High-energy fission cross sections induced by deuterons on ^{232}Th and protons on ^{nat}Pb targets

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Total fission cross sections induced by deuterons with energy of 1.6, 2.5, and 4.0 GeV on ^{232}Th targets and by protons on ^{nat}Pb targets at energy of 2.0 GeV were measured during irradiations at the Nuclotron accelerator, JINR, Dubna. The fission cross sections induced by deuterons on ^{232}Th were determined by using solid-state nuclear track detectors as 1277 ± 216, 1232 ± 207, and 1153 ± 198 mb, which corresponded to the energies mentioned above. The total fission cross section of protons on ^{nat}Pb was estimated by the same method as 131 ± 30 mb. These results were compared to the previous systematic parametrization of proton-induced fission, and new values for the parameters of deuteron-induced fission on actinides ^{232}Th and ^{238}U as well as of proton-induced fission on ^{nat}Pb were deduced. Fitting results obtained for deuterons on actinides are discussed and are compared to the results for protons.

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Fission induced by light particles at high energies is quite different from the low-energy process. Studies on low-energy fission involve reactions that proceed through the stage of compound nucleus formation due to fusion of the projectile with the target [1]. In this case, the fissioning nucleus is well defined and has definite excitation energy. The cross section of fusion diminishes and may even vanish at projectile energies higher than 50–100 MeV/nucleon [2]. The fission process at low incident energies is about equal to the reaction cross section since the direct process cross section is a small fraction of the reaction cross section and preequilibrium processes are improbable. As the projectile energy increases, the compound nucleus formation cross section becomes progressively smaller than the reaction cross section due mainly to the increasing probability of particle emission. Fission induced by high-energy particles is described as a two-step process: Collisions induce the rapid formation of an excited prefragment, which gets deexcited by particle emission and/or fission [3,4]. In heavy compound nuclei, fission is a competing decay mode to other mechanisms, especially if the compound nucleus formed has a high angular momentum. Therefore, the compound nucleus cross section is the sum of the cross sections that correspond either to evaporation residues or to pairs of fission fragments. The high-energy part of the fission cross sections represents the energy region in which the compound nucleus formation is restricted, whereas, more rapid processes, such as fragmentation reactions take place by considering that inelastic cross sections at high energies remain stable with increasing energy. Fission studies at intermediate and high energies are of great interest for the research of the reaction mechanisms because fission can be produced directly by the projectile-target interaction at both large and small impact parameters but also because it can be the ending effect of spallation reactions.

In the evolution of fission studies, which is connected to the history of accelerator energies and facilities in the transition region, 70–1000 MeV, the fission cross-section data and their evaluation are missing from the literature, especially for light projectiles heavier than protons. Most of the data in the literature refer to fission induced by protons, such as in the extended report by Hufner [5] of proton-induced reactions. The systematics of Viola *et al.* [6] also includes fission cross-section data in a wide range of proton energies. The experimental data of proton-induced fission cross sections for subactinides, such as ^{nat}Pb and ^{209}Bi, in the energy range below 1 GeV, were reproduced by calculation, and a systematics of fission cross section has been derived [7].

A multitude of data on the fission mechanism has been presented that concerns deuterons and, especially, α particles as projectiles but mostly at low energies [8–14]. Limited results are published on fission as a parallel product of a high-energy reaction mechanism, i.e., spallation fission. Some of those studies [3,4,15,16], which refer to proton- and deuteron-induced spallation or fission, underline the different origins of fission at lower energies. In recent years, fission research has been extended to higher energies at GeV due to the applications in accelerator-driven systems. However, limited experimental data have been presented in the literature with regard to deuteron projectiles [17–19], and even less have been presented for α particles [20], although they are very useful for the comparison of the experimental data to both statistical and dynamical models of fission [2]. Some of those results, which refer to high-energy deuterons on actinide and subactinide targets [17,19], were obtained during experiments at the Nuclotron accelerator, JINR, Dubna, in the frame of the international collaboration "Energy plus Transmutation" [21].

In the present Brief Report, the total fission cross section of ^{232}Th due to deuteron beams of 1.6 and 2.5 GeV was determined as a continuation of a previous paper [19] that referred to 4-GeV deuteron-beam-induced fission on actinides (^{238}U, ^{235}U, and ^{232}Th) and subactinides (^{209}Bi and ^{197}Au). In addition, the total fission cross section of ^{nat}Pb, induced by 2-GeV protons, was estimated by evaluating previous irradiation data. Cross-section determination was achieved by using fissionable targets, manufactured in the CNRS,

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TABLE I. Total fission cross-section data (mb).

Energy (GeV)	$^{nat}Pb\ (p,f)$	$^{232}Th\ (d,f)$
2.0	131 ± 30	
1.6		1277 ± 216
2.5		1232 ± 207
4.0		1153 ± 198

Strasbourg, France, by evaporation on Lexan foils [22]. Lexan sheets were also used for the detection of fission fragments. The mass of ^{232}Th targets was measured using α- and γ-ray spectrometry at the Laboratory of Nuclear Physics of the Aristotle University of Thessaloniki, Greece, whereas, the mass of ^{nat}Pb was given by the manufacturers. A detailed analysis of the instrumentation and method applied has been presented in a previous paper [19]. The total fission cross-section data, obtained in the current Brief Report, are presented in Table I.

The fission cross section as a function of proton energy depends on parameters of different physical meanings according to the evaluation performed for proton-induced fission on subactinides in the medium-energy region by using calculation codes [7]. The following equation reproduces well the experimental data that describe the systematics of the fission cross section at energies below 1 GeV [7]:

$$S = P_1\{1 - \exp[-P_2(E_p - P_3)]\}, \quad (1)$$

where P_1 is the fission "saturation cross section" that corresponds to the maximum of the cross-section systematics, P_2 is the "saturation constant," which describes the increasing rate of the fission cross section with energy up to a maximum value, and P_3 is the "apparent energy threshold" for the projectile-target system studied. In Ref. [23], an extension to higher proton energies was provided for actinides and for subactinides as well. The improved systematics introduces an additional fitting parameter P_4 to Eq. (1) to reproduce the decrease in the fission cross sections at high energies. The new formula is given as

$$S_{new} = S\,(1 - P_4 \ln E_p). \quad (2)$$

The parameter P_4, named by us as the fission "decrease constant" depends on the projectile-target system. The decreases in the fission cross sections at intermediate and high energies are attributed to the increase in more violent processes than fission as the energy of the projectile increases [5].

This fitting successfully describes the fission cross-section's behavior versus proton energy, especially for actinides. In the case of subactinides, there are contradictory results in the literature, depending on the experimental data selected [23]. Proton-induced fission on ^{nat}Pb targets presents an unclear situation as to whether the cross sections continue to be stable or present a decrease (Fig. 1). A saturation of fission cross sections with energies at the intermediate and high ranges has been presented according to data published after 2001 [24]. The total fission cross section at 2-GeV protons on ^{nat}Pb, estimated in the present Brief Report, matches the experimental data of earlier papers [22,24,25]. By taking into account all available data on proton-induced fission on ^{nat}Pb presented until today [22,24–28], saturation can be accepted for total fission cross sections at high energies. Therefore, we performed the same fitting process by including the recent and our experimental results for ^{nat}Pb by using Eqs. (1) and (2). Both equations reproduce well the experimental data (Table II) with Eq. (2), which appears to be more successful than Eq. (1). The necessity of additional experimental data, especially at high energies, is apparent to clarify the behavior of the ^{nat}Pb fission process at that energy range.

Typical fitting curves of fission cross sections are given in Fig. 2 as a function of proton energy for ^{232}Th and ^{238}U, according to the results presented in Ref. [23]. The general observation in Fig. 2 is the similar behavior of the fission

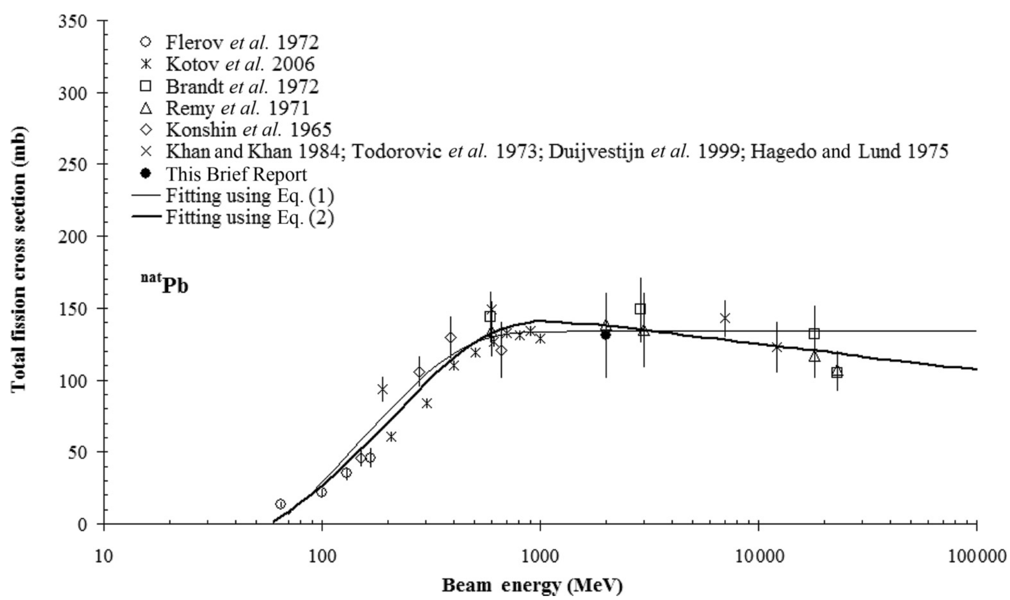

FIG. 1. Proton-induced fission cross section on ^{nat}Pb. The solid curves represent the fitting according to the parameters given in Table II.

TABLE II. Fitting parameters determined on the proton-induced fission cross-section data of ^{nat}Pb.

	Using Eq. (2) $r^2 = 92\%$	Using Eq. (1) $r^2 = 89\%$
Saturation cross section P_1 (mb)	198 ± 24	134 ± 9
Saturation constant $P_2 \times 10^{-3}$ (MeV^{-1})	4.2 ± 0.7	6.3 ± 0.9
Apparent threshold energy P_3 (MeV)	58 ± 13	62 ± 13
Decrease constant $P_4 \times 10^{-3}$ (MeV^{-1})	40 ± 9	

cross sections as a function of projectile energy independent of the projectile type. Both curves present an increase at low energies, which continues up to a maximum. After this point, heavy nuclei, such as actinides, present a decreasing cross section with projectile energy. By assuming that both actinide isotopes follow the same pattern of fission process as demonstrated by proton-induced fission, fitting parameters can be calculated by using the available data on deuteron-induced

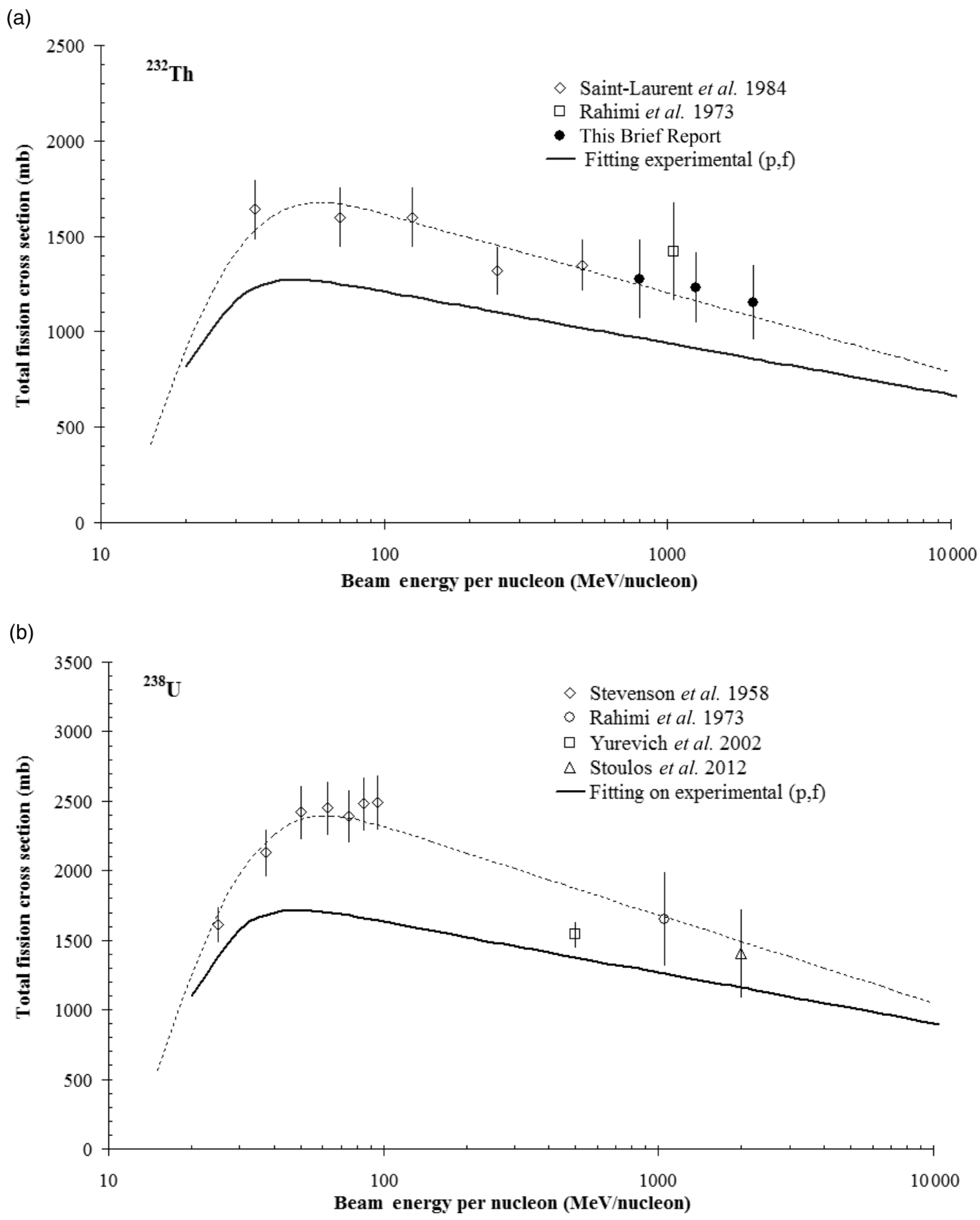

FIG. 2. Deuteron-induced fission cross section on (a) ^{232}Th and (b) ^{238}U. The solid lines represent the fitting of proton data [23], whereas, the dashed lines represent the fitting of deuteron data according to the parameters given in Table III.

TABLE III. Fitting parameters determined on deuteron-induced fission cross-section data on actinides ^{238}U ($r^2 = 90\%$) and ^{232}Th ($r^2 = 70\%$). The data of proton-induced fission are presented in Ref. [23].

	^{232}Th		^{238}U	
	p	d	p	d
Saturation cross section P_1 (mb)	1750	2572 ± 392	2360	3781 ± 379
Saturation constant $P_2 \times 10^{-3}$ (MeV^{-1})	111	41 ± 17	111	38 ± 11
Apparent threshold energy P_3 (MeV)	12.1	24.3 ± 9.4	12.1	24.3 ± 9.4
Decrease constant $P_4 \times 10^{-3}$ (MeV^{-1})	67	70 ± 9	67	73 ± 8

fission. By taking the available data of ^{238}U at low energies (<100 MeV/nucleon) into consideration, the fitting process can be applied by using Eq. (2) to estimate parameters P_2 and P_3, which cannot be calculated by using the ^{232}Th fission cross section since there are limited experimental data at low energies. The contribution of the specific work on ^{232}Th fission at high energies permits the calculation of parameter P_4 by fitting Eq. (2) on ^{232}Th data by taking into account the parameters estimated from the data of ^{238}U. The parameters deduced by the fitting with deuteron projectiles have a better correlation for ^{238}U ($r^2 = 90\%$) than ^{232}Th ($r^2 = 70\%$) and are presented in Table III. In the same table, the parameters produced by the new fitting for deuterons are compared to the ones for protons [23].

The fission saturation cross section P_1, which represents the maximum of the fission cross section, is estimated for deuteron with ^{232}Th interaction as 2.57 ± 0.39 b. This value is 1.47 ± 0.22 times higher than the proton's one. The same conclusion arises from the ^{238}U saturation cross section (3.78 ± 0.38 b), which is 1.60 ± 0.16 times higher than the corresponding proton's cross section. Similar ratios are observed by comparing the fission cross-section data available in the literature for protons and deuterons at the same energy ranges [8–10,24–28]. The deuteron fission cross section is 1.36–1.69 times higher than in the case of protons for energies around 100 MeV, whereas, for energies at the GeV range, the deuteron fission cross section is reduced, varying between 1.03 and 1.24 times the proton's cross sections. This result could be connected to the difference observed in neutron multiplicities when massive spallation targets (such as Bi, Pb, Th, and U) are irradiated with deuteron beams at the GeV range [29,30].

The fission saturation constant P_2 of ^{232}Th and ^{238}U for deuterons is about one third relative to protons. Therefore, the maximum of the fission cross section induced by deuterons is shifted towards higher energy (∼20 MeV/nucleon) relative to protons for which the maximum appears around 50 MeV.

The apparent energy threshold P_3 of deuterons was estimated to be twice the one that corresponded to protons as a result of the double mass of deuterons relative to protons. Both proton and deuteron fitting results estimate an apparent energy threshold of 12 MeV/nucleon.

The fission "decrease constant" P_4, of both actinides (^{232}Th and ^{238}U) appears to be similar to the decrease constant of protons within the fitting uncertainties. However, the fitting parameter P_4, at these energies, is based on limited experimental data available in the literature for deuteron-induced fission on actinides, especially for ^{238}U. The subactinides fission cross-section data are of special interest for investigating the decrease in fission processes with increasing energy since the available proton data are either limited or/and contradictory. Further fission studies at intermediate-high energies that use light particles are necessary since the fission cross-section drop provides valuable information regarding the competition between fission and other mechanisms at high energies.

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