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DETERMINATION OF FISSION FRAGMENT COUNTING LOSSES FROM THE FISSION CHAMBER SPECTRUM

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Part I: Idealized plane targets

1. INTRODUCTION

Parallel plate ionization fission chambers (FC) are often used as fission detectors in fission cross-section and fission ratio measurements, but also for neutron flux determination in the reactor physics field and in a broad variety of nuclear data measurements. In spite of the advantageous 2π - geometry and the high Q-value of the fission reaction, counting losses occur and have to be corrected. The accuracy of this reaction then influences the uncertainty of the whole measurement. For example, the accurate determination of the fission chamber detection efficiency now seems to be the most serious problem in the precise absolute fission cross-section measurements carried out at the Technical University of Dresden.

The usual procedure of estimating the detection efficiency (see e.g. /1,2/) is based on two separate corrections (Fig.1):

- The amount of fission events which do not generate an electronic pulse due to total absorption of both fragments within the backing and the fissile layer is calculated using a plane layer model; anisotropy of the fission process as well as pulse transfer from the incident neutron are considered, a range parameter (mean range of fission fragments in the target material) is required.
- The amount of fission events which generate pulses below the counting threshold set by electronic devices (e.g. constant fraction trigger) is estimated from the amplitude spectrum of the fission chamber pulses, assuming a linear behaviour of the "plateau" region down to pulse height zero.

Looking at this procedure with a critical view, serious objections are obvious /1,3,4/:

- The linear plateau shape is not proved, even for small pulse amplitudes.
- The plane layer model gives only a coarse description of real target layers. In practice, photographies obtained by microscopy show a lot of scratches which have a depth larger than the target thickness typical e.g. for fission cross-section measurements /5/.

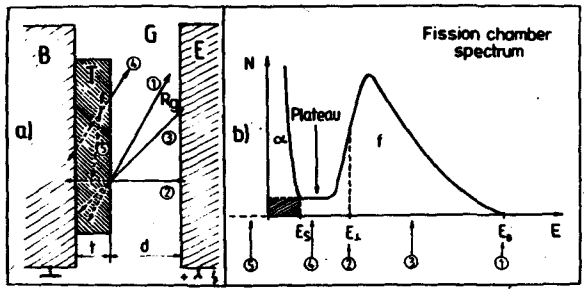

Fig.1: Various kinds of fission fragment tracks in a parallel plate fission chamber and its representation in the fission chamber spectrum (schematical view). The chamber is of a "differential" type, i.e. the target - electrode distance is smaller than the fission fragment ranges R_g in the chamber gas. Counting losses due to fragment absorption (track ⑤) as well as FC pulses in the plateau region (track ④) are caused by "flat" tracks (small inclination against the target surface).
B - backing; T - target layer; G - fission chamber gas; E - electrode; E_s - counting threshold

- The range parameter R_o depends on the chemical composition of the target layer, which is not always known and may change with the targets age. Further on, an inhomogeneous chemical composition of the fissile layer due to the technique of target production or due to oxidization processes cannot be excluded.

This facts, in general, are not considered in the uncertainties stated for FC detection efficiencies. Unfortunately, experimental techniques which allow a direct and absolute measurement of FC detection efficiencies with an accuracy of $\lesssim 0.5$ % are not widely applicable because of an expensive equipement /4/ and/or restrictive experimental conditions, e.g. special fission chamber design (Gridded chamber /4/) and low alpha activity of the fissionable material /4/, spontaneous fissioning target nuclei /6, 7/. Therefore, efforts are required to improve the correction procedure and to guarantee the consideration of individual features of the fissile layers.

Hitherto, no use was made of the close correlation between fragment absorption and the plateau height in a corresponding FC spectrum. The unity of the physical process - slowing down of fission fragments within the fissile layer - which leads to small

pulse heights in the plateau region as well as to absorption of both fragments, suggests to interpret the plateau height as a measure of the total counting loss. In this paper, some simple relations are deduced and investigated which give a foundation of such a practice.

2. GENERAL RELATION BETWEEN ABSORPTION LOSSES AND ENERGY SPECTRUM OF PARTICLES LEAVING A TARGET LAYER

A target arrangement, consisting of a target layer (T) situated on a thick backing (B), is considered (Fig.2). Charged particles with an initial energy E_0 are produced in the target layer; the range R_0 of these particles in the target material is given by the range-energy relation $R(E)$:

$$R_0 = R(E_0)$$

We assume that each particle leaving the target by passing the surface (T-D) with an energy $E=E_0-\Delta E$ is registered in an energy spectrum; the amount of particles not registered is described by an "absorption correction" K.

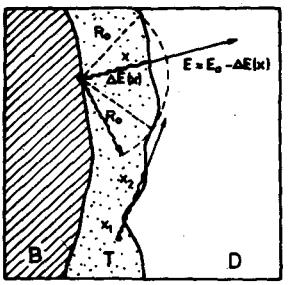

Fig.2:
Illustration of a target arrangement
B - backing
T - target layer
D - detection volume

If it is guaranteed that no trajectory of any particle leaving the target traverses the backing material, the energy loss ΔE and therefore the recorded energy E of any particle registered depends only on the path length x in the target; the relationship is given by

$$x = R_0 - R(E) \qquad (1).$$

The distribution $\varphi_x(x)$ of the path lengths (normalization: $\int_0^\infty \varphi_x(x)dx = 1$) is defined by the target geometry and the distributions of origins and emission angles of the particles produced. On the one hand, the energy distribution of the registered particles can be deduced if $\varphi_x(x)$ is known:

$$\varphi(E)dE = \varphi_x(x)\cdot(-dx) \qquad (x < R_o)$$

Considering (1), one obtains

$$dx = -\frac{dR(E)}{dE}\,dE$$

and

$$\varphi(E) = \varphi_x(R_o - R(E))\ \frac{dR(E)}{dE} \qquad (2).$$

On the other hand, $\varphi_x(x)$ defines the absorption correction: Even particles with $x \geq R_o$ are not registered in the energy spectrum, and therefore

$$K(R_o) = \int_{R_o}^{\infty}\varphi_x(x)dx = 1 - \int_{0}^{R_o}\varphi_x(x)dx\ .$$

If $K(R_o)$ is known for each range parameter in the interval $0 < R_o < \infty$, $\varphi_x(x)$ can be derived from

$$\varphi_x(x) = -\frac{dK(R_o)}{dR_o}\ \Bigg|_{R_o=x} \qquad (3).$$

A combination of (2) and (3) yields

$$\boxed{\varphi(E) = -\frac{dK(R')}{dR'}\ \Bigg|_{R'=R_o-R(E)}\cdot\frac{dR(E)}{dE}} \qquad (4).$$

This formula describes the correlation between absorption correction and energy spectrum of the particles leaving the target in a general way. It is based only on assumptions which are made in any case if absorption losses are calculated from an analytic formula:

i) rectilinear trajectories, i.e. neglect of angular straggling and scattering processes;

ii) a well defined dependence of the energy loss on the path length in the target, i.e. neglect of energy straggling and presume of a unitary range-energy relation.

The second assumption also confines the target arrangements permitted: Either the difference in the range-energy relation of backing and target material is negligible, or the geometry of

the target arrangement has to guarantee that particles which enter into the energy spectrum do not traverse the backing material. Moreover, a plane or convex target surface is demanded if the detection volume is filled with an agent causing noticable energy losses; if the energy losses in the detection volume are negligible, "wavy" surface structures can be considered by summing up the path lengths x_i of all separate sections of the trajectory (Fig.2). Essential examples of geometries which allow to deduce the energy distribution from the absorption correction using (4) are

- idealized plane target layers (analytic formulas describing the absorption losses in parallel plate fission chambers are based on this idealization in any case);
- spherical or cylindrical target arrangements with a convex target surface.

It is interesting to look at the ratio of the distributions $\varphi_1(E)$ and $\varphi_2(E)$ belonging to target arrangements which are described by different absorption corrections $K_1(R_o)$ and $K_2(R_o)$, but a unitary range-energy relation R(E): (4) yields

$$\frac{\varphi_1(E)}{\varphi_2(E)} = \left| \frac{dK_1(R') / dR'}{dK_2(R') / dR'} \right|_{R'=R_o - R(E)} \qquad (5).$$

This relation allows to investigate how the energy spectrum behaves at a given energy if the absorption correction is modified, e.g. due to a changed target thickness, target geometry, or angular distribution of particles produced in nuclear reactions (consideration of pulse transfer and anisotropy).

The formulas (4-5) describe the correlation between energy spectrum and absorption losses of particles emitted from a target layer only in a formel manner; but applicable relations can be derived if concrete models of the geometry of the target arrangement and the slowing-down of particles in the target material are introduced. Because we are interested in getting more information about the counting inefficiency of the parallel plate fission chambers used in our fission cross-section measurements /8-10/, these general relations are applied to this special problem.

3. THE PLANE LAYER MODEL

3.1 Specification of the general relation to a parallel plate fission chamber with an ideal plane target layer and isotropic emission of fission fragments

The most simple case of a target arrangement is a homogeneous, ideal plane target layer. If the backing is thick, only particles emitted "forward", with emission angles $\vartheta < \pi/2$ (see Fig.3), have a chance to be registered. We define an absorption correction $K(R_o)$ which is related to the number of "forward" particles. For an isotropic distribution of the emission angles, this correction is simple and well known (see e.g. /11/):

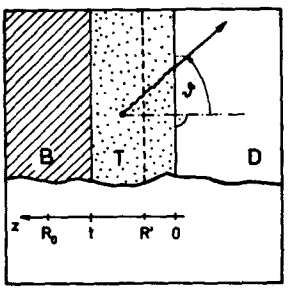

Fig.3: Illustration of the plane layer model

$$K(R_o) = \frac{t}{2R_o} \quad \text{for} \quad t < R_o \qquad (6)$$

t...target thickness

To calculate the energy distribution $f(E)$ in the whole energy range, the knowledge of $K(R')$ is required for $R' < t$, too. A corresponding correction formula can be derived easily, considering that no particle generated in a depth $z > R'$ is registered, and that the amount of registered "forward" particles in the depth range $0 \leq z \leq R_o$ is 1/2 (6):

$$K(R') = \frac{N_r}{N} = 1 - \frac{R'}{2t}$$

N....total rate of registered "forward" particles

N_r...rate of registered "forward" particles

Replacing R_o by R' in (6) and applying (4), one obtains

$$f(E) = \begin{cases} \dfrac{t}{2R'^2} \cdot \dfrac{dR(E)}{dE} & \text{for } R' = R_o - R(E) \geq t \\ \dfrac{1}{2t} \dfrac{dR(E)}{dE} & \text{for } R' = R_o - R(E) < t \end{cases} \qquad (7).$$

This model is appropriate to describe the energy spectrum of fragments from spontaneous or thermal neutron induced fission in a parallel plate fission chamber: Because each fission process generates two fragments, the rate of "forward" fragments agress with the fission rate; and an isotropic angular distribution can be assumed. One has to note that the range-energy relation depends on the fragments mass and load; therefore, the energy distribution must be calculated by summing the contributions of the individual fission products (A,Z) and kinetic energies E_k:

$$\varphi_{\Sigma}(E) = \sum_{(A,Z)} \left\{ Y_{(A,Z)} \cdot \int f_{(A,Z)}(E_k)\ \varphi^{E_k}_{(A,Z)}(E)\ dE_k \right\} \quad (8).$$

$Y_{(A,Z)}$ ... yield of fission products (A,Z)

$f_{(A,Z)}(E_k)$ ... kinetic energy distribution of the fission products (A,Z)

$\varphi^{E_k}_{(A,Z)}$ ... energy spectrum of the fission products (A,Z) with an initial energy E_k

To derive an applicable relation between the amount of fissions not detected and characteristic quantities of the energy spectrum which can be obtained experimentally, one has to specify the range-energy relation, i.e. the model of slowing-down of fission fragments in matter.

3.2. The "Triangle" stopping-power model

The most simple stopping-power model for fission fragments is the "Triangle" model (Fig.4). In this case, the range-energy relation is completely defined by the initial energy E_o and the range R_o of the fission fragment:

$$R(E) = R_o \sqrt{E/E_o}$$

The energy distribution $\varphi(E)$ for a given "sort" of fragments (E_o, R_o) then is determined by E_o and the ratio t/R_o:

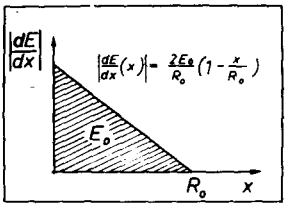

Fig.4:
"Triangle" stopping-power model for fission fragments

$$\mathcal{J}(E) = \frac{1}{4E_o\sqrt{E/E_o}} \begin{cases} \frac{t}{R_o} \cdot \frac{1}{(1-\sqrt{E/E_o})^2} & \text{for } E \le E_o(1-\frac{t}{R_o})^2 \\ \frac{R_o}{t} & \text{for } E > E_o(1-\frac{t}{R_o})^2 \end{cases} \quad (9)$$

Fig.5 shows a distribution, calculated for a "mean" fission fragment (E_o= 84 MeV) and a target thickness t = 0.05 R_o. In contrary to the usual assumption of a linear plateau, a strong rise must be stated due to the growing factor dR(E)/dE at E→0 (7).

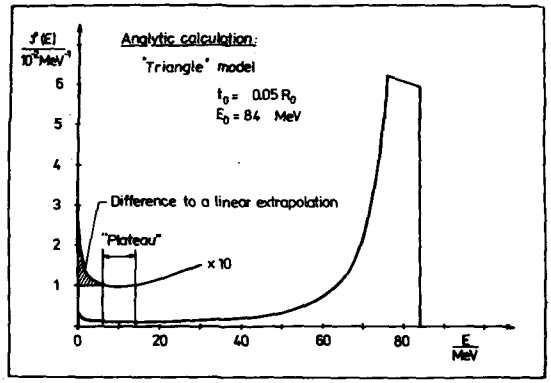

Fig.5: Energy distribution for "mean" fission fragments: A plateau region characterized by a nearly constant $\mathcal{J}(E)$ function is observed

The simple model allows to quote an explicite formula describing the amount of forward fragments which are stored in the energy spectrum with energies below E_{thr}:

$$K_{thr} = \int_0^{E_{thr}} \mathcal{J}(E)dE = \frac{t}{2R_o} \cdot \frac{\sqrt{E_{thr}/E_o}}{1-\sqrt{E_{thr}/E_o}}; \quad E_{thr} < E_o(1-\frac{t}{R_o})^2 \quad (10)$$

The detection efficiency of a fission chamber for "mean" fragments then is described by

$$\varepsilon_{FC} = 1 - K_{abs}(\frac{t}{R_o}) - K_{thr}(\frac{t}{R_o}, E_o, E_{thr}) \quad (11)$$

where $K_{abs}(t/R_o) = K(R_o)$ means the absorption correction and E_{thr} the energy which corresponds to the electronic threshold (linear dependence of the FC pulse height on the energy of the registered fission fragments assumed).

Furthermore, characteristic parameters of the energy distribution $\mathcal{J}(E)$ as the minimum value $\mathcal{J}_p$ and the corresponding energy E_p can be determined easily:

$$E_p = \frac{1}{9} E_o; \qquad \varphi_p = \varphi(E_p) = \frac{27}{16} \frac{1}{E_o} \cdot \frac{t}{R_o} \qquad (12)$$

The error made by the usual linear extrapolation of the plateau down to pulse height (energy) zero then is given by

$$\Delta K_{thr} = K_{thr}(\frac{t}{R_o}, E_o, E_p) - \varphi_p \cdot E_p = \frac{1}{16} \cdot \frac{t}{R_o} = \frac{1}{8} K_{abs}(\frac{t}{R_o})$$

and cannot be neglected.

Looking at the relations derived, the most interesting fact is that the ratio of the so-called "plateau height" φ_p to the absorption correction K_{abs}, but also to the total counting loss $K_{tot} = 1 - \varepsilon_{FC} = K_{abs} + K_{thr}$ depends neither on the target thickness nor on the range parameter R_o: This means, that the counting losses of various plane target layers behave like the plateau heights of the corresponding fission chamber spectra, even for different tnicknesses and range parameters, i.e. different chemical compositions; only identical counting thresholds are assumed.

3.3. Realistic stopping-power models

The triangle model, of course, represents only a coarse description of the slowing-down of fission fragments in matter; its advantage is the possibility to derive simple formulas which give a notion of the real relationships. Based on these experiences, the relation (7) can be discussed in a more general way:

1) A convex shape of the range-energy function R(E) at fission fragment energies below the counting threshold (< 20 MeV) as quoted in /12,13/ leads to a rise of dR(E)/dE and therefore to a rising function $\varphi(E)$ at $E \rightarrow 0$. The usual linear extrapolation of the plateau region then underestimates the counting losses caused by the counting threshold.

2) The ratio c of the energy distribution value $\varphi(E)$ at any energy point in the region $R' = R_o - R(E) > t$ to the absorption correction $K(R_o)$ does not depend on the target thickness t, but only on the range-energy relation:

$$c(E) = \frac{\varphi(E)}{\varphi(R_o)} = \frac{R_o}{R'^2} \cdot \frac{dR(E)}{dE}$$

It can be seen easily that a constant factor α changing the stopping-power values

$$\frac{dE}{dx} \longrightarrow \alpha \frac{dE}{dx} \; ; \quad R(E) \longrightarrow \frac{1}{\alpha} R(E)$$

does not influence this ratio.

These assertions keep its validity if the energy distribution is composed of separate amounts considering the individual fission products (A,Z), but also the kinetic energy distribution for each fission product (8). This leads to an interesting conclusion: The plateau height in the fission chamber spectrum should be a substantially more realistic measure of the absorption losses than the target thickness itselfs. The latter is usually determined by alpha counting and therefore related to the contents of fissionable material; the conversion to the total areal density including inactive materials, but also the estimation of a range parameter R_o suppose a well known chemical composition of the sample. Unknown contaminations or long-term modifications of the sample chemistry (e.g. oxidization processes) change the total areal density as well as the mean range of fission fragments, but the corresponding change of the absorption losses is not considered anywhere in the usual correction procedure. However, a chemical modification should influence the shape of the stopping-power curve much less than the absolute stopping-power values (related to the contents of fissionable material), and therefore a rising absorption loss is reflected in an approximatively proportional rise of the plateau height.

We want to remark that the discussed independence of the ratio c(E) on the absolute normalization of the stopping-power data explains, why estimates of fission chamber counting losses by fitting a spectrum obtained by Monte-Carlo calculations to a measured one show only a weak dependence on the stopping-power formulas or tables used in the calculations /14,15/. Consequently, the ratio plateau height / FC inefficiency obtained by a simple application of (7-8) with realistic R(E) functions is not very sensitive to the used R(E) data (detailled quantitative estimates are planned).

3.4. Application of the derived relations

The plateau height φ_p is a quantity which can be obtained experimentally, if the amplitude of the fission chamber signal is proportional to the residual energy of the corresponding fission fragment at the moment of leaving the target layer. In the case of a differential fission chamber (see Fig.1), the geometrical cut-off of the fragments tracks in the active volume violates this assumption for most of the fission fragments, leading to the characteristic fission fragment edge in the FC spectrum. But even the fragments causing the visible plateau region are fully stopped in the FC gas, and therefore the so-called "plateau region" can be well interpreted by the derived formulas if it is broad enough to be not affected by the alpha- and fission fragment edges or electronic noise (Fig.6).

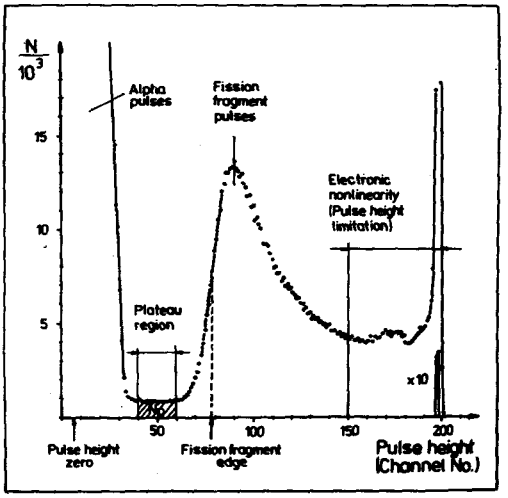

Fig.6:
Typical FC spectrum obtained at the TU Dresden. The used electronic system (current-sensitive preamplifier, fast amplifier, nanosecond stretcher /16, 8/) guarantees a signal amplitude proportional to the energy release in the FC gas as well as a broad and plane plateau region.
Target: U-235
FC gas: methane, 110 kPa
Target-electrode distance: 3 mm
Visible plateau region: ~ (9 - 14) MeV

To determine the ratio of the counting losses in various targets, one has to analyze the corresponding FC spectra which are recorded at identical experimental conditions, using the same fission chamber and electronic equipment. A plateau region is defined relative to characteristic spot points of the pulse height scale (amplitude zero; fission fragment edge; see Fig.6), and the number N_p of events in the plateau region is related to the total number N_Σ of fissions (roughly corrected for counting losses).

The ratio of counting losses, corresponding to an identical counting threshold, then is given by

$$\frac{K_{tot,1}}{K_{tot,2}} = \frac{N_{p,1}/N_{\Sigma,1}}{N_{p,2}/N_{\Sigma,2}}$$

Not only a relative, but also an absolute determination of the FC inefficiency becomes possible, if the energy scale of the recorded FC spectrum is calibrated. The experimental plateau height then is obtained from

$$\varphi_{exp} = \frac{N_p}{N_\Sigma \cdot \Delta E}$$

ΔE ... width of the analyzed plateau region

A simple method of calibrating the energy scale in FC spectra, obtained by current pulse spectrometry /16/ in a differential fission chamber, is the use of the fission fragment edge as a spot point /17/. The corresponding energy can be calculated, but it depends on the absolute stopping-power data in the fission chamber gas which is known with an accuracy of only ~ 10 % /18/. However, an experimental determination is possible /19/ and should reduce the error contribution of the energy calibration to the measured plateau height.

The total counting loss then is derived by combining the measured plateau height φ_{exp} with the plateau height / FC inefficiency ratio calculated from a realistic stopping-power model. As an example, a calculation based on stopping-power data for Br-97 and Sb-139 ions in U_3O_8 which were generated with the code STOPOW /13/, is shown in Fig.7. The distribution $\varphi_\Sigma(E)$ was

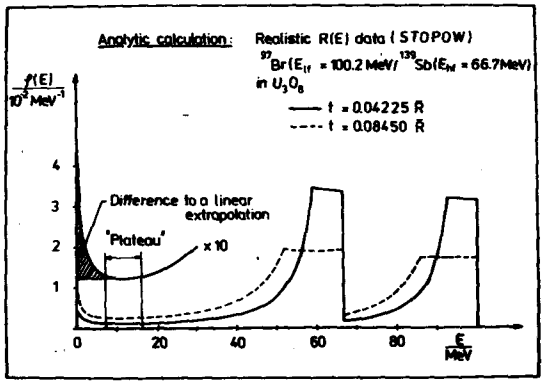

Fig.7: Energy distribution $\varphi_\Sigma(E)$ calculated with realistic stopping power data for a light (Br-97) and a heavy (Sb-139) fragment

assumed to consist of a light fragment and a heavy fragment component with corresponding yields of $y_{lf}=y_{hf}= 0.5$. A plateau height $\mathcal{Y}_p= 1.23\cdot10^{-3}$ $(MeV)^{-1}$, averaged over the energy range E = 8...16 MeV, was obtained for a target thickness $t=0.04225\ \bar{R}$; $\bar{R}$ is the mean range (derived from the ranges R_{lf} and R_{hf} which were determined from the range-energy data): $(1/\bar{R}) = (1/R_{lf}) + (1/R_{hf})$. The relations

$$K_{abs} = 0.0172 \frac{\mathcal{Y}_{exp}}{10^{-3}(MeV)^{-1}} \qquad (13)$$

$$\Delta K = 0.0036 \frac{\mathcal{Y}_{exp}}{10^{-3}(MeV)^{-1}} \qquad (14)$$

K_{abs}... absorption correction

ΔK ... additional counting loss due to the rise of the distribution $\mathcal{Y}_\Sigma(E)$ at $E \longrightarrow 0$ (difference to the linear extrapolation of the plateau region)

can be derived from this calculation. A range parameter R_{exp} which reproduces the FC inefficiency obtained from (13-14) with the usual correction procedure (linear extrapolation!) then is given by

$$R_{exp} = 24.0 \frac{10^{-3}(MeV)^{-1}}{\mathcal{Y}_{exp}} t \qquad (15)$$

3.5. Extension to non-isotropic emission of fission fragments

Finally, we want to remark that the formalism summarized in the formulas (4-5) is capably to describe energy distributions of fission fragments leaving a plane target layer even for fissions induced by fast neutrons: Because of the known absorption corrections considering the fission fragment anisotropy and the pulse transfer from the incident neutron /20-22/, the function $\mathcal{Y}(E)$ can be obtained by analytic calculations. As an example, the ratios of the plateau heights in "forward" and "backward" geometry at a neutron energy E_n to the plateau height for thermal fission, deduced from (5) and the absorption correction formulas from /21,22/, are:

$$\frac{\varphi_{\text{forward}}}{\varphi_{\text{thermal}}}(E) = \frac{3}{3 + a(E_n)} \left(1 - \frac{R'^2}{t^2} \frac{v_o^2}{v^2}\right)$$

$$\frac{\varphi_{\text{backw.}}}{\varphi_{\text{thermal}}}(E) = \frac{3}{3 + a(E_n)}$$

with $R' = R_o - R(E)$

$a(E_n) = \frac{W(0^\circ)}{W(90^\circ)} - 1$ (anisotropy of the angular distribution of fission fragments at E_n)

v_o... velocity of the centre-of-mass system in the lab. system

v ... velocity of the fission fragment in the centre-of-mass system

By combining these relations with the known absorption loss formulas, it becomes possible to estimate counting losses from plateau heights measured for fast-neutron induced fission. This is important, if targets of non-fissile nuclides must be investigated, e.g. in the case of U-238.

(References are listed in part II of this publication!)