



Fission induced by nucleons at intermediate energies

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Abstract

Monte Carlo calculations of fission of actinides and pre-actinides induced by protons and neutrons in the energy range from 100 MeV to 1 GeV are carried out by means of a recent version of the Liège Intranuclear Cascade Model, INCL++, coupled with two different evaporation-fission codes, GEMINI++ and ABLA07. In order to reproduce experimental fission cross sections, model parameters are usually adjusted on available (p, f) cross sections and used to predict (n, f) cross sections for the same isotopes.

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1. Introduction

Fission induced by nucleons at intermediate energies, i.e. from pion production threshold (~ 150 MeV) to a few GeV, is important from both basic and applied viewpoints. Even if fission is explained as a decay process of residual nuclei formed at the end of the fast nucleon cascade in the spallation reaction, many details are not yet clarified and deserve further experimental and theoretical work.

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Important applications of intermediate energy fission are energy production with accelerator driven systems [1], radioactive waste transmutation [2] and radiation shield design for accelerators: these applications require proton and neutron fission cross sections to be determined with high accuracy in a wide energy range.

Many experimental data have accumulated in the last sixty years: Ref. [3] gives a detailed review of the (p, f) and (n, f) measurements up to the beginning of the present century and Ref. [4] proposes a parametrization of (p, f) cross sections based on the same experimental systematics.

Among the recent (p, f) experiments a prominent role is played by Kotov et al. [5], who give the cross sections tabulated in steps of 100 MeV in the range from 200 MeV to 1 GeV for several actinides very important for applications, ^{232}Th , $^{233,235,238}\text{U}$, ^{237}Np and ^{239}Pu , and for two pre-actinides, ^{nat}Pb and ^{209}Bi , forming the eutectic system acting as a spallation target and as a coolant in an accelerator driven system.

A similar role for (n, f) experiments is currently being played by the n_TOF facility [6] at CERN, which can measure fission cross sections from thermal energies up to about 1 GeV, with a pulsed neutron beam produced by 20 GeV/c protons from the PS accelerator impinging on a lead spallation target. Since measuring an absolute cross section requires simultaneous determination of fission events and neutron flux, which is a very difficult task, the measurements performed up to the present time are relative to $^{235}\text{U}(n, f)$ and absolute cross sections have been obtained by normalizing the experimental ratios to an evaluated $^{235}\text{U}(n, f)$ cross section, commonly taken from the ENDF/B-VII.1 library [7] up to $E_n = 30$ MeV and from the JENDL/HE-2007 library [8] from 30 MeV to 1 GeV. (n, f) cross sections up to 1 GeV have already been published for ^{234}U and ^{237}Np [9], as well as for ^{nat}Pb and ^{209}Bi [10]. Preliminary data have been obtained for ^{232}Th and $^{233,238}\text{U}$.

It is experimentally known [3] that at the lower extremum of the intermediate energy range ($\sim 100\text{--}150$ MeV) the (n, f) cross section is systematically lower than the (p, f) cross section for a given target nucleus, the effect being larger for pre-actinides than for actinides, but the difference tends to decrease with increasing incident energy, so that at 1 GeV the behavior of protons and neutrons is expected to be quite similar and the corresponding fission cross sections of the same order.

Main purpose of the present work is to check whether available (p, f) and (n, f) data for a given target nucleus can be reproduced with satisfactory accuracy using the same set of model parameters, or, at least, with very close values; in the affirmative, where only (p, f) data exist in the energy range of interest, it is reasonable to use them to predict (n, f) data for the same target nucleus, or vice versa.

Our work is similar in spirit to Ref. [11], where use was made of the Los Alamos codes CEM2k + GEM2 (cascade-exciton model plus generalized evaporation model) and LAQGSM + GEM2 (quark-gluon string model plus generalized evaporation model) in order to reproduce (p, f) cross sections for pre-actinides and actinides, from ^{165}Ho to ^{239}Pu , taken mainly from Prokofiev's systematics [4], extending the calculations to a large energy range, from tens of MeV to 5 GeV. With CEM2k + GEM2, good fits were obtained by adjusting only two parameters, the ratio, a_f/a_n , of level density parameters in the fission and evaporation channels for fissioning nuclei with atomic number $70 \leq Z_f \leq 88$ and a constant, $C(Z_f)$, in a semi-empirical parametrization of the ratio, Γ_n/Γ_f , of neutron and fission width for $Z_f \geq 89$. Using the same parameters, (n, f) , (π, f) and (γ, f) cross sections were calculated for the same nuclei and reasonable agreement with experimental data was obtained in several cases. With LAQGSM + GEM2, the set of parameters fitted from (p, f) reactions made it possible to reproduce fis-

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