A study for measuring proton induced fission cross sections using surrogate reaction method

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Introduction

Nuclear data sets for neutron and proton induced reactions are of great importance for application part as well as for understanding the nuclear processes. Nuclear data for short lived nuclei is scarce and difficult to measure, so indirect methods such as "surrogate reaction technique" have to be used. Surrogate reaction method is used to determine the reaction cross sections for short lived nuclei or when the required incident particle energy or flux is not available. This method is based on Bohr's independence hypothesis and requires validity of Weisskopf - Ewing approximation which states that decay of a compound nucleus is independent of the parity and spin of the compound nucleus. The intermediate compound nucleus formed in desired reaction ($\mathrm{a + A \rightarrow B^* \rightarrow C + c}$) is populated in a surrogate reaction ($\mathrm{d + D \rightarrow B^* + b}$). Cross section for the desired reaction can be given as

$$\sigma^{\alpha\beta}(\mathrm{E}) = \sigma^{\alpha}_{\mathrm{CN}}\mathrm{P}^{\beta}(\mathrm{E})$$

Where entrance and exit channels are represented by α and β respectively. The compound nucleus formation cross section $\sigma^{\alpha}_{\mathrm{CN}}$ can be calculated using optical model potentials. Decay probability $\mathrm{P}^{\beta}(\mathrm{E})$ is measured experimentally by measuring total number of ejectiles and coincidences between ejectile b and β (decay channel). In literature there are different versions of this method absolute surrogate method, surrogate ratio method and hybrid surrogate ratio method [1].
This method have been used extensively for calculating the cross sections for neutron induced reactions e.g. $(n, f), (n, \gamma)$, and (n, p). In principle reaction cross sections for proton induced reactions can also be measured using this method [2]. To study the possibility of doing so, we have calculated $^{240}Pu(p, f)$ reaction cross sections using the experimental decay probabilities of $^{241}Am^*$ from the work of R. J. Casperson *et al.* [3]. They used surrogate ratio method to calculate $^{240}Am(n, f)$ cross sections. In the following section we have described the method used to calculate the $^{240}Pu(p, f)$ cross sections. In this work we have assumed the validity of independence hypothesis and Weisskopf - Ewing approximation.

Methodology

Our desired reaction is

$$^{240}\mathrm{Pu} + \mathrm{p} \rightarrow ^{241}\mathrm{Am}^* \rightarrow \mathrm{fission}$$

Same compound nucleus (i.e. $^{241}Am^*$) is formed in following reaction

$$^{240}\mathrm{Am} + \mathrm{n} \rightarrow ^{241}\mathrm{Am}^* \rightarrow \mathrm{fission}$$

. Since both nuclei ^{240}Pu and ^{240}Am have same number of nucleons in them, we can assume the validity of Weisskopf- Ewing approximation. Hence same surrogate reaction can be used for calculating experimental decay probabilities of the compound nucleus. The cross sections for $^{240}\mathrm{Am(n, f)}$ reaction were measured by R.J. Casperson *et al.* [3] for neutron energies $0 - 14$ MeV. They used $^{235}\mathrm{U(n, f)}$ as reference reaction and compound nuclei $^{241}\mathrm{Am}^*$ and $^{236}\mathrm{U}^*$ were formed in $^{243}\mathrm{Am(p, t)}^{241}\mathrm{Am}^*$ and $^{238}\mathrm{U(p, t)}^{236}\mathrm{U}^*$ reactions. The experimental details can be

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found in Ref. [3]. Based on Hauser-Feshbatch formalism we can write the following equation

$$\frac{\sigma({}^{240}_{94}\mathrm{Pu(p,f))(E)}}{\sigma({}^{240}_{95}\mathrm{Am(n,f)(E))}} = \frac{\sigma_{\mathrm{CN}}^{{}^{240}_{94}\mathrm{Pu+p}}(\mathrm{E})}{\sigma_{\mathrm{CN}}^{{}^{240}_{95}\mathrm{Am+n}}(\mathrm{E})} \frac{\mathrm{P}_{\mathrm{f}}^{{}^{241}_{95}\mathrm{Am}}(\mathrm{E})}{\mathrm{P}_{\mathrm{f}}^{{}^{241}_{95}\mathrm{Am}}(\mathrm{E})}$$

The fission decay probabilities will cancel each other out, and we are left with following relation

$$^{240}\mathrm{Pu(p,f)(E)} = \frac{\sigma_{\mathrm{CN}}^{{}^{240}\mathrm{Pu+p}}(\mathrm{E})}{\sigma_{\mathrm{CN}}^{{}^{240}\mathrm{Am+n}}(\mathrm{E})} {}^{240}\mathrm{Am(n,f)(E)}$$

Experimental data for $^{240}\mathrm{Am(n,f)}$ was retrieved from EXFOR data library (Entry number 14397). Nuclear reaction code EMPIRE-3.2 was used to calculate compound nucleus formation cross sections. Excitation energies of $^{241}Am^*$ were calculated from neutron energies by using $\mathrm{E}(^{241}\mathrm{Am}) = (\frac{\mathrm{A}}{\mathrm{A+1}})\mathrm{E_n} + \mathrm{S_n}(^{241}\mathrm{Am})$ and equivalent proton energies were calculated from these excitation energies: $\mathrm{E_p} = (\frac{\mathrm{A+1}}{\mathrm{A}})(\mathrm{E}(^{241}\mathrm{Am}) - \mathrm{S_p}(^{241}\mathrm{Am}))$, here $\mathrm{S_n}(^{241}\mathrm{Am})$ and $\mathrm{S_p}(^{241}\mathrm{Am})$ are neutron and proton separation energies of $^{241}\mathrm{Am}$ respectively. The uncertainties of $^{240}\mathrm{Am(n,f)}$

TABLE I: Neutron and proton separation energies used for the calculation.

CN	Transfer reaction	$S_n(MeV)$	$S_p(MeV)$
^{241}Am	$^{243}Am(p,t)^{241}Am$	6.647	4.479

cross sections were propagated through second equation to calculate uncertainties in $^{240}\mathrm{Pu(p,f)}$ cross sections by using general law of uncertainty propagation, the uncertainties in compound nucleus formation cross sections were not taken in to account for the present calculations. Calculated cross sections with error bars are shown in Fig. 1.

Results

The fission cross sections for the desired reaction were also calculated using TALYS 1.8 [4]. We used different fission models with different fission barriers, like fismodel 1 (fission barriers based on experimental data), fismodel 2 (it uses extended Thomas-Fermi plus Strutinsky integral calculations), fismodel 3 (rotating finite range model i.e. RFRM) and fismodel 4 (it uses rotating liquid drop model (RLDM)) [4]. Cross sections calculated for $^{240}\mathrm{Pu(p,f)}$ reaction are in agreement with the JENDL-4.0 data and also with fission model 2 and 3 while calculations from experimental fission barriers (i.e. fismodel-1) are small as compared with the present results, given in Fig. 1. The fair agreement of calculated values with theoretical predictions and JENDL-4.0 data library shows that proton induced fission cross sections can be derived using the surrogate reaction technique.

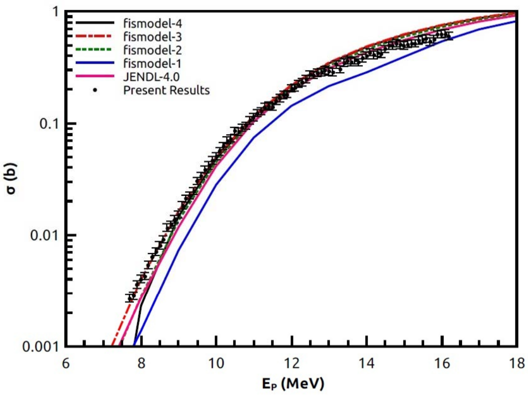

FIG. 1: $^{240}Pu(p,f)$ reaction cross sections with varying proton energies.

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