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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ  
YEREVAN PHYSICS INSTITUTE

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FISSION AS A FILTER FOR THE STUDY OF HEAVY  
HYPERNUCLEI AND OTHER EXOTIC ATOMS AND NUCLEI



ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

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Միջուկների ճեղքումը որպես ջնիշ ծանր շիջումի միջուկների  
ԵՎ ԱՅԼ ԷԿՉՈՏԻԿ ԱՏՈՄՆԵՐԻ ԵՎ ՄԻՋՈՒԿՆԵՐԻ  
ՎԵՏԱՉՈՏՈՒՅՑՈՒՆՆԵՐՈՒՄ

Միջուկների ճեղքումը առաջարկվում է օգտագործել որպես կտիչ ծանր հիպերմիջուկների, պրոնային խորը կառված առումների, պրոնային, ղ-մեզոնային և հակապրոտոնային միջուկների, ինչպես նաև միջուկի միջավայրում Δ-մեզոնանսի վարքի հետազոտություններում: Նախապահմանի միջուկների հետ առանց հետաքրքրվածի ռեակցիաներում բացվածքի անկյան մեթոդի կիրառմամբ կարելի է հասնել ֆոնի ուժեղ ճնշմանը: Քննարկվում են ճեղքման ակտիվ թիրախներ՝ հիմնված ցածր ճնշման համեմատական խցիկների վրա:

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I. Introduction

The use of nuclear fission as a reaction filter for the dynamics of low-to-intermediate energy nucleus-nucleus collision study has been widely exploited over the past decade [1]. The nuclear fission as an inelastic reaction tag has been also used in the total absorption cross section measurement experiments carried out by real [2, 3] and virtual [4] photons on uranium isotopes. The delayed fission as a tag has been proposed [5] and used also in the heavy (Bi, U) hypernuclear lifetime measurement experiments with antiproton [6, 7], electron [8] and photon beams [9].

Several properties of the fission reaction contribute to its usefulness as a reaction filter.

The large Coulomb field between the fragments at scission produces highly energetic fragments (~ 80-100 MeV/fragment) that can be easily differentiated from other reaction products. For liquid drop fission (i.e. the fission at  $E_{ex} \geq 20$  MeV excitation energies) the average total kinetic energy released in fission is given by a simple Coulomb expression

$$\langle E_k \rangle = 0.119 Z^2/A^{2/3} + 7.3 \text{ MeV,}$$

where Z and A refer to the fissioning nucleus. Furthermore, the released average fission kinetic energy is nearly independent

on the excitation energy of the fissioning nucleus; i.e. the most of the heat of the system at scission is converted directly into excitation of the fragments.

The mass division is binary and approximately symmetric. Further, the binary character of fission insures that the fragments must separate axially, with equal momenta in the center-of-mass system.

Any deviation of the average fragment separation angle ( $\theta_{AB}$ ) from  $180^\circ$  must therefore be associated with the dynamics of the formation process and can be used as an additional criterium to select reactions in which we are interested in. The basic concept behind the fission fragment angular correlation technique [10, 11] is that any deviation from co-linearity exhibited by the separating fragments must on the average resulted by the recoil momentum carried by the fissioning nucleus. Thus, measurement of the fragment-fragment folding angle,  $\theta_{AB}$ , translates into a determination of the fissioning nucleus recoil momentum. In Fig. 1 a schematic diagram of a representative fission-fragment folding-angle technique is shown. The symbols  $V$ ,  $V_1$ ,  $V_1'$  represent the velocities of the fissioning system, fragment  $i$  in the laboratory system and fragment  $i$  in the center-of-mass system, respectively.

The fission fragment angles in the lab. frame  $\psi_1$  are related to the fragment angle in the center-of-mass system  $\theta_{cm}$  by the following [10, 11]:

$$\begin{aligned}\tan \psi_1 &= \sin \theta_{cm} / (X_1 + \cos \theta_{cm}) \\ \tan \psi_2 &= \sin \theta_{cm} / (X_2 - \cos \theta_{cm}).\end{aligned}$$

where  $X_1^2 = (V/V_1')^2$ .

For high energy fission, symmetric division is the most probable mode. Because of momentum conservation the fragment velocities are equal, therefore maximum coincidence value  $X^2$  must be determined.

The fission fragment angular correlation technique was employed for the recoil momentum determination in the CERN heavy hypernuclei lifetime measurement experiments [6, 7].

For preactinide nuclei ( $Z \leq 82$ ) the fission probability strongly depends on the excitation energy  $E_{ex}$ , when  $E_{ex} \leq 100$  MeV. For example, the photofission cross section of the Bismuth nucleus at photon energy  $E_\gamma = 135$  MeV is  $\sim 10^6$  times larger than that at  $E_\gamma = 20$  MeV [12]. In the Fig. 2 the calculated fission probabilities as a function of the excitation energy for  $Z = 81-84$  nuclei are presented. The calculation performed in the framework of the statistical model [13] following Martins et al. [14]. Here, for the comparison the experimental values of fissilities for Bi, received in photofission experiments [15] are shown. For each photon energy the excitation energy of nucleus was defined by Monte-Carlo cascade program [16].

The strong dependence of the fission probabilities on the excitation energy can be used as a tag for differentiating the reactions with high and low values of excitation energy.

## 2. Investigation of Heavy Hypernuclei by Fission Fragment Detection

The main source of background in the hypernuclear research experiments is the quasi-free production of  $\Lambda$  and  $\Sigma$  hyperons (see, for example [17]). In principle, the more complete registration of each individual event makes it possible to discriminate feasible sources of background. In the KEK experiments with stopped kaons [18] and in the  $(\Pi, K)$  associated production reaction [19] the background has been suppressed in the case of active plastic scintillator target by "tagging" in thorough analysis. As it is pointed out by Yamazaki [20], in connection with the DAPHNE hypernuclear program [21], the method of the  $\Lambda$  detection is very powerful to suppress background from quasi-free  $\Lambda$  and  $\Sigma$  production (see also [22]). The thin target implemented in TPC as an active target for  $\Sigma$ -hypernuclei formation experiment at KAON has proposed by Paul [23].

We propose to carry out investigations on heavy hypernuclei using nuclear fission after the decaying of bound hyperons as a tag for the study of associated ejectiles. Indeed, in the case of heavy hypernuclei, the nonmesonic decays  $\Lambda + N \rightarrow N + N$ ,  $\Sigma + N \rightarrow N + N$  will predominate and more than 160 MeV energy is liberated. Then one may expect that the residual nuclei can be excited to energies substantially exceeding the fission barriers. The expected fission probability of Bi nuclei, for example, after nonmesonic decay of  $\Lambda$  hyperon ranges from 0.05 to 0.25 [7].

As to background quasi-elastic production of  $\Lambda$ ,  $\Sigma$  hyperons, usually it is believed that in the "quasi-free" processes the hyperon is in the free space, but some part of the quasi-free hyperons does not fly away, as the rescattering of  $\Lambda$  and  $\Sigma$  brings them back to the "bound" hypernuclei. This multistep process has been considered as possible way of the heavy hypernuclei formation in the  $(\gamma, K^+)$  reactions [24] as well as with stopped antiprotons [25]. The efficiency of this multistep process was estimated to be 10-20%

Therefore about 80-90% of the quasi-free process claiming that not only the pion or kaon, but also the hyperon is in free space. In this case the possible excitation energies of residual nucleus are much smaller ( $\leq 20$  MeV). As a result the probability of nuclear fission is very low (see Fig. 2). Thereupon the simultaneous detection of the fission fragments with formation particles results in elimination of the background reactions for at least 80-90% of events.

By the similar reason this technique can be used in the  $\Sigma^-$  [26, 29], and  $\Xi^-$  [29] Coulomb assisted hybrid bound states, or in double and H hypernuclei search experiments in  $(K^-, K^+)$  reactions [30].

The  $\Lambda$  hypernuclei may be studied even without measuring the formation particles, if one has a suitable way to identify the hypernuclei. One of the ways is to detect fission fragments from the "delayed" processes [5] by means of the recoil distance technique [31]. The detection of fission fragments in delayed processes in coincidence with the decay particles

allows to perform "delayed particle spectroscopy", detecting e.g.  $\gamma$ -quanta from  $\gamma$ -cascade of hypernuclei. In experiments with stopped  $K^-$  or kaons in flight on preactinide nuclei when  $(K, \Pi)$  reaction is the single inelastic one, the use of the fission as a tag is enough to identify the hypernuclei production, because in the case of elastic or quasi-elastic processes, the fission probability is low.

### 3. Fission as a Filter for the Study of Deeply Bound Pionic Atoms, Pionic, $\eta$ -Mesonic and Antiprotonic Nuclei

The traditional method to measure energies and widths of pionic atom states, by looking at the X-rays from the electromagnetic decay has severe limitations as  $Z$  increases. The properties of 1S states are not known for  $Z$  larger than about 14, of 2P states for  $Z$  larger than about 35, etc (for instance, for  $Z \geq 14$  the 2P absorption width is about 2-3 orders of magnitude larger than the electromagnetic one due to the X-transition 2P-1S and therefore this X-transition is very difficult to observe). For heavy nuclei, like Pb, the information is available on the 3d and 4f levels. If the separation between levels of more deeply bound states is smaller than the width of these states the experimental observation of these individual states would be highly problematic. However, all standard pionic atom potentials predict widths which are appreciably smaller than the separation between levels [32-33]. This

makes a clear case for their experimental observation in some nuclear reactions if an adequate reaction is used.

The list of suggestions to produce directly these states without going through a cascade as in the X-ray technique, is long: pion transfer reactions  $(n, p)$  [33, 34, 35],  $(n, d)$  [36],  $(p, {}^2\text{He})$ ,  $(p, {}^3\text{He})$  [34-36],  $(\Pi^-, \Pi^+)$  [37],  $(\Sigma^-, \Lambda)$  [38], pionic decay of  $\Lambda$ -hypernuclei [39], resonant production by photons [40], resonant Compton scattering [41], radiative trapping of pions in the flight [42].

A search for deeply bound pionic states by means of  ${}^{208}\text{Pb}(n, p)$  reaction, undertaken at TRIUMF using the CHARGEEX facility shows no significant signal in 10 MeV window of the predicted binding energy for  ${}^{208}\text{Pb}\Pi^-$ . The result gave an upper limit on the cross section of 0.3 mb/sr [43]. In initial plane wave calculation predicted a cross section on the order of 1 mb/sr for the  ${}^{208}\text{Pb}(n, p)$  reaction leading to the 1S state in pionic  ${}^{208}\text{Pb}$ . The discrepancy with plane wave calculation was later explained by the large effect of distortion and the large momentum mismatch in the  $(n, p)$  pion transfer reaction [35].

Practically in all above mentioned reactions the ratio effect/background is  $\sim 10\%$  in the best cases. To increase this ratio one must use additional tags.

In this paper the nuclear fission that takes place after the bound  $\Pi^-$ -meson absorption by the nucleus is suggested as an additional criterion for separation of deeply bound states. About 135 MeV energy is liberated as a result of bound pion

absorption. A pair of nucleons are mainly involved in the absorption process because of the requirement of the conservation of energy and momentum. It follows that the liberated energy ( $\sim 135$  MeV) is shared between the nucleons. Depending on the point of the absorption and the direction of the recoil motion, the recoiled nucleons can either escape without interactions or undergo collisions with other nucleons and thereby initiate the internuclear cascades bringing to particle evaporation and fission. The mechanism of the absorption and the decay of the nucleus has already been considered theoretically [44-48] and experimentally [49-53] in the case of stopped  $\pi^-$ , when the pion absorption takes place in the peripheral region of the nucleus (mainly from 4f orbit) in the case of heavy nuclei. The direct measurement of the fission probability has been performed for the stopped  $\pi^-$  absorption reaction of  $^{209}\text{Bi}$  by Shinohara et al. [53]. The fission probability,  $P_f$ , was determined as  $P_f = (3,01 \pm 0,34) \cdot 10^{-3}$  with the aid of the pionic X-ray measurement. With an assumption that the equilibrated nucleus is  $^{208}\text{Pb}$ , the excitation energies of the system are derived to be located in a region of rather low energy range compared with the initial excitation energy of 140 MeV (see Fig. 2). It is interesting to compare this result with the value of Bi nuclei fission probability by 100-140 MeV photons [12, 15]. Photons of these energies as well as stopped pions, are absorbed by nucleon pairs, but unlike the latter, the absorption takes place in each part of nucleus volume. Owing to this the excitation energies of the equilibrated

system are located in a region close to the initial photon energy and the fission probability is  $\sim 0.1$ . Therefore, the expected fission probability of deeply bound pionic atoms, when pion absorption occurs from S or P orbits, will range from  $3 \cdot 10^{-3}$  to 0.1. By analogy with hypernuclei, one can expect that in case of background reactions the fission probability is lower than the expected values in case of pion absorption from S or P orbits. However, in the formation reactions of deeply bound pionic states, unlike the hypernuclei production reactions, only a part of background is conditioned by quasielastic production mechanisms. Another part caused by inelastic processes, absent in the hypernuclei case, but also bringing the nuclei to excitation and fission.

Therefore, each reaction used to produce the deeply bound pionic state must be examined individually.

At present the fission probabilities for exclusive reactions are absent.

Theoretical calculations can be provided with the framework of Intranuclear Cascade (INC) Monte-Carlo models that allow to describe the development of the cascade with reliable accuracy due to the energetic probe absorption and the subsequent deexcitation by evaporation-fission processes.

Excitation energy distribution for neutron interactions with nuclei of  $^{209}\text{Bi}$  at 420 MeV energies we have obtained with the use of the INC of Ref. [54]. The obtained excitation energy distribution  $N(E_{ex})$  is shown in Fig. 3. The peak in 140 MeV energy region obviously is connected with pion production and

their further absorption. This result is more clearly shown in Fig. 4, where the mean excitation energy  $\langle E_{ex} \rangle$  is shown as a function of produced proton momentum. The mean value of the excitation energy in the region immediately below the pion production threshold, where the bound pionic states are expected, is 47 MeV. Therefore, the fission probability of the formed compound nuclei ( $Z \leq 82$ ) is  $\leq 6 \cdot 10^{-5}$  (see Fig. 2). Out of  $6 \cdot 10^4$  events only in three ones the angles of the protons produced appear in the angle interval  $\pm 2^\circ$ , that corresponds the geometry of the experiment [43]. For these 3 events the mean excitation energy is  $\sim 37$  MeV.

Thus, using only the act of fission in the experiment  $^{209}\text{Bi}(n, p) ^{209}\text{Bi}\pi^-$  to search deeply bound pionic states the background may be reduced for more than 50 times.

However, this is not the limit. The matter is that in case of background inelastic reactions not only excitation energy passes to the nuclei, but also the recoil momenta correlated with it [55]. In case of deeply bound pionic atom formation the recoil nucleus obtains some momenta conditioned by the production reaction kinematics.

Therefore, the determination of the recoil momentum by the measurement of the fragment separation angle can be used as an additional criterium to select the reaction in which we are interested in. The strong effect of background suppression may be reached by the employment of this technique in recoilless reactions with preactinide nuclei. Indeed, with the use of the INC it is possible to show that in the case of background re-

actions small values of momentum transfer are correlated with the small values of excited energies. This may be seen in Fig. 4 of Ref. [56], where the calculated mean excitation energy  $\langle E_{ex} \rangle$  of compound nuclei formed after the interaction of monochromatic photons of 500, 900 and 1000 MeV energies with  $^{197}\text{Au}$  nuclei, as a function of its total momentum  $\vec{p}$  are shown. For the  $\vec{p} \leq 100$  MeV/c the  $\langle E_{ex} \rangle \approx 35$  MeV. Therefore, the fission probability for background reactions with low value of recoil momentum will be very low (for  $Z \leq 82$ ;  $\langle E_{ex} \rangle = 35$ ;  $p_f \leq 10^{-6}$ ).

By this reason the recoilless reactions like  $(n, d)$ ,  $(p, ^2\text{He})$ ,  $(d, ^3\text{He})$ , [34-36] in preactinide nuclei are very suitable for the deeply bound pionic states search purposes.

Practically all above mentioned reactions and their isotopic invariants can be used for the pionic nuclei [57] search.

Such a technique can be employed even with more success in the case of recoilless  $(\pi^-, P)$  [58],  $(\pi^+, P)$  [59] and  $(P, P)$  [60] reactions for the deeply bound double pionic atoms,  $\eta$ -mesonic and antiprotonic nuclei research. For these reactions the mean value of excitation energy after the absorption of two pions,  $\eta$ -mesons and antiprotons is higher than in the case of deeply bound pionic atoms, where only one pion is absorbed and the expected values of fission probability for Bi nuclei is  $\sim 0.1$ . As the expected value of fission probabilities for the background reactions is  $\leq 10^{-6}$ , therefore the ratio effect/background can be increased  $\sim 10^5$  times in above mentioned reactions, and  $10^3$ - $10^4$  times in deeply bound pionic atom search

experiments.

It is interesting to note that, in endothermic recoilless reactions, when the primary particle momentum exceeds the "magic" value (at which the recoil momentum is zero) the nuclei receive recoil momentum directed back to primary particle momentum. This fact may be used for the further suppress of background reactions.

The use of fission folding-angle technique for the study of interactions of  $\gamma$ -quanta with uranium nuclei in the resonance energy region, where the fission probability is  $\sim 100\%$  [2], allows one to select coherent processes and carry out investigation of the A-resonance production mechanisms in nuclear environment [61, 62]. The uranium target may be used also in the other cases, that will permit us to increase the absolute rate of the reactions examined. Yet, in this case the background reactions may be suppressed only kinematically, by the recoil momentum choice measured with the help of fission fragment folding-angle technique.

#### 4. Active Fissile Targets Based on Low Pressure Multiwire Proportional Chambers

We propose to detect the fission fragments and measure their directions by means of low-pressure multiwire proportional chambers (LPMWPC) [63] or multi-step chambers (LPMSC) [64]. The low-pressure operation mechanism of detectors, like MWPCs and MSCs is characterized by a fast avalanche growth

and high gain, resulting in excellent timing [65, 66] and imaging characteristics. Typical time resolution of larger, position sensitive detectors are of the order of few hundred PS. A position resolution of about few hundred  $\mu\text{m}$ , when measuring charges induced on cathode wires or strips, connected to commercial tapped delay lines can be obtained.

Due to high values of the reduced electric field, positive ions produced during the avalanche process are collected within about 1  $\mu\text{s}$ , more than an order of magnitude faster than at normal gas pressure. This fast collection time considerably reduces space charge effects, typical to avalanche formation, thus allowing a high rate operation to the order of  $10^5 \text{ c/s.cm}^2$ .

These detectors are very slightly sensitive to background radiation, especially that of relativistic particles.

Two kinds of fissile targets are suggested. In the first case, the thin ( $\sim 1 \text{ mg/cm}^2$ ) target located at low grazing angle with respect to the incident beam to increase the effective length of the target up to  $\sim 10 \text{ mg/cm}^2$ , surrounded by LPMWPCs or LPMSCs which detect the fission fragments and measure their directions without touching the incident beam (Fig. 5). This kind of active target can be used in intense beams. Delayed fission can be investigated by means of this experimental set-up as well selecting geometry corresponding to "recoil distance technique" [31].

In the second case an active segmented target consisting of thin ( $\sim 1 \text{ mg/cm}^2$ ) fissile targets directly coupled to the LPMWPCs or LPMSCs are proposed (Fig. 6). The active target with the

total length of few hundred  $\text{mg}/\text{cm}^2$  can be constructed by this way. The segmentation allows better determination of the vertex, and this appears to be helpful in improving the energetic resolution in spectroscopic measurements. The fission fragments or recoil nucleus traversing target foils yield large number of secondary electrons, in proportion for their energy loss in foil [67]. These electrons can be measured in LPMSCs providing a tool for parallax free imaging of fission fragments, which is prime importance for fission fragment folding-angle technique employment purposes.

The good position resolution of LPMSCs ( $200 \mu\text{m}$ ) allows one to carry out the delayed fission detection by means of the modified [68] recoil-distance technique.

The LPMWPCs can be used in cases when the detection of one of the fission fragments is enough for the background suppression, e.g. in experiments on heavy hypernuclei or deeply bound pionic states with the help of  $^{209}\text{Bi}(n,p)$   $^{209}\text{Bi}\alpha$ -reactions. Such kind of active uranium targets have been constructed [69] and exploited in photo-fission [3] and electro-fission [4] experiments. In these experiments the registration of only one fission fragment with the help of LPMWPCs permits to suppress the electromagnetic background more than  $10^6$  times, and separate distinctly the nuclear absorption of real and virtual photons. This equipment has worked stable in photon and electron beams with the  $10^9$  phot/s and  $10^7$  e/s (duty factor  $\sim 1\%$ ) registering with the 100% efficiency the fission fragments and separating them among high background of relativ-

istic particles [70].

The expected time resolution of the LPMWPCs or LPMSCs is of the order of few hundred ps (FWHM), which may be of prime importance for fast trigger purposes.

## 5. Summary

In this paper the use of fission reactions as a tag for the study of heavy hypernuclei and other exotic atoms and nuclei are suggested. The strong effect of background suppression may be reached by the employment of the fission fragment folding-angle technique in deeply bound pionic atoms, pionic,  $\eta$ -mesonic, antiprotonic nuclei search experiments with the help of recoilless reactions on the preactinide nuclei.

The use of this technique for the study of interactions of  $\gamma$ -quanta with uranium nuclei allows one to select coherent processes and carry out investigation of the  $\Delta$ -resonance production mechanism in nuclear environment.

Two kinds of active fissile targets based on LPMWPCs and LPMSCs are proposed which can find an employment in experiments at CERN, FILAC and KAON. These active targets have time resolution (FWHM) of the order of few hundred ps and can be used also as a fast trigger and as a start detector in time of flight measurements.

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Figure Captions

Fig. 1. Vector diagram of the fission fragment folding-angle technique. The symbols are defined in the text.

Fig. 2. Nuclear fissility plotted against excitation energy for  $Po^{209}$ ,  $Bi^{209}$ ,  $Pb^{208}$ , and  $Tl^{208}$  nuclei. In the case of  $Pb$  and  $Tl$  the fissility values for  $A=207$  and  $209$  are shown. The points refer the experimental values for Bismuth (from Ref. [15]).

Fig. 3. Excitation energy distributions  $N(E_{ex})$  of compound nuclei formed in the interactions of 420 MeV neutrons with  $Bi^{209}$  nuclei calculated by means of an INC Monte-Carlo code [54]. Total number of interactions is  $6 \cdot 10^4$ .

Fig. 4. The calculated mean excitation energy  $\langle E_{ex} \rangle$  of compound nuclei formed after the interaction of 420 MeV neutrons with  $Bi^{209}$  nuclei, as a function of the produced proton momentum.

Fig. 5. Sketch of the active target, which can be used in intense beams.

Fig. 6. Sketch of the active multisection target. A MWPC (A) with a preamplification (PA) step is used for the time and position measurements of the secondary electrons emitted when a nucleus traverses the target plane.

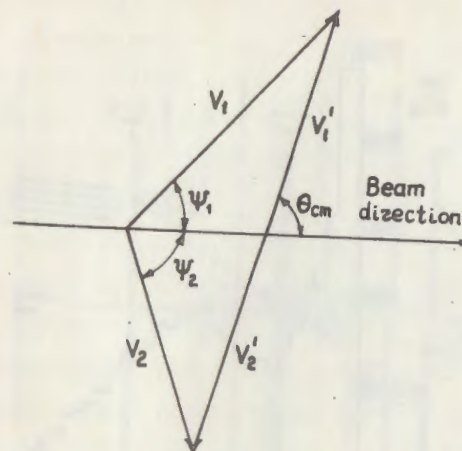


Fig 1

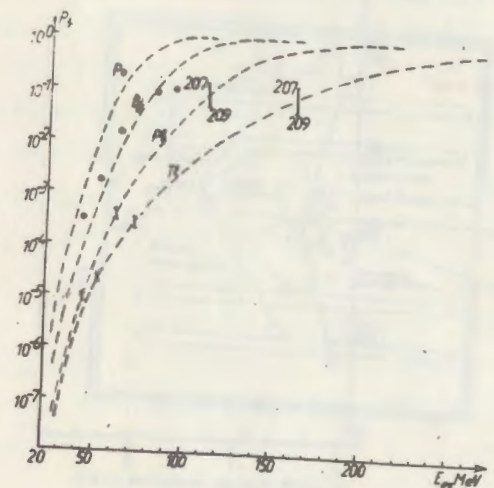


Fig.2

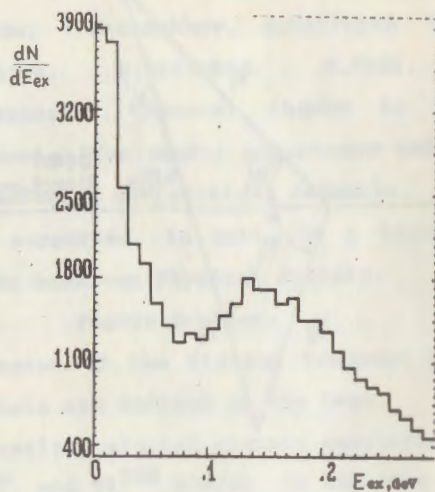


Fig. 3

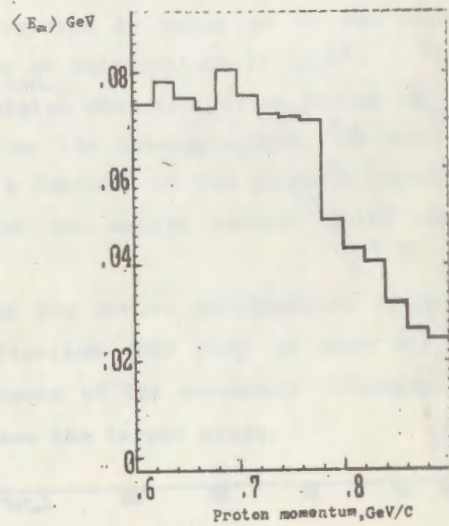


Fig. 4

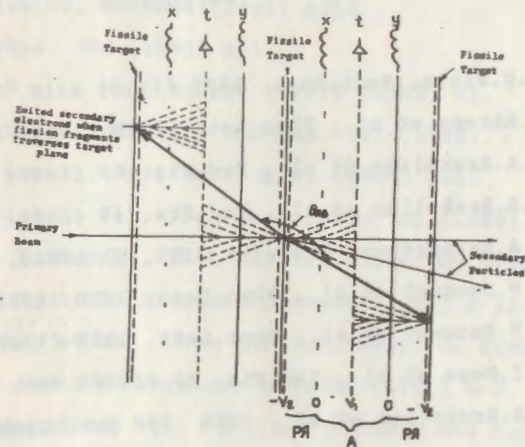


Fig 5

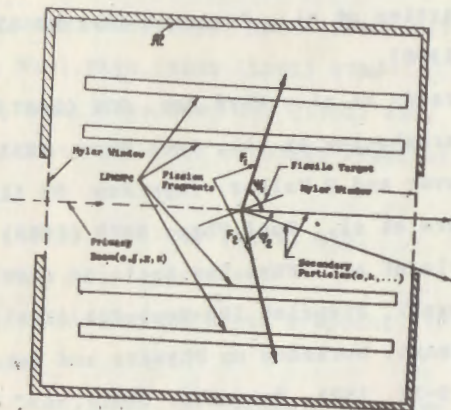


Fig. 6

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