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Mass dependence of pion-induced fission cross sections on the level density parameter

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Abstract: Fission probabilities and fission cross sections strongly depend on the mass number of the target and energy of the projectile. In this research work, a cascade-exciton model (using CEM95 computer code) has been implemented to observe the dependence of pion-induced fission cross sections and fission probabilities on the target mass and ratio of the level density parameter in fission to neutron emission. The analysis has been performed for both the positive and negative pions as the projectile at 80, 100 and 150 MeV energies. The computed cross sections satisfactorily reproduced the experimental findings when compared with the available experimental data in the literature. We observed a smooth dependence at 150 MeV, and a sharper dependence at 80 and 100 MeV pion energy, in the fissility region above 29.44.

Key words: CEM95, fission cross section, level density parameter

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1 Introduction

Due to strongly interacting particles, a field particle of nuclear forces and imparting the maximum of its energy to the target nucleus, pion-induced nuclear reactions have earned unique significance in the understanding of the fundamentals of nuclear physics [1–4]. The pion-induced fission studies are important for nuclear applications such as cascades in heavy nuclear spallation targets which are partly propagated by pions [5]. For many applications in basic and applied nuclear science, reactions induced by pions are very important, like the reactions induced by nucleons and photons. The pion-induced nuclear reactions, particularly fission have not been studied as much as the reactions induced by other probes [6]. Pions are important ingredients of nuclear reactions at intermediate energies because their couplings to major nuclear de-excitation modes can determine the final reaction products starting from several beam species [6]. Pion-induced fission reactions are different from others as the resting mass energy of the pion, i.e. 140 MeV, is first absorbed by the correlating nucleons, and then the energy spreads over the rest of the system via collisions of the fast moving nucleons [7]. Secondly, the pion behaves as a field to mediate not only the forces among the nucleons, but also as an intermediate step for nuclear reactions begun by other intermediate energy probes such as heavy ions, antiprotons and photons [8]. The full absorption of the pion can lead to fission from a state of imparting negligibly low angular momentum and high excitation energy.

Nuclear fission phenomenon, induced by pion or other fission invoking nuclei, strongly depends on the nature & energy of the projectile as well as on the mass & charge of the target. In our previous studies, different characteristics of pion-induced fission have been studied. It has been observed that at the same excitation energy features of pion-induced fission are similar to those of proton-induced fission [6, 9]. For lighter nuclei, like tin, the fission cross sections and hence fission probabilities increase with the pion energy but for gold and bismuth fission cross sections increase with the beam momentum and saturation has been observed at higher beam energies [1]. For heavier nuclei, the fission cross sections and fission probabilities decrease with the energy of the incident

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pion [2].

In the present work, the target mass dependence of pion-induced fission cross sections has been analyzed due to a number of reasons. Firstly, the mass dependence of pion-induced fission at intermediate energies has not been performed theoretically in any previous studies using any theoretical model such as the cascade-exciton model. Secondly, there was a need to check a vital role of the pion sign in the change of the fissility parameter from Z^2/A to $(Z\pm1)^2/A$. Thirdly, because pion beams are not common and are always weak in intensity, it seems difficult to study pion-induced fission experimentally as compared with the fission induced by other probes. Moreover, the cost of experiments at accelerators is very high and the beam time is limited. Fourthly, to observe the effect of the ratio of the level density parameter in fission to neutron emission, i.e. $a_\mathrm{f}/a_\mathrm{n}$ on the mass of the target. Lastly, the different experiments, ALICE, CMS, ATLAS, etc, at the Large Hadron Collider (LHC) at CERN, Switzerland have increased the importance of pion-induced nuclear reactions as a large number of pions are created during p-p collisions and Pb-Pb collisions. These pions induce different types of reactions in the materials of the detectors and so a large amount of data of pion-induced reactions is required to simulate the physics in these detectors by using the code like Geant3 or Geant4. The experimental data of pion-induced cross sections are not available as much as compared with the data available for nucleons and photons. Therefore, different models and computer codes are an essential part in basic and applied nuclear physics as well as in high energy physics. Here in this work, we have performed calculations using the cascade-exciton model code CEM95 [10] and results have been compared with the available experimental data. Reasonably good agreement is observed among the theoretical calculations and the experimental data points.

2 Simulation of fission cross sections

The fission cross sections and probabilities induced by both negative and positive pions have been computed using CEM95 computer code [10]. This code has been selected as this model has a good predictive power and has already been used extensively to study pion-nucleus interactions, particularly pion-induced fission reactions [1–4, 11–13]. The code CEM95 computes the fission cross sections and probabilities on the basis of the cascade-exciton model of nuclear reactions [14]. CEM95 is an extended version of the code CEM92M [11]. We have already successfully used this code in a new manner to compute the fission cross sections induced by pions and other nucleons [1–4]. The same approach has been employed in the present study as in previous ones. The detail about the calculations of fission cross sections using CEM95 can be found in Ref. [1]. A change in the ratio of $a_\mathrm{f}/a_\mathrm{n}$ has been taken into account with the change in the incident energy of the pion or with the mass of the target. It is very important to select the proper value of $a_\mathrm{f}/a_\mathrm{n}$, as fission cross sections are very sensitive to this ratio [1, 15, 16] and often problems have to be faced in choosing the best values for this ratio [13, 17]. Iljinov et al. [18] have obtained the $a_\mathrm{f}/a_\mathrm{n}$ values for zero energy pions ($a_\mathrm{f}/a_\mathrm{n}$=1.2) and energetic protons with the incident energies of 150 ($a_\mathrm{f}/a_\mathrm{n}$=1.17), 660 ($a_\mathrm{f}/a_\mathrm{n}$=1.06), and 1000 ($a_\mathrm{f}/a_\mathrm{n}$=1.04) MeV from the analysis of evaluated fissilities. We have selected $a_\mathrm{f}/a_\mathrm{n}$ values by taking the advantage of or keeping in mind the values evaluated by Iljinov. In the present work, our analysis region is 80, 100, and 150 MeV. The reason for selecting beam energies at 80, 100, and 150 MeV is the lying of these regions in the delta-resonance and the availability of experimental data at these energies for comparison.

3 Results and discussion

The mass dependence of pion-induced fission cross sections and fission probabilities computed using CEM95 at 150 MeV pion energy is shown in Figs. 1, 2, respectively. The cross sections are plotted against the fissility parameter, $(Z\pm1)^2/A$. The solid and dashed lines are the fission cross sections and

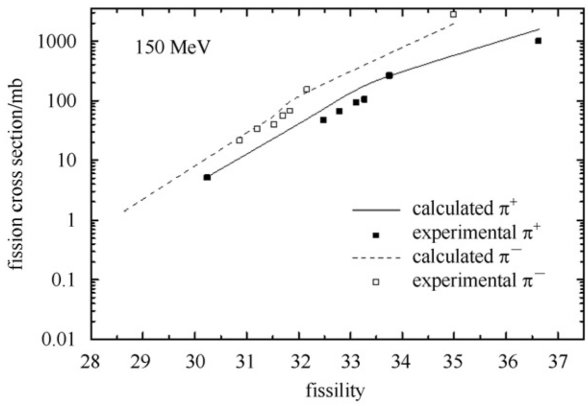

Fig. 1. Fissility parameter, $(Z\pm1)^2/A$, dependence of fission cross sections for 150 MeV beam energies for π^+ and π^-. The curves are the fission cross sections computed using CEM95 and the squares are the experimental data from Ref. [19].

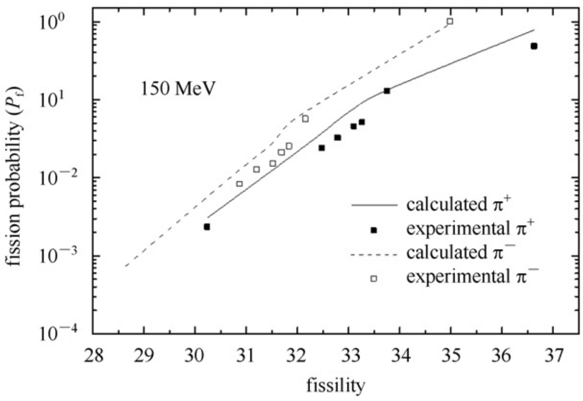

Fig. 2. Fissility parameter, $(Z \pm 1)^2/A$, dependence of fission probabilities for 150 MeV beam energies for π^+ and π^-. The curves are the fission cross sections computed using CEM95 and the squares are the experimental data from Ref. [19].

fission probabilities induced by positive and negative pions computed using CEM95, respectively.

The computed predictions show a reasonable agreement with the experimental data in Ref. [19]. The curves indicate the smooth upward trends of fission cross sections and fission probabilities with the target mass. The dramatic increase of cross sections with mass is directly correlated with the strong decrease of fission barriers with mass [19, 20]. As we have shown in our previous studies, for CEM95, the computed fission cross sections heavily depend on the ratio of the level density parameter in fission to neutron emission, i.e. on $a_{\rm f}/a_{\rm n}$ [1, 13]. Dependence of fission cross sections on $a_{\rm f}/a_{\rm n}$ has also been observed in other models and this ratio has different values in different models [15–17, 20]. Hence, we have carefully selected this ratio in the present study. The $a_{\rm f}/a_{\rm n}$ values for 150 MeV negative pion-induced fission on targets ^{181}Ta, ^{197}Au, ^{205}Tl, ^{203}Tl, ^{207}Pb, ^{206}Pb, ^{209}Bi and ^{231}Pa are, 1.17, 1.155, 1.195, 1.110, 1.13, 1.135, 1.17 and 1.195, respectively. The excitation energy dependence of fission barriers is taken into account, for ^{181}Ta, ^{197}Au, ^{205}Tl & ^{231}Pa as proposed by Sauer, Chandra, and Mosel [21] and for other nuclei proposed by Barashenkov, Gereghi, Iljinov and Toneev [22]. Similarly, for 150 MeV positive pion-induced fission on targets ^{181}Ta, ^{197}Au, ^{205}Tl, ^{203}Tl, ^{207}Pb, ^{209}Bi, ^{231}Pa, the $a_{\rm f}/a_{\rm n}$ values are: 1.165, 1.165, 1.12, 1.125, 1.150, 1.172, 1.120, respectively. For positive pion, the excitation energy dependence of the fission barrier is also taken in to account, for ^{181}Ta, ^{197}Au, and ^{231}Pa proposed by Sauer Chandra and Mosel [21] and for other nuclei proposed by Barashenkov, Gereghi, Iljinov and Toneev [22]. For all the nuclei, except ^{231}Pa, calculations are performed with a single humped fission barrier and for ^{231}Pa with double humped fission barrier. For all the nuclei, the other important CEM95 parameters used are: the third Iljinov et al. systematics for the level density parameters [23]; the fission barriers of Krappe, Nix, and Sierk [24]; Turan, Cameron and Hilf's shell corrections [25].

The computed mass dependence of positive and negative pion-induced fission cross sections and fission probabilities at 80 MeV and 100 MeV are shown in Figs. 3–6, respectively.

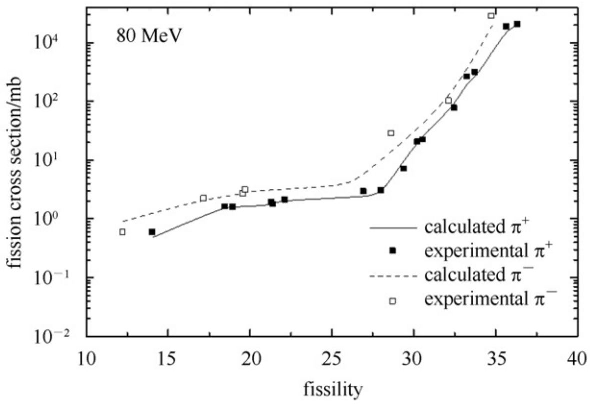

Fig. 3. The same as Fig. 1, but for 80 MeV beam energies and the experimental data from Ref. [26].

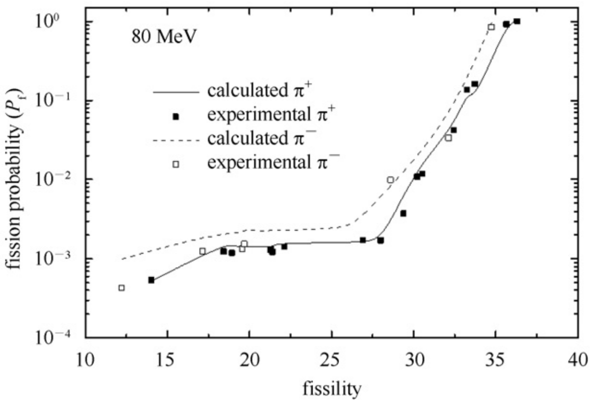

Fig. 4. The same as Fig. 2, but for 80 MeV beam energies and the experimental data from Ref. [26].

The cross sections are plotted against the fissility parameter, $(Z \pm 1)^2/A$. The computed values show a reasonable agreement with the experimental data. For 80 MeV positive pion, the ratio $a_{\rm f}/a_{\rm n}$ for targets ^{91}Zr, ^{93}Nb, ^{108}Ag, ^{112}Cd, ^{122}Sb, ^{152}Eu, ^{165}Ho, ^{178}Hf, ^{181}Ta, ^{184}W, ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th and ^{238}U are: 1.130, 1.15, 1.12, 1.2, 1.25, 1.17, 1.13, 1.105, 1.135, 1.130, 1.11, 1.2, 1.2, 1.13 and 1.17, respectively. For 100 MeV positive pion, the ratio of $a_{\rm f}/a_{\rm n}$ for targets, ^{91}Zr, ^{93}Nb, ^{108}Ag, ^{152}Eu, ^{165}Ho, ^{178}Hf, ^{181}Ta, ^{184}W,

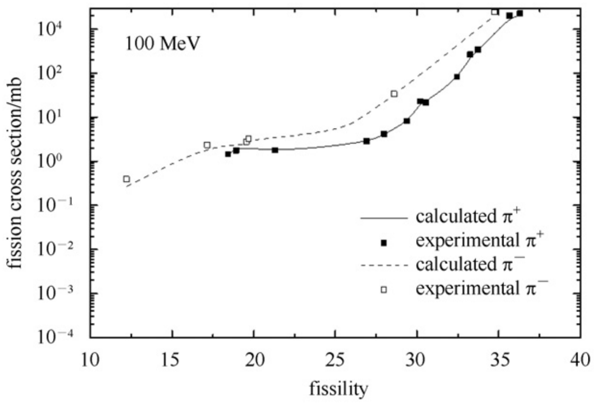

Fig. 5. The same as Fig. 1, but for 100 MeV beam energies and the experimental data from Ref. [26].

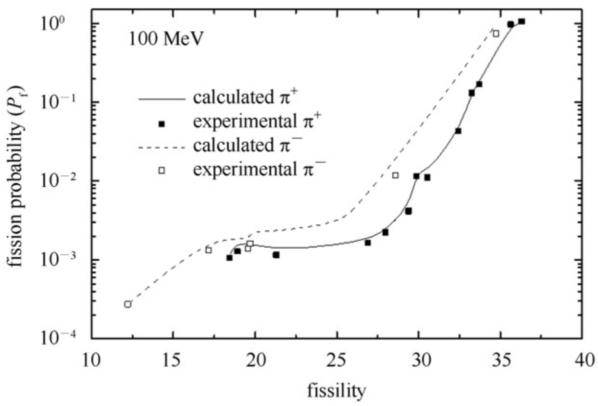

Fig. 6. The same as Fig. 2, but for 100 MeV beam energies and the experimental data from Ref. [26].

^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th and ^{238}U are: 1.207, 1.01, 1.295, 1.180, 1.236, 1.232, 1.131, 1.227, 1.203, 1.209, 1.231, 1.200 and 1.250, respectively. The other important CEM95 parameters used are: the third Iljinov et al. systematics for the level density parameters [23]; the fission barriers of Krappe, Nix [24], and Sierk; Truran, Cameron and Hilf's shell corrections [25]. The fission cross sections and fission probabilities show a slowly changing trend up to the fissility parameter 29.44, for lighter nuclei, but then indicate a steep rise with the fissility parameter above 29.44.

For 80 MeV negative pions, the ratio of a_f/a_n for targets, ^{64}Cu, ^{93}Nb, ^{108}Ag, ^{112}Cd, ^{122}Sb, ^{152}Eu, ^{165}Ho, ^{181}Ta, ^{209}Bi, and ^{238}U are: 1.01, 1.01, 1.240, 1.30, 1.295, 1.248, 1.180, 1.165, 1.235 and 1.20, respectively. For 100 MeV negative pion, the ratio of a_f/a_n for targets, ^{64}Cu, ^{93}Nb, ^{108}Ag, ^{112}Cd, ^{122}Sb, ^{152}Eu, ^{165}Ho, ^{181}Ta, and ^{238}U are 1.30, 1.18, 1.282, 1.271, 1.297, 1.240, 1.205, 1.177 and 1.20, respectively. The other CEM95 parameters are the same as for positive pion.

In nearly all the cases we have observed, the fission cross sections and probabilities first show a smooth increase with the fissility and then a sharp increase with the fissility parameter. The results are comparable to previous studies [9].

Note that for all the nuclei and at all energies, the values of a_f/a_n are greater than unity. This is because both in the case of near spherical and non spherical nuclei the ground state equilibrium deformation of the residual nucleus, after neutron emission, is associated with a lower than average single particle level density, while the deformation of the fissioning nucleus is associated with a higher than average single particle level density [27, 28]. Furthermore, at the same incident energy, the values of a_f/a_n are different for different targets due to the differences in the nuclear structure of different targets and hence due to the difference in the fission barriers. Also note that the cross sections can also be reproduced by using a single value of a_f/a_n, showing almost the same trend but with a little bit more difference from the experimental values. This is shown in Fig. 7 where a single value of the ratio a_f/a_n, 1.290 has been used for all the nuclei.

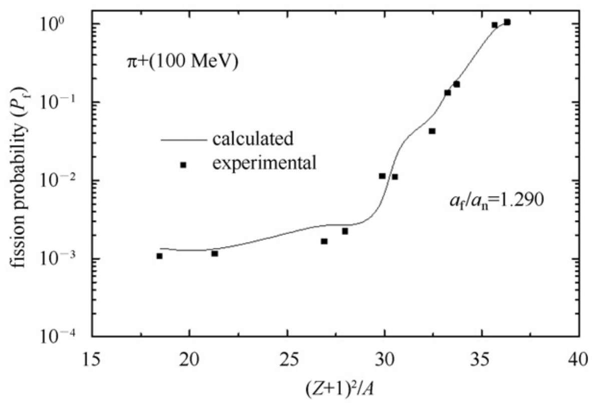

Fig. 7. Fissility parameter, $(Z+1)^2/A$, dependence of fission probabilities for 100 MeV beam energies for π^+. The curve is the fission probabilities computed using CEM95 and the squares are the experimental data from Ref. [26] (Peterson, et al., 1995).

4 Conclusions

We have studied theoretically the effect of level density parameter on mass, in the intermediate energy range and across the delta resonance, of pion-induced fission cross sections and fission probabilities using the cascaded-exciton model code CEM95. The computed cross sections and probabilities for fission are in good agreement with the experimental data from literature and are comparable with the other studies, induced by protons and photons, in the literature. For lighter nuclei, the cross sections show a low and slowly changing trend and then a sharply increasing trend with the mass of the target. Secondly, there is a difference in the cross sections for both signs of pions. In the mass region where cross sections show a low and slowly changing trend with the fissility, the π^+ cross sections are less than those of π^- and in the region where the cross sections show a sharply increasing trend with the fissility the π^+ cross sections are larger than or about equal to those of π^- fission cross sections. The reason for this may be due to the different absorption mechanisms for both the negative and positive pions with the target mass. For the lighter mass nuclei, the absorption process seems to be quasi-free scattering which leads to fission. The quasi-free mechanism would lead to a lower nuclear charge for π^+ reactions than for π^-, leading to a lower fission cross section and fission probability for π^+ than for π^-. We conclude that the dependence of mass on the ratio of level density parameter of pion-induced fission, theoretically, can now be understood well.

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