Study of fission cross sections induced by nucleons and pions using the cascade-exciton model CEM95

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Abstract

Nucleon and pion-induced fission cross sections at intermediate and at higher energies are important in current nuclear applications, such as accelerator driven-systems (ADS), in medicine, for effects on electronics etc. In the present work, microscopic fission cross sections induced by nucleons and pions are calculated using the cascade-exciton model code CEM95 for different projectile-target combinations; at various energies and the computed cross sections are compared with the experimental data found in literature. A new approach is used to compute the fission cross sections in which a change of the ratio of the level density parameter in fission to neutron emission channels is taken into account with the change in the incident energy of the projectile. We are unable to describe well the cross sections for fission without using this new approach. Proton induced fission cross sections are calculated for targets ^{197}Au, ^{208}Pb, ^{209}Bi, ^{238}U and ^{239}Pu in the energy range from 20 MeV to 2000 MeV. Neutron induced fission cross sections are computed for ^{238}U and ^{239}Pu in the energy range from 20 MeV to 200 MeV. Negative pion induced cross sections for fission are calculated for targets ^{197}Au and ^{209}Bi from 50 MeV to 2500 MeV. The computed values exhibited reasonable agreement with the experimental values found in the literature across a wide range of beam energies.

Keywords: fission cross sections, proton, neutron, pions, cascade-exciton model, CEM95

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1. Introduction

The nuclear reaction cross section data, in general, and fission cross sections data, particularly, not only provide the most important parameters required for theoretical simulations in the fields of reactor physics and nuclear engineering, but, also for Accelerator Transmutation of Waste (ATW), Accelerator-Based Conversion (ABC), Accelerator Driven Energy Production (ADEP) etc. Just as for nuclear reactor designing, nuclear cross section data, particularly microscopic fission cross sections, of all the materials that are used in the reactor core is required; similarly, a large amount of nuclear reaction data, including fission cross sections at intermediate and higher energies is required for current applications such as ATW for elimination of long-lived radioactive wastes with a spallation source, ABC aimed to

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complete the destruction of weapon plutonium, ADEP which proposes to derive fission energy from ^{232}Th with concurrent destruction of the long-lived waste and without the production of weapon usable material, for Accelerator Production of Tritium (APT) etc.

Nuclear fission of heavy nuclei induced by nucleons in the transitive energy region 20-200 MeV is one of the main reaction channels (the fission cross section for actinide region can reach the value 0.8-0.9 of the total reaction cross section). Accurate neutron cross section data is fundamental to the reliable design of any transmutation device, and, in particular, of an Accelerator Driven System (ADS). Proton induced reactions are used for generating neutrons. Pions are produced from proton-proton collisions when the energy of the proton is about 500 MeV or more [1]. Pions may easily induce secondary reactions in the thick target system. Thus, the reactions induced by nucleons and pions are very important. In basic research, pion induced reactions are important because interactions of pions with matter have been extensively used to understand the nuclear structure. The absorption of the pion in the nucleus may results in the deposition of its full rest mass energy as well as kinetic energy, leading to high nuclear excitations. Due to the above mentioned consequences the nuclei with high fission barriers are also subjected to disintegration under bombardment with pions. It is known that at higher energies the photon absorption is through pions [2]. Moreover, it is also well known that pions are strongly interacting particles and are strongly absorbed by the nuclei. Hence, nucleon and pion-induced reactions at intermediate and higher energies are very important to develop a comprehensive type of an evaluated nuclear data library, like libraries developed for conventional nuclear reactor systems, and also to understand nuclear characteristics.

In the present work, nucleon and pion-induced fission cross sections on some heavy targets nuclei are computed using a cascade-exciton model implemented in the code CEM95 [3]. It is observed that fission cross sections are heavily dependent on the ratio of the level density parameters in the fission and evaporation modes i.e a_f/a_n, respectively. To describe the fission cross sections in the best way, a change in the ratio of the level density parameters with the change in the incident energy of the projectile and variation in projectile–target combination has been taken into account. A modified version of CEM95 known as CEM98 has been used already to estimate the fission cross sections of different isotopes [4]. We have used CEM95 in its standard form to compare our experimental data of pion induced fission in Au and Bi [5], and for heavy targets [6]. In the present work, the approach is extended to neutrons and protons as projectile incident on some selected targets which are considered as useful materials for accelerator-driven systems [7]. Fission cross sections have been calculated for protons on targets ^{197}Au, ^{208}Pb, ^{209}Bi, in the energy range from 40 MeV to 2000 MeV, on targets ^{235}U and ^{239}Pu in the energy range from 20 MeV to 2000 MeV, for neutrons on targets ^{238}U and ^{239}Pu in the range from 20 MeV to 200 MeV, due to lack of available experimental data in literature for comparison, and for negative pions on ^{197}Au and ^{209}Bi from 50 MeV to 2500 MeV. In the present work it is shown with several examples that CEM95 in its standard form does not describe well the fission cross sections of nuclei at least that of preactinidies. But if the change of the ratio of the level density parameter is taken into account with the change in the incident energy of the projectile, then a good description of the measured fission cross sections is possible. Using this strategy, the fission cross sections are calculated and are compared with the available experimental data. A good agreement is observed among the computed cross sections for fission and the experimental data points. Some of the literature search for experimental fission cross sections was performed using the Nuclear Science References (NSR) database [8].

2. Theoretical modeling

A detailed description of the initial version of the CEM is given in Ref. [9] and an extended version of CEM95, known as CEM98, used for calculating fission cross sections can be seen from Ref. [4]. Recently, we have used standard CEM95 to compare our experimentally determined fission cross sections of pion induced fission in Au and Bi [5]. Therefore, in this paper only its basic parts and the more relevant data related to fission cross sections have been described. There are three stages incorporated in this code. First is the Intra Nuclear Cascade (INC) in which primary particles can be re-scattered and produce secondary particles several times prior to absorption by or escape from the nucleus. The excited residual nucleus remaining after the cascade determines the particle-hole configuration and this is the starting point for the pre-equilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of an improved Modified Exciton Model (MEM) of pre-equilibrium decay followed by the equilibrium evaporative final stage of the reaction. All the three parts contribute to experimentally measured outcomes. A brief introduction of the parameters used in calculating fission cross sections of nucleons and pions is presented below.

There are a lot of parameters like level density parameters, the microscopic and macroscopic fission barriers, ground state shell corrections, shell and pairing corrections at the saddle point, excitation energy dependence of fission barriers, angular momentum dependence of fission barriers and many others incorporated in CEM95. The most important parameter on which sensitivity of fission cross sections depend is the ratio of the level density parameters a_f and a_n corresponding to the saddle point of fission and equilibrium deformation of nucleus, respectively.

There are several different level density parameter systematics incorporated in CEM95. Most of these use the formula given first by Ignatyuk [10] to find the level density parameter,

$$a\left(Z,A,E^*\right)=\tilde{a}\left(A\right)\left[1+\delta W\left(Z,A\right)\frac{1-\exp\left[-\gamma\left(E^*-\Delta\right)\right]}{E^*-\Delta}\right],$$

where $\tilde{a}\left(A\right)$ is the asymptotic value of the level density parameter at high excitation energies and is given by,

$$\tilde{a}\left(A\right)=\alpha A+\beta A^{2/3}B_s\,,$$

Here, A, Z, and E^* are the mass, charge, and the excitation energy of the nucleus, $\delta W\ (Z, A)$ is the shell correction, Δ is the pairing correction, α, β, and γ are phenemoligical constants, and

B_s is the surface area of the nucleus in units of the surface for the sphere of equal volume. For nuclei with equilibrium deformation $B_s \approx 1$, while for the saddle point $B_s > 1$. In the previously used CEM98 [4], the parameter B_s was adjusted to provide the best agreement with the experimental data.

In the present paper we are using a very simple approach in which no adjustment of any functions or parameters, except ratio of level density parameters, is required. Only the ratio of level density parameters is adjusted to get the desired results. The calculated fission cross sections are found to be remarkably sensitive to the variation of the a_f / a_n. The variation in a_f / a_n only a few percent changes the cross sections to 1.5 to 2 times [4]. There are a lot of expressions used for the determination of a_n and hence, a_f [11].

The LeCouteur's expression for the level density parameter a_n, which is given by

$$a_n = \frac{A}{B_0}\left[1 + 1.5\left(\frac{A - 2Z}{A}\right)^2\right],$$

has been used in NMTC and HETC. In the above expression Z is the atomic number and B_o a parameter having values in the range of 8~20 MeV [11]. Some researchers prefer to use very simple expressions such as $a_n = A/20$ or $a_n = A/10$.

As for the level density parameter a_f, Vandenbsoch and Huizenga made a table of a_f / a_n obtained from analysis of fission excitation functions for the nuclei from ^{173}Lu to ^{213}At [12]. So a simple expression linear in Z^2/A given by

$$a_f / a_n = 1.0 + 0.1\left(\frac{Z^2}{A} - 29.0\right) \qquad (1)$$

can be used to find the ratio of the level density parameters.

The above mentioned expressions are independent of the excitation energy or incident energy of the projectile. But we have shown in this paper that in the intermediate and high energy regions rather than Z^2/A of a_f / a_n into consideration it would become necessary to take energy dependence, because nuclear characteristics dependent on Z and N would become obscure. In Ref. [13], Iljinov et al. obtained the a_f / a_n values for zero energy pions (a_f / a_n=1.2) and energetic protons with the incident energies of 150 (a_f / a_n=1.17), 660 (a_f / a_n=1.06), and 1,000 (a_f / a_n=1.04) MeV from analysis of experimental fissilities. By fitting a quadratic equation to these a_f / a_n values, fission cross sections are calculated from these values at different incident energies of the projectile. The expression obtained is given by:

$$a_f / a_n = a\left(E^*\right)^2 + bE^* + c \qquad (2)$$

where a = 1.0×10^{-7} $(\text{MeV})^{-2}$, b = -3.0×10^{-4} $(\text{MeV})^{-1}$, c = 1.2049, and E^* is the incident energy of the projectile.

It is more convenient to use $a_f / a_n \rightarrow k \times a_f / a_n$, instead of using the value of a_f / a_n obtained from equation (2), where, k is a constant whose value is adjusted according to the nature of the projectile (i.e n, p or pion), energy of the incident projectile and nature of the target nucleus (i.e ^{197}Au, ^{208}Pb etc). Coefficient k is necessary to take into account the Z and A dependence of the target and nature of the incident particle, and to approach the optimal value of a_f / a_n, because a few percent variations from the optimal value changes the fission cross sections by a factor of 1.5-2 [4].

For validation of code CEM95 and new methodology used, fission cross sections induced by nucleons and pions on different targets are calculated. The results are shown in Figs. 1 to 11 with comparison to experimentally measured fission cross sections. Calculations are performed by using those parameters that best describe the experimental data. Hence, the best parameters used to compute fission cross sections induced by protons and negative pions are: Krappe, Nix, and Sierk fission barriers [14], Truran, Cameron, and Hilf shell and pairing corrections for the fission barriers and for the level density parameter [15], the third Iljinov et al. systematics for the level density parameters [16], with a dependence of $B_f\left(E^*\right)$ on excitation energy is estimated from Ref [17], the value of the moment of inertia of a nucleus at the saddle-point J_{sp} from Ref. [18], without taking into account the dependence of B_f (L) on angular momentum. For fission induced by neutrons, no excitation energy dependence of fission barriers is taken into account but with a dependence B_f (L) estimated by a phenomenological approach from Ref. [19] with the value of the moment of inertia of a nucleus at the saddle point J_{sp} from Ref [18] and Cameron shell and pairing corrections for the fission barriers and for the level density parameters [20]. The other parameters are same as for used above for negative pions and protons. It is observed that CEM95 describes correctly the shape and the absolute value of the fission cross sections at these intermediate and higher incident energies.

3. Results and discussion

Theoretically calculated fission cross sections induced by nucleons and negative pions are plotted in Figs. 1 to 11. Solid curves show the calculated fission cross sections using the code CEM95 whereas open and solid circles represent the experimental data points. In all the Figs. the range of values of a_f / a_n that are obtained from eq. (2) are also indicated to facilitate the readers or users of CEM95.

Proton induced fission cross sections on targets ^{197}Au, ^{208}Pb, ^{209}Bi, ^{235}U and ^{239}Pu are shown in Figs. 1 to 5. Computed fission cross sections are compared with the experimental data from Refs. [7, 21-47]. Approach uses describe well the experimental fission cross sections for preactinidies, but overestimate the calculated fission cross sections for actinides at lower energies. Fission cross-sections, for proton induced fission exhibit an increase with an increase in the incident proton energy reach to a maximum value and then start decreasing. The increase in the cross-sections is largely due to an increase of coulomb barrier penetrability, and decrease may be due to opening of new reaction channels, like spallation

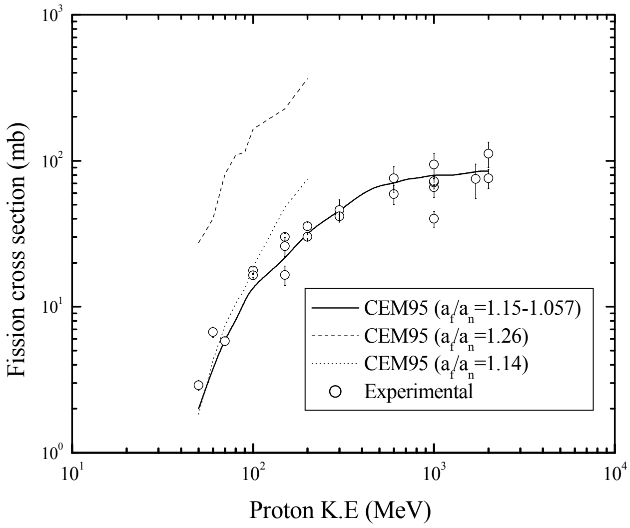

Fig. 1. Energy dependence of the proton induced fission crosses-sections for ^{197}Au. Results obtained from CEM95 are shown as solid, dashed and dotted lines, while the circles represent the experimental data of refs. [21-30].

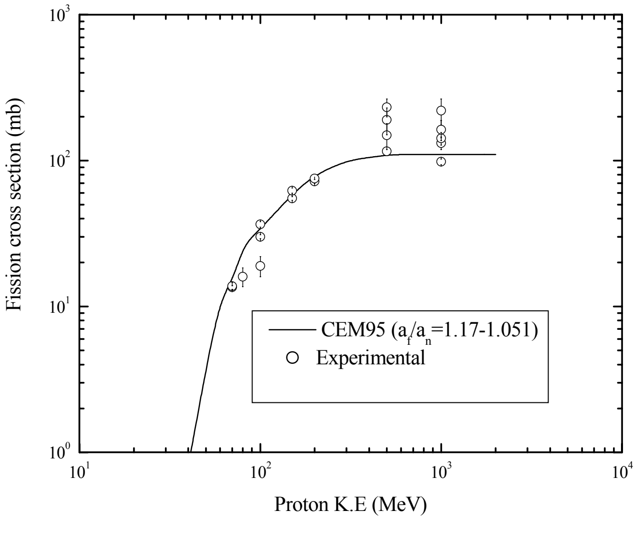

Fig. 2. Energy dependence of the proton, induced fission crosses-sections for ^{208}Pb. Results obtained from CEM95 are shown as solid line, while the circles represent the experimental data of refs. [24, 26, 27, 29, 31, 43-47]

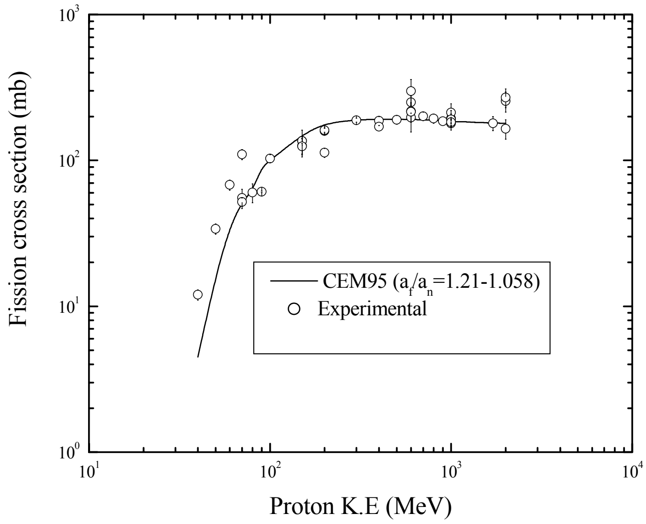

Fig. 3. Energy dependence of the proton-induced fission crosses sections for ^{209}Bi. Results are compared with the experimental data from Refs. [21-39]

etc. at higher energies. The decrease is much slower for lighter nuclei. For heavy nuclei the maximum values of fission cross sections is observed in the energy region 40-70 MeV and for lighter nuclei the maximum value is located at a higher energy near about 1GeV.

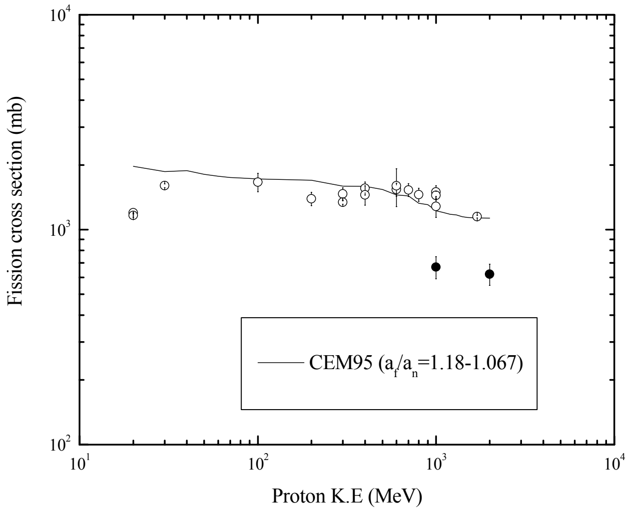

Fig. 4. Energy dependence of the proton-induced fission crosses sections for ^{235}U. Solid circles are from Ref [36], whereas open circles are from Refs. [23, 25, 27, 34-35, 40-42]

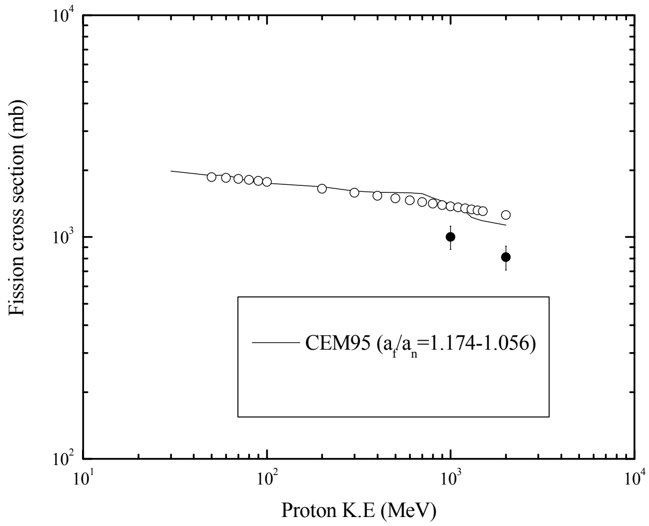

Fig. 5. Energy dependence of the proton-induced fission crosses sections for ^{239}Pu. Open circles are from Ref. [7], whereas solid circles are from Ref. [36].

We cannot describe well the fission cross sections if we use a single value of the ratio of the level parameter, particularly for preactinidies. The dependence of fission cross sections to the ratio of the level density parameters is indicated in Fig. 6 for proton induced fission in ^{208}Pb, using different ratios of level density parameters i.e 1.2, 1.17 and 1.14. Remarkable variation in fission cross sections is observed. Use of a single value of the ratio from eq (1) or any other optimal value, the fission cross sections sharply rise as indicated in Fig. 1 for proton induced fission in gold, where two values are used one from eq. (1) and the other is taken any optimal value. This indicate that theoretically calculated fission cross sections are heavily dependent to the ratio of the level density parameters in the fission and neutron emission channels, a_f / a_n. A few percent variation in the value of the a_f / a_n from the optimal value changes the value of the cross sections to a large extent. This is indicated in Fig.1 for proton induced fission in gold. So it is important that for using the cascade-exciton model in standard form to calculate fission cross sections, a change in the ratio of the level density parameter is essential to best estimate the fission cross sections. Similar behavior was observed for negative pion induce fission in bismuth as shown in Fig. 11, where a single value of the ratio of the level density parameter does not match with the experimental data. The dependency of fission cross sections on other parameters of the model like the macroscopic and microscopic fission barriers, shell and pairing corrections, nuclear masses, saddle-point moments of inertia, angular and excitation energy dependence of fission barriers etc. are found to be lower as compared to the value of a_f / a_n.

Fig. 7 shows the effect on fission cross sections of the angular momentum dependence of the fission barriers. Three values of B_f (L) are tested. One for which no dependence of B_f on L is taken into account. In the second case, the phenomenological dependence of B_f on L was taken into account with the Strutinsky's value for the moment of inertia [18] of the nucleus at

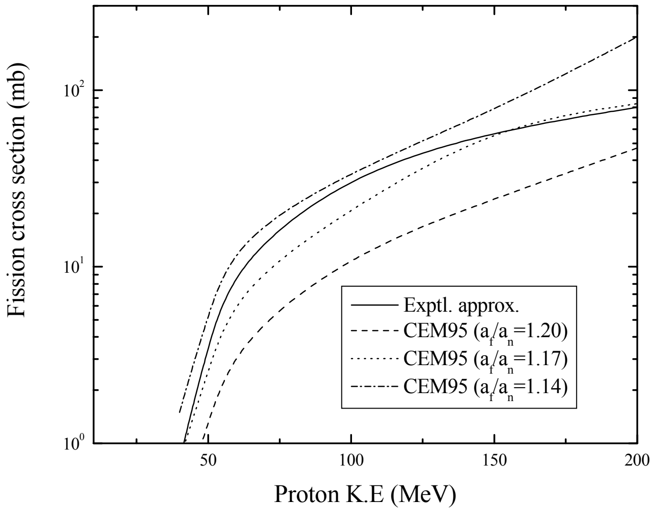

Fig. 6. Effect of the ratio of level density parameter on fission cross sections for proton induced fission in ^{208}Pb.

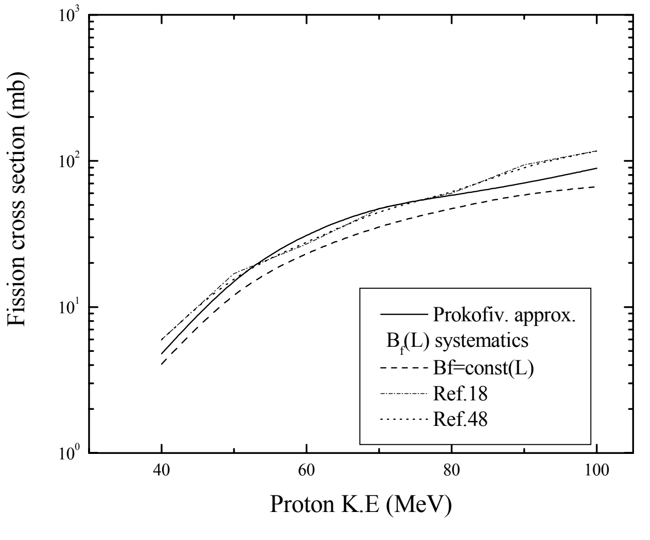

Fig. 7. Effect of the angular momentum dependence of fission barriers on fission cross sections for proton induced fission in ^{209}Bi.

the saddle point J_{sp}. In the third case, the phenomenological dependence of B_f on L was taken into account but with the Swiateckis's value for the moment of inertia [48] of the nucleus at the saddle point J_{sp}. A weak influence on cross sections is observed as compared to the effect of the ratio of the level density parameters. This may be due to the small angular momentum being imparted to the nucleus by incident projectile in the energy region under study. The majority of these choices give nearly the same shape to the fission excitation function.

Figs. 8 and 9 show the fission cross sections induced by neutrons on targets ^{238}U and ^{239}Pu. Results are compared with the experimental data from Refs. [49-54]. Neutron induced fission cross sections of heavy nuclei are found to decrease with the neutron energy. There is again problem at lower energies, fission cross sections calculated with CEM95 under estimates the results at lower energies, but there is good matching at higher energies. There is contradiction among the two different experimental data sets used for comparison to the computed cross sections for fission of ^{239}Pu, but the results of the Yavshits et al are close to the theoretical values as compared to the results of Scherbakov which seem to be more conflicting.

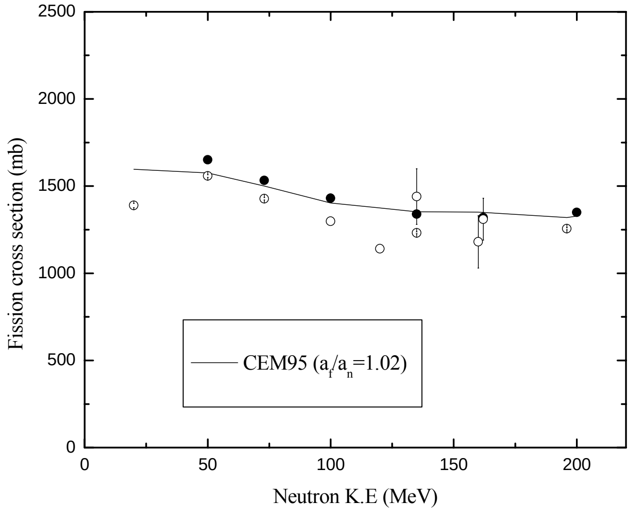

Fig. 8. Energy dependence of the neutron-induced fission crosses sections for ^{238}U. Solid circles are from Ref. [49], whereas open circles Refs. [50-53]

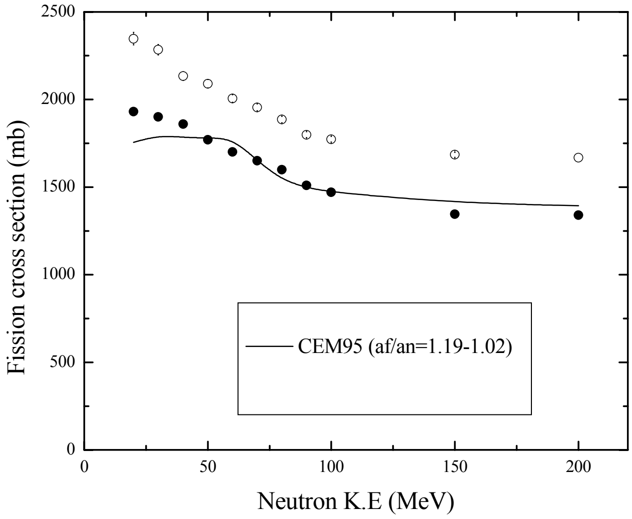

Fig. 9. Energy dependence of the neutron-induced fission crosses sections for ^{239}Pu. Open circles are from Ref. [49], whereas solid circles are from Ref. [54].

Fission cross sections induced by negative pions on targets ^{197}Au and ^{209}Bi are shown in Figs. 10 and 11, respectively. There is good matching among the computed fission cross sections and experimental data points [5, 55-60]. A saturation of the cross sections at higher energies is observed in both the methodologies i.e experimental and theoretical. For negative pions induced reactions, fission cross sections showed increasing trend with an increase in the incident pion energy, eventually reached to a maximum value and then started decreasing. The decrease is very much slower for both, and in comparison decrease is very much slower for gold than bismuth. If we compare the fission cross sections by protons and negative pions, we see that both indicate the similar behavior. In both cases, cross sections showed increasing trend with an increase in the energy of the incident projectile, eventually reached to a maxima and then started decreasing. Decrease is slower for lighter nuclei.

We also note that the ratio of the level density parameter decreases with increase of the incident particle energy. It must also be noted that the a_f / a_n ratio have different values for different nuclei. This may be due to the influence of shell effects.

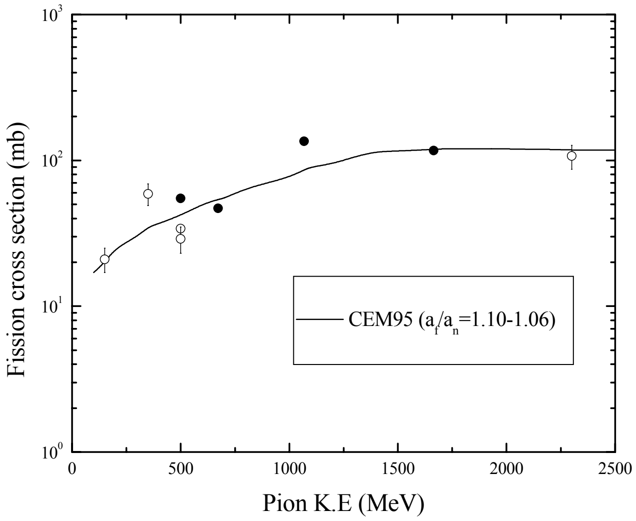

Fig. 10. Energy dependence of the negative pion-induced fission crosses sections for ^{197}Au. Solid curve is the result of computations using CEM95. Solid circles indicate the data obtained using CR-39 track detectors [5], whereas open circles indicate the experimental data obtained using mica and Makrofol SSNTDs [5, 56, 59, 60]

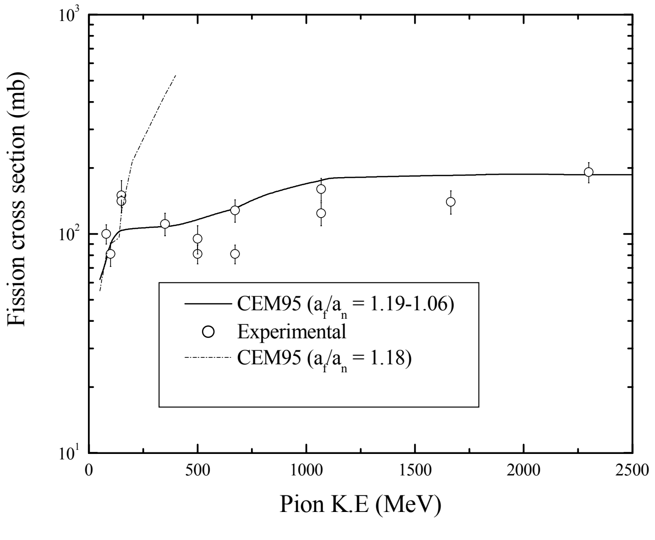

Fig. 11. Energy dependence of the negative pion-induced fission crosses sections for ^{209}Bi. Results are compared with the experimental data from Refs. [5, 55-60], measured using mica and Makrofol SSNTDs.

4. Summary and conclusions

Nucleon and pion induced fission cross sections have been calculated on some important targets using the standard code CEM95. It is shown that fission cross sections are strongly dependent to the ratio of the level density parameter as compared to the other parameters of the model. Use of a single value of the ratio of the level density parameter cannot describe accurately the cross sections for fission. We can safely conclude that the new approach used in CEM95, taking into account the change of the ratio of the level density parameter with the change in the incident energy of the projectile, seems to be adequate for the best estimation of fission cross sections induced by nucleons and pions on variety of targets, and in a wide energy range. The cross sections are useful for new current applications like accelerator driven-systems etc., and for understanding the nuclear structure characteristics.

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