

Study of Fission Cross Sections Induced by Nucleons and Pions Using the Cascade- Exciton Model CEM95

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Introduction

*“Oh what idiots we all have been!
Oh but this is wonderful! This is
just as it must be! Have you and
Lise Meitner written a paper about it?”*

Neils Bohr to Otto Frisch upon being told about
the discovery of nuclear fission.

- Nuclear fission covers the areas ranging from nuclear structure models to accelerator- driven systems.
- Pion-induced fission is as important as fission induced by nucleons.
- Cascades in heavy nuclear spallation targets are partly propagated by pions.

Problems attributed to conventional nuclear reactors

- **Firstly, spent fuel from nuclear power plants is an enormous problem both from radiation hazard and economical point of view.**
- **Secondly, proliferation resistance of the spent nuclear fuel is an additional concern i.e unavoidable production of fissile material (^{239}Pu), which can be diverted to military applications.**
- **Thirdly, there is inefficient use of the nuclear fuel in the conventional nuclear reactors.**
- **Fourthly, safety issues and possibility of nuclear accidents like Three Mile Island (TMI) and Chernobyl.**

Solution to the problems

- **The new generation of nuclear power plants must have solutions for all of these problems.**
- **Therefore, to overcome or to at least minimize the above mentioned problems, hybrid reactor systems or accelerator driven systems (ADS) are recently getting more importance.**
- **An ADS cannot become critical or supercritical.**
- **No problem of nuclear waste.**
- **Need of nuclear data at intermediate and at higher energies for ADS.**

Importance of Nuclear Data for the ADS

- **Inaccuracies in nuclear data can cause serious systematic errors in the results of any type of nuclear device simulation.**
- **Critical reactors have neutron energies up to about 10 or 20 MeV, but in hybrid reactors very high energy neutrons will be present.**
- **The maximum energy will be the incident beam energy, which in most design concepts lie in the range 1000-2000 MeV range.**
- **For the design of fission reactors, the nuclear data file for neutrons below 20 MeV is available and well evaluated such as Japanese Evaluated Nuclear Data Library, version 3 (JEND-3) in Japan, Evaluated Nuclear**

- **Data File, part B, version 6, (ENDF/B-VI) in the United States, and so on. These data libraries were preliminarily developed for LWR deterministic calculations as a main priority, and their accuracy for this purpose is normally sufficient.**
- **However, when applied to fast subcritical systems, they yield unacceptably large differences in their prediction of important system parameters vital to the safety and economy of these systems.**
- **Moreover the computer codes or tools available to model a conventional nuclear reactor are not directly applicable for numerical simulation of ADS systems for a number of reasons.**

Brief Introduction to Cascade-Exciton Model code CEM95

- Nucleon and pion-induced fission cross-sections of light and heavy nuclei, up to 2500 MeV, are calculated using the code CEM95 and results are compared with the experimental data.
- Three stages are incorporated in the code: **the cascade**, **pre-equilibrium**, and **compound nucleus stage**.
- The model uses the Monte Carlo Method to simulate all three stages of the reactions.
- Two methodologies have been incorporated in CEM95, one is the direct Monte Carlo simulations and other is the Monte Carlo sampling by means of statistical functions.

➤ According to the statistical weight method the fission cross sections are estimated as,

$$\sigma_f = \frac{\sigma_{in}}{N_{in}} \sum_{i=1}^{N_{in}} (W_f)_i$$

Where,

σ_f = Microscopic fission cross-section

σ_{in} = Total reaction cross-section

N_{in} = Total number of simulated inelastic interactions

W_f = The probability of the nucleus to fission at any of the chain stages and is determined from the following expressions:

$$\Gamma_j = \frac{(2s_j + 1)m_j}{\pi^2 \rho_c(U_c)} \int_{V_j}^{U_j - B_j} \sigma_{inv}^j(E) \rho_j(U_j - B_j - E) E dE$$

$$\Gamma_f = \frac{1}{2\pi \rho_c(U_c)} \int_0^{U_f - B_f} \rho_f(U_f - B_f - E) E dE$$

- In original version of CEM95, by using a constant value of the ratio of the level density parameter i.e. a_f/a_n fission cross sections can not be described accurately,
- but if the change in the ratio of the level density parameter is taken into account with the change in the incident energy of the projectile, then we can describe well the cross-sections for fission.
- The calculated fission cross sections are found to be remarkably sensitive to the variation of the a_f/a_n .

- There are a lot of expressions used for the determination of a_n and hence a_f .
- The LeCouteur's expression for the level density parameter, which is given by

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

- Some researchers prefer to use very simple expressions such as $a_n = A/10$ or $a_n = A/20$.
- 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 ,

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

- But by using the above expressions for a_f/a_n fission cross sections can't be described accurately.
- Hence, a new approach is used according to which the change in the ratio of the level density parameter is taken in to account with the change in the incident energy of the projectile.
- Iljinov et al. obtained the ratio a_f/a_n 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 values, fission cross sections are calculated from these values at different incident energies of the projectile. The expression obtained is given by:

$$a_f / a_n = a(E^*)^2 + bE^* + c$$

Where, $a = 1.0 \times 10^{-7} \text{ (MeV)}^{-2}$, $b = -3.0 \times 10^{-4} \text{ (MeV)}^{-1}$, $c = 1.2049$, 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 above equation, 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).

Results and Discussion

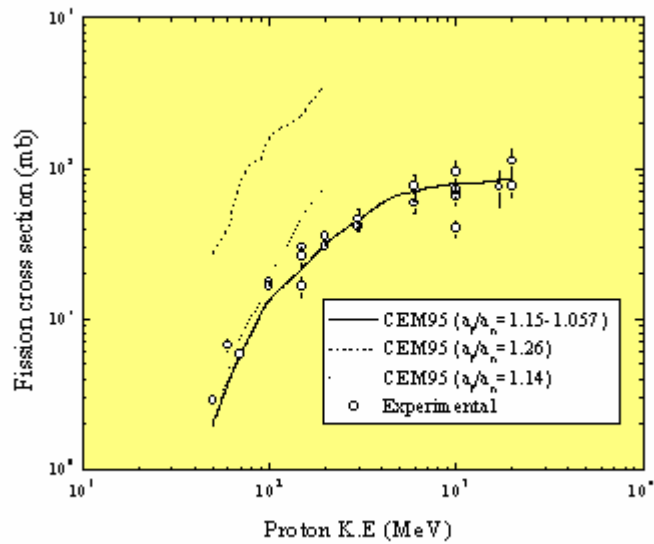


Fig. 1

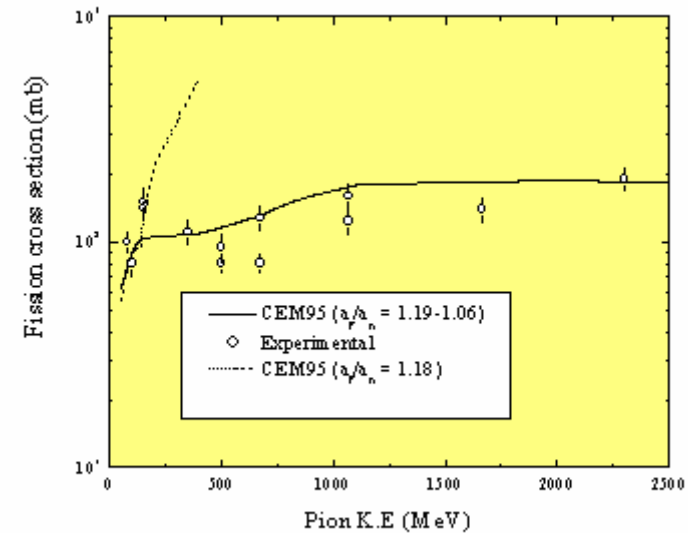


Fig. 2

Figs. 1 and 2 are showing the effect of the ratio of the level density parameters on fission cross sections for proton and pion induced fission, respectively.

Results and Discussion

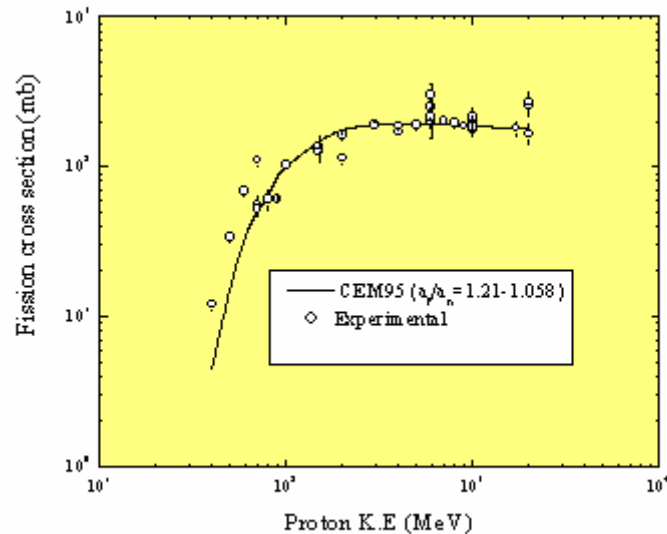


Fig. 3 Computed fission cross sections induced by protons in ^{209}Bi are shown as solid curve and are compared with the experimental data, shown as open circles.

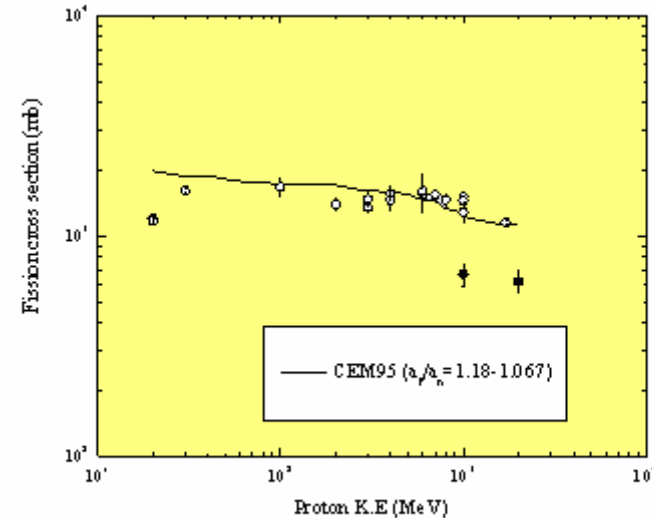


Fig. 4 Computed fission cross sections induced by protons in ^{235}U are shown as solid curve and are compared with the experimental data, shown as open and solid circles.

Results and Discussion

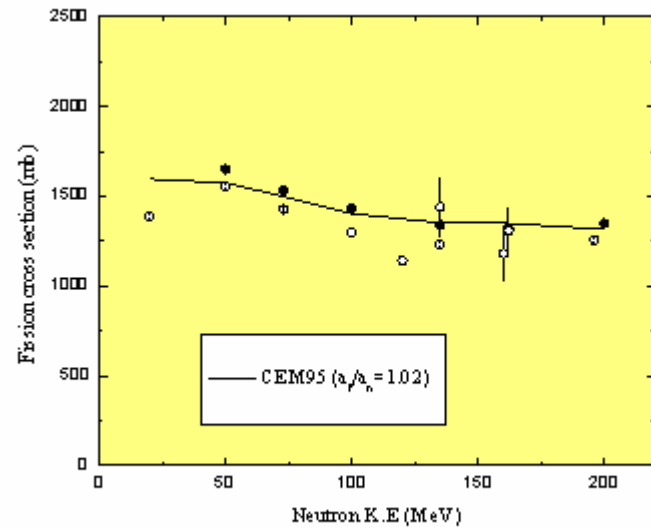


Fig. 5 Computed fission cross sections induced by neutrons in ^{238}U are shown as solid curve and are compared with the experimental data, shown as open and solid circles.

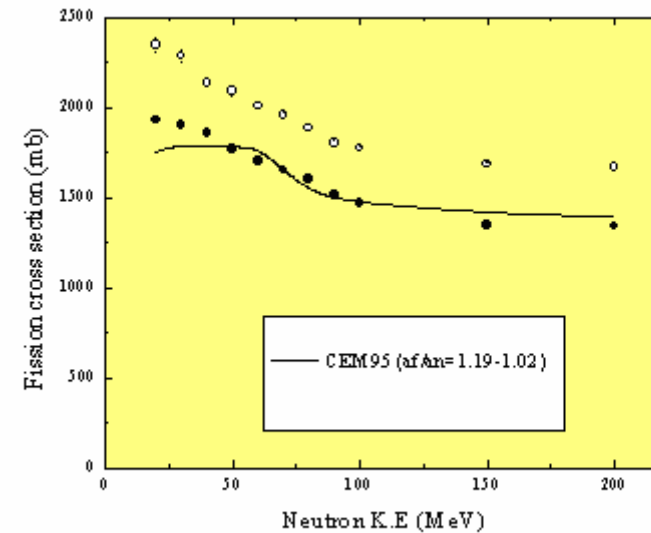


Fig.6 Computed fission cross sections induced by neutrons in ^{239}Pu are shown as solid curve and are compared with the experimental data, shown as open and solid circles.

Results and Discussion

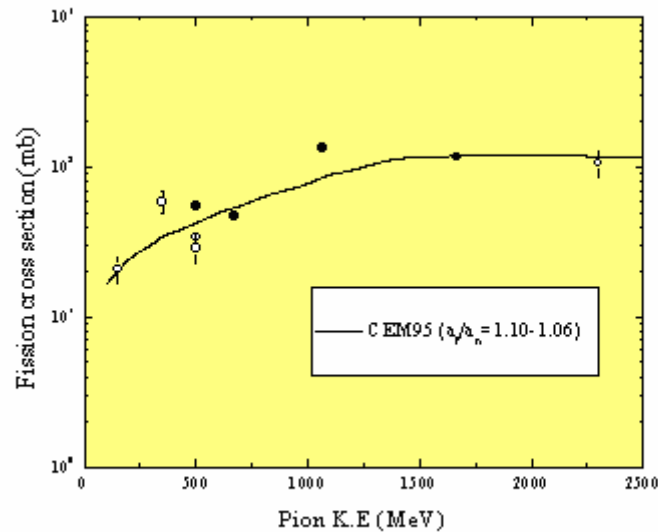


Fig. 7 Computed fission cross sections induced by negative pions in ^{197}Au are shown as solid curve and are compared with the experimental data, shown as open and solid circles.

Results and Discussion

- The new approach used in CEM95 to compute the fission cross sections is valid for nucleons and pions.
- Fission cross sections are found to be 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.
- For light nuclei, fission cross sections indicate an increasing trend with the incident pion energy and then a saturation is observed.

Results and Discussion

- For the selected heavy nuclei, fission cross sections exhibited an increase with an increase in the incident pion energy, eventually reached a maximum value and then started decreasing.
- The increasing behavior is largely due to an increase of coulomb barrier penetrability or due to variations in the reaction cross-section; the decrease in fission cross sections may be due to the opening of new reaction channels or competition with more violent processes.
- The cross sections are useful for new current applications like accelerator driven-systems etc., and for understanding the nuclear structure characteristics.

Thank you