$

and from eqs. (19), (21), (22), and (25), we obtain

$$\mathcal{N} = \frac{4N_T}{e^2(r_{mp}-r_m)} . \tag{27}$$

The parameter q can be evaluated by noting that for $r > r_{mp}$ both the expected and observed distributions should give practically the same number of tracks, i.e., $f(r) = g(r)$. Hence, from eqs. (23) and (24), one obtains

$$q(r) = \frac{(r-r_{mp}) - (r_{mp}-r_m)}{\ell n\left[\frac{4}{e^2}\,\frac{r_{mp}-r_m}{r-r_m} \times \exp\left(\frac{r-r_m}{r_{mp}-r_m}\right) - 1\right]} \quad , \quad r > r_{mp} \quad . \tag{28}$$

The value of q depends upon the track-length chosen. However, numerical calculations have indicated that very good agreement is achieved between the expected and observed track-length distributions when the q-value is calculated at the point of inflection, that is,

$$q = q(r_{in}) = \lim_{r\to r_{in}} q(r) = \lim_{r\to 2r_{mp}-r_m} q(r) = r_{mp}-r_m \quad . \tag{29}$$

In this way, the observed track-length distribution as described by eq. (23) is substituted by a new, corrected track-length distribution whose expression is given by (24) with parameters p, $\mathcal{N}$, and q calculated, respectively, by eqs. (26), (27), and (29). It is shown in Fig. 4 an illustrative example of comparison between an observed track-length distribution and the correspondent "corrected" distribution as obtained by the method described above.

Finally, once the corrected track-length distribution has been derived, it is possible to obtain the corrected total number of tracks observed per unit area, N_c, by calculating

$$N_c = \int_{r_m}^{\infty} \frac{\mathcal{N}\,dr}{1 + \exp\left(\frac{r-p}{q}\right)} \quad , \tag{30}$$

where $\mathcal{N}$, p , and q are given, respectively, by eqs. (27), (26), and (29). The result is

$$N_c = 1.15\ N_T\ , \tag{31}$$

which shows that the corrected total number of tracks of $r > r_m$ recorded per unit area is 15% in excess of the total number of tracks actually observed per unit area. In Fig. 4 such a correction is represented by the hatched area.

4.2 *Cross section and effective thickness*

~~The cross~~ section (or the fission yield, σ) for a given irradiation condition can be now obtained from the track-length distribution as given by eq. (14). As remarked before, etched fission tracks are in practice identified only from a minimal measurable track-length r_m . Besides, for the aims of the present analysis, we may consider the normal track-length distributions of the fission modes (eq. 11) extended up to $\overline{r}_0+3s$. These considerations enable us to rewrite eq. (14) as

$$\frac{dN}{dr} = \frac{\cos^2\overline{\phi}_c}{2\xi} \int_{\overline{r}_0+3s}^{r} \frac{n}{s\sqrt{2\pi}} \exp\left[-\frac{(r_0-\overline{r}_0)^2}{2s^2}\right] dr_0 , \quad r \geq r_m . \tag{32}$$

Finally, by integrating with respect to r over the range $r_m \leq r \leq \overline{r}_0 + 3s$, the corrected total number of tracks per unit area will be given by

$$N_c = \frac{\eta\cos^2\overline{\phi}_c}{2\xi}\int_{r_m}^{\overline{r}_0+3s}\int_{\overline{r}_0+3s}^{r}\frac{1}{s\sqrt{2\pi}}\exp\left[-\frac{(r_0-\overline{r}_0)^2}{2s^2}\right]dr_0 dr =$$

$$= \frac{\eta}{2\xi}\cos^2\overline{\phi}_c\ (\overline{r}_0-r_m) \quad . \tag{33}$$

Recalling that $\xi = \overline{r}_0/\overline{a}_0$, $N_c = 1.15N_T$, and $\sigma = \eta M/(Q\rho N_0)$, the cross section formula results to be

$$\sigma = \frac{N_T}{Q\,\frac{\rho N_0}{M}\,\frac{\overline{a}_0}{2}\,(1-\frac{r_m}{\overline{r}_0})\,\cos^2\overline{\phi}_c \times \frac{1}{1.15}} \quad . \tag{34}$$

This expression differs from that one obtained for the case of identical fragments (eq. 8) in the factor 1.15, which corrects the number of tracks observed for losses due to identification of tracks near track-length threshold (see Fig. 4). It differs also in the quantities a_0, r_0, and ϕ_c, which are now replaced by their average values. Again, we identify and interpret the different quantities appearing in eq. (34): $\overline{x}_{ef} = \overline{a}_0/2$ is the average effective thickness of thick target, $\overline{\varepsilon}_0 = 1-r_m/\overline{r}_0$ is the average efficiency factor related to observation of tracks, and $\overline{\varepsilon}_d = \cos^2\overline{\phi}_c$ is the average etching efficiency. The combined efficiency is, therefore, $\varepsilon = \overline{\varepsilon}_0\overline{\varepsilon}_d/1.15$. Since the evaluation of the quantities r_m, $\overline{r}_0$, and $\overline{\phi}_c$ from track measurement is subjected to errors, the 15% correction on the total number of tracks actually observed may result comparable with the uncertainty of the product efficiency $\overline{\varepsilon}_0\overline{\varepsilon}_d$. We recall that $\overline{r}_0$ represents the average maximum track-length corresponding to the most probable (or median) fission mode. Values of $\overline{r}_0$ can directly be evaluated from observed track-length distributions. As discussed before $\bar{r}_0$ locates the point of inflection of the distribution curves (see Fig. 4) and, therefore, its value is given by $\bar{r}_0 = 2r_{mp}-r_m$. Formula (34) contains the necessary corrections coming from the use of thick targets in contact with plastic track detectors, and it has proved to give reliable results on fission yields of our previous bremsstrahlung-induced fission experiments [4-6].

5. Conclusions

The use of thick target elements in contact with plastic solid state nuclear track detectors is a possible alternative arrangement for measuring binary fission yields in induced-fission experiments. A cross section formula which incorporates the main correction factors resulting from energy absorption effects of fission fragments by a thick target material has been deduced. It has been shown that the target average thickness which contributes effectively to fission fragments recorded on a track detector equals to half of the residual range of the median fission fragment in the target material. Whenever thin target elements are not available in laboratories for sample preparation, the method developed in the present work can easily be extended and applied to similar experimental problems, such as other cases of particle-induced fission experiments, natural or induced emission of nuclear fragments, and other nuclear reaction studies.

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Figure Captions

Fig. 1. a) Arrangement of thick target samples and solid state nuclear track detectors in the configuration of contact to measure induced fission yields. b) Trajectory of a nuclear fragment from a point-origin inside the target and crossing the target-detector interface.

Fig. 2. Expected track-length distributions of fission tracks recorded on a nuclear track detector in contact with a thick target. a) shows the r_0-distribution (eq. (11)) which is equivalent to a situation of thin target. b) takes into account the thickness of the target sample (eq. (13)). c) shows the final effect on track-length reduction due to fragment absorption by a thick target (eq. (14)).

Fig. 3. Various observed track-length distributions from different irradiation conditions in photofission experiments using thick target elements in contact with makrofol track detector [4]. Bremsstrahlung end-point energies are indicated.

Fig. 4. Comparison between "observed", $(dN/dr)_o$, track-length distribution and the correspondent "corrected", $(dN/dr)_c$, distribution for the irradiation condition indicated. The histogram results from track measurement on a sample of 254 etched fission tracks. The curves are constructed as described in the text (eqs. (23) and (24)).

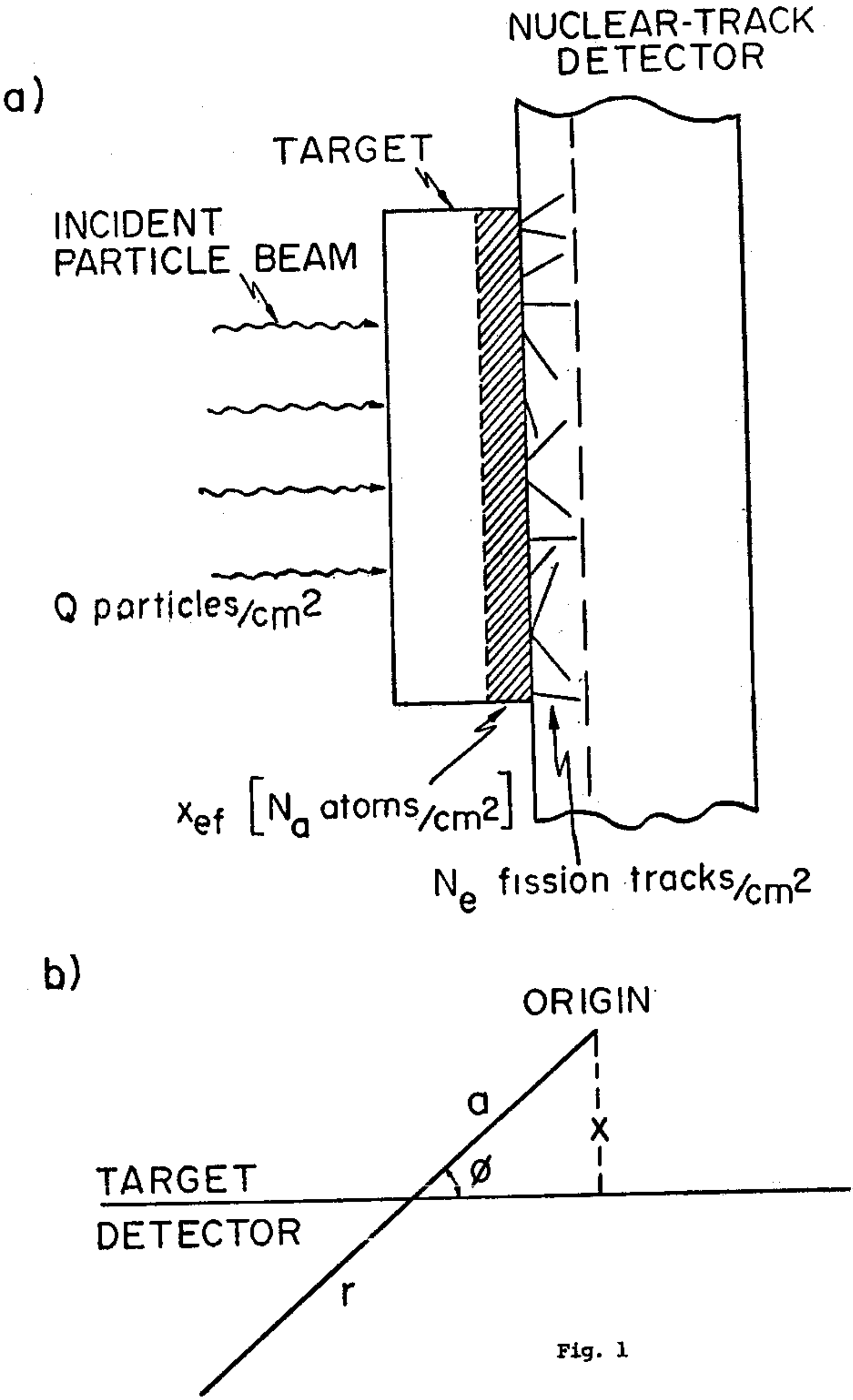
a)
NUCLEAR-TRACK
DETECTOR
TARGET
INCIDENT
PARTICLE BEAM
Q particles/cm2
xef [Na atoms/cm2]
Ne fission tracks/cm2
b)
ORIGIN
a
x
ø
TARGET
DETECTOR
r

Fig. 1

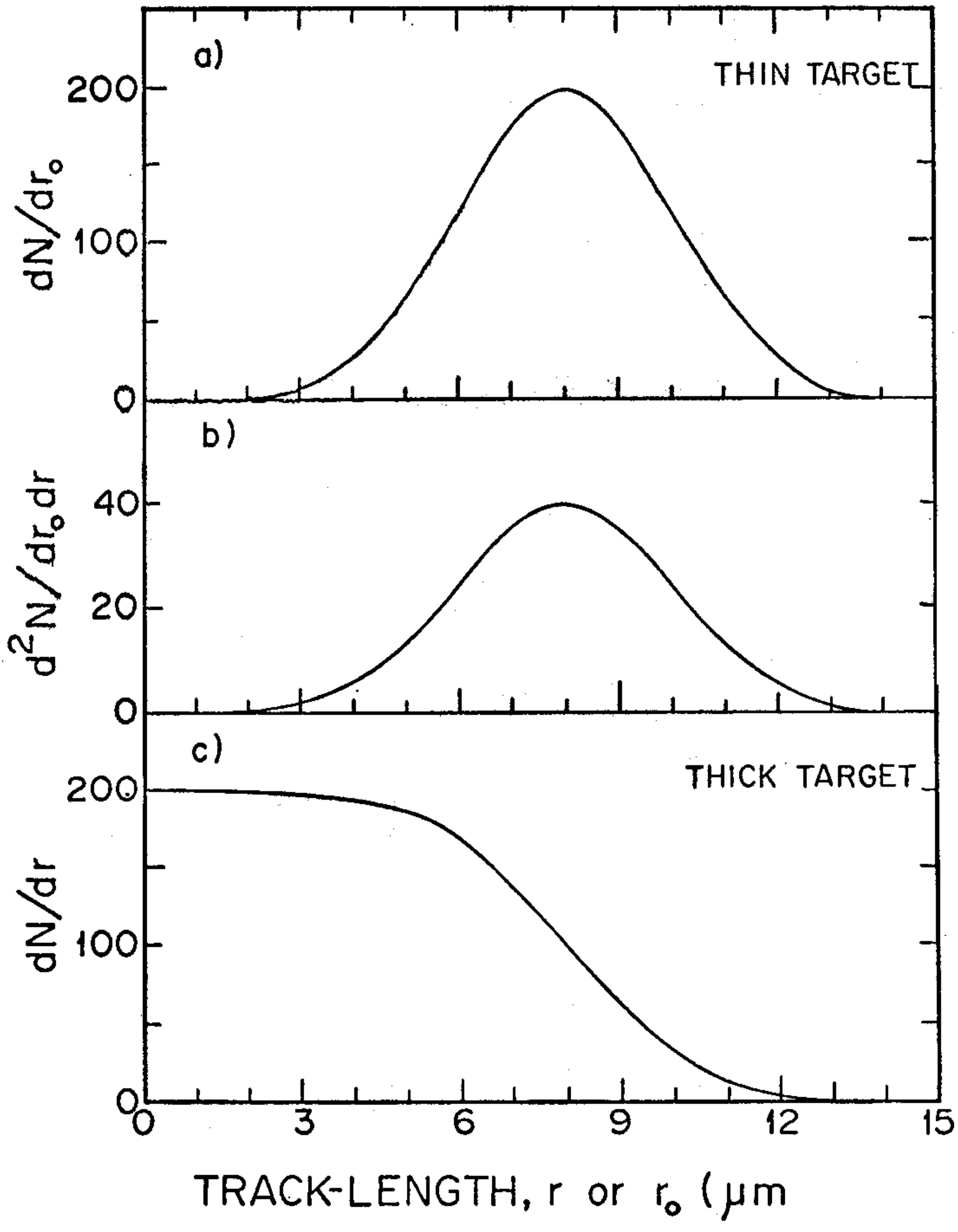
a)
THIN TARGET
200
100
0
dN/dr$_o$
b)
40
20
0
d^{2}N/dr$_o$dr
c)
THICK TARGET
200
100
0
dN/dr
0
3
6
9
12
15
TRACK-LENGTH, r or r$_o$ (μm

Fig. 2

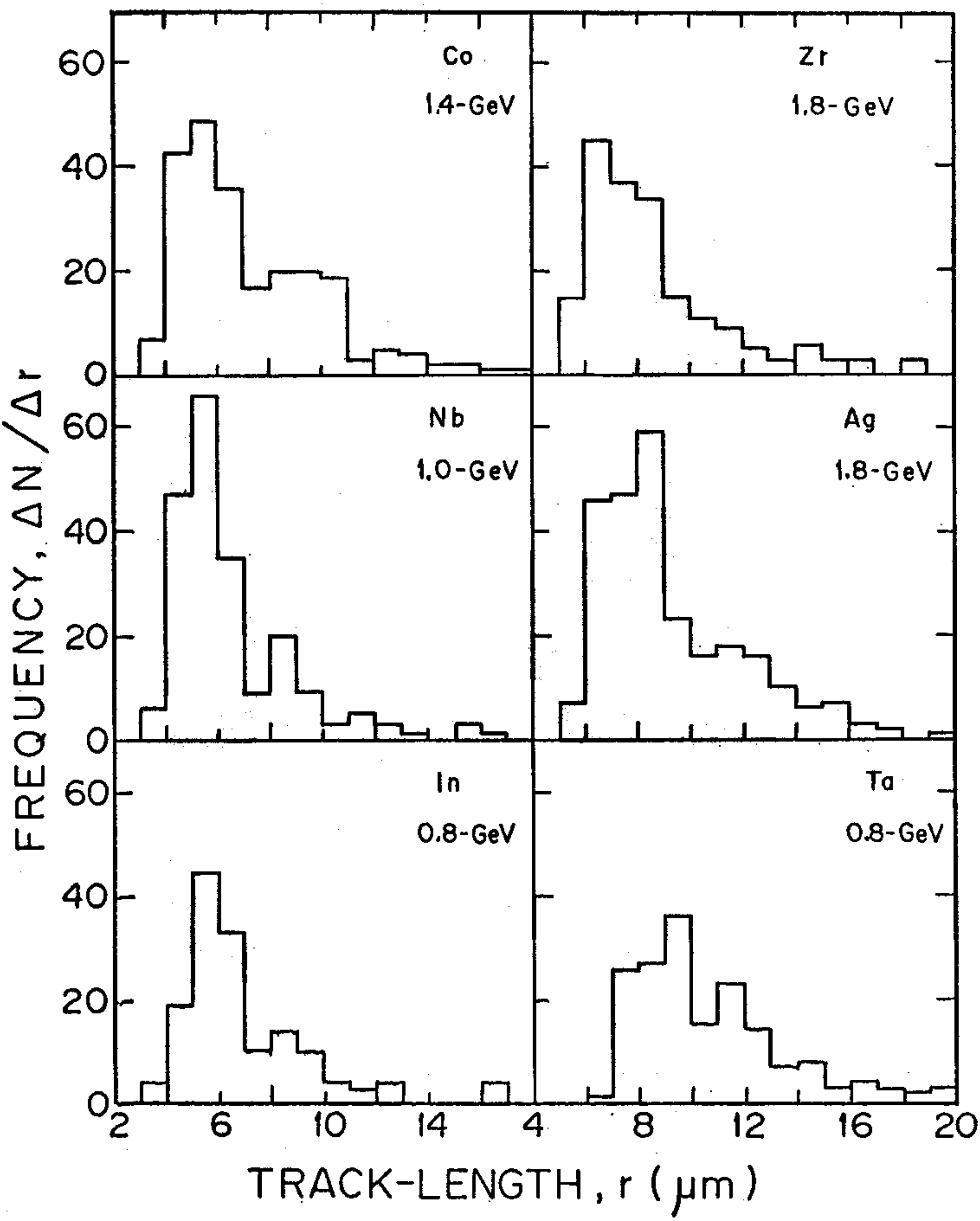
Co
1.4-GeV
Zr
1.8-GeV
Nb
1.0-GeV
Ag
1.8-GeV
In
0.8-GeV
Ta
0.8-GeV
FREQUENCY, ΔN / Δr
TRACK-LENGTH, r (μm)
0
20
40
60
2
6
10
14
4
8
12
16
20

Fig. 3

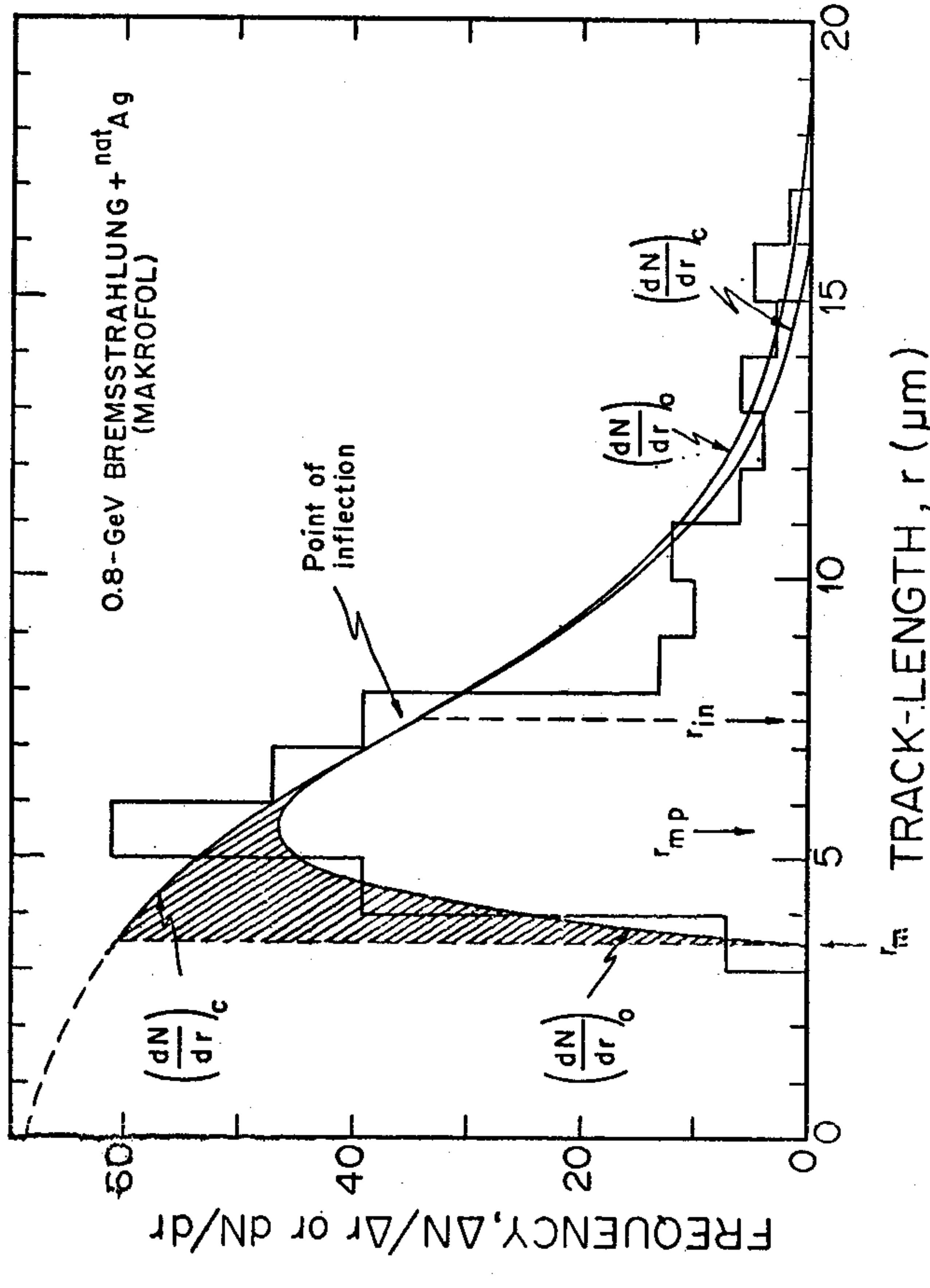
0.8-GeV BREMSSTRAHLUNG + natAg
(MAKROFOL)
Point of inflection
(dN/dr)c
(dN/dr)o
rin
rmp
rm
TRACK-LENGTH, r (μm)
FREQUENCY, ΔN/Δr or dN/dr
0
5
10
15
20
0
20
40
60

Fig. 4

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