Determination of the ^{234}Pa(n,f) reaction cross section by hybrid surrogate ratio method

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Introduction

In recent years, the surrogate reaction methods in various forms have been employed to get indirect estimate of the neutron induced fission reaction cross sections of many compound systems in actinide region that are unavailable because of the lack of the target material of suitable lifetime[1–4]. In an earlier work, we employed a new hybrid surrogate ratio approach to determine the ^{233}Pa(n,f) cross sections for the first time in the equivalent neutron energy range of 11.5 MeV to 16.5 MeV using ^{6}Li+^{232}Th transfer-fission correlation measurements. The ^{234}Pa isotope produced in thorium-uranium fuel cycle is having half-life of 6.8 hrs. There is no neutron induced fission cross section data available in the literature for this system. We report first time results on ^{243}Pa(n,f) cross sections in the equivalent neutron energy range of 10.5 MeV to 15.5 MeV using ^{7}Li+^{232}Th transfer-fission correlation measurements with in the framework of hybrid surrogate method. Using a single target the compound nuclei ^{235}Pa and ^{236}U are formed in-situ in two different direct reaction channels ^{232}Th(^{7}Li, α)^{235}Pa and ^{232}Th (^{7}Li,t)^{236}U having ground state Q-values 5.60 MeV and -7.04 MeV respectively. Because of the opposite signs of the Q-values in the two reaction channels, it is possible to populate the ^{235}Pa and ^{236}U compound systems at overlapping energies in ^{7}Li+^{232}Th reaction for bombarding energies around 39.0 MeV. The projectile-like-fragment (PLF)-singles and coincidence between PLF and fission fragment measurements were carried out to determine the fission decay probabilities of the ^{236}U and ^{235}Pa compound nuclei produced in the transfer reactions within the framework of the absolute surrogate method by dividing the number of PLF-fission coincidences ($N_{\alpha_i,f}$) by associated PLF-singles (N_{α_i}) data as follows:

$$\Gamma_f^{CN}(E_{ex}) = \frac{N_{\alpha_i - f}}{N_{\alpha_i}} \qquad (1)$$

Where α_i denotes the alpha or triton channel corresponding to ^{235}Pa or ^{236}U compound nucleus. The relative fission probabilities of the compound nuclei are multiplied with relative neutron induced corresponding surrogate reaction compound nuclear formation cross sections of $\sigma^{CN}_{n+^{234}Pa}$ and $\sigma^{CN}_{n+^{235}U}$ to obtain the ratio of the compound nuclear reaction cross section at same excitation energies of n+^{234}Pa → fission and n+^{235}U → fission reactions as follows:

$$\frac{\sigma_f^{n+^{234}Pa\rightarrow^{235}Pa}(E_{ex})}{\sigma_f^{n+^{235}U\rightarrow^{236}U}(E_{ex})} = R(E_{ex})$$

$$= \frac{\sigma^{CN}_{n+^{234}Pa}(E_{ex})}{\sigma^{CN}_{n+^{235}U}(E_{ex})} \times \frac{\Gamma_f^{235}Pa(E_{ex})}{\Gamma_f^{236}U(E_{ex})} \qquad (2)$$

The n+^{235}U → ^{236}U → fission cross section which is well measured has been used as reference monitor to determine n+^{234}Pa → ^{235}Pa → fission cross section from the R(E_{ex}) measurement. This is hybrid surrogate approach which involves aspects of both absolute and ratio surrogate method.

Experimental Details

A self-supporting thorium target of thickness 2.0mg/cm^2 was bombarded with ^{7}Li beam of energy E_{lab}=39.5 MeV from 14MV Pelletron accelerator at Mumbai. A solid state ΔE-E

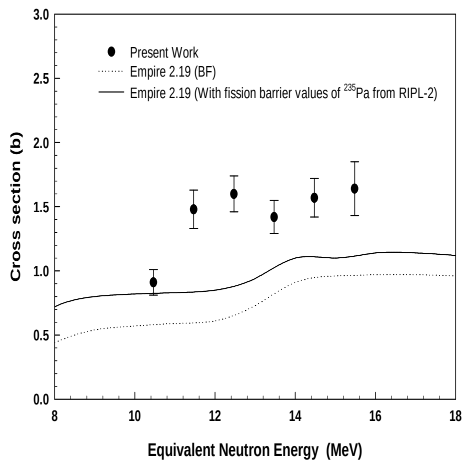

FIG. 1: Experiment ^{234}Pa(n,f) cross section and calculated results using the Empire2.19 code.

telescope of thickness 150.0μm - 1.0mm was kept at $\theta_{\rm lab}$=90° with respect to the beam direction around the transfer grazing angle to identify the PLFs. A 16 strip solid state detector (each strip of size 2.0mm×64.0mm) was placed at back angle covering laboratory angular range of 141° to 158° to detect fission fragments in coincidence with PLFs. The time correlation between PLFs and fission fragments are recorded through a time-to-amplitude converter(TAC). The ratio of the coincidence to single counts for ^{232}Th(^{7}Li, α)^{235}Pa and ^{232}Th (^{7}Li,t)^{236}U reaction channels were determined as a function of excitation energy using two-body kinematics.

Results and Discussion

The ratios of coincidence to singles counts were determined in steps of 1.0 MeV excitation energy bins in the excitation energy range 16.5 to 21.5 MeV for ^{235}Pa and ^{236}U nuclei. For each excitation energy bin the ratio of fission decay probability of ^{235}Pa and ^{236}U was determined. Using Eqs. (1) and (2), the ^{234}Pa(n,f) cross sections for each excitation energy bin was obtained using n+^{235}U $\rightarrow$ ^{236}U $\rightarrow$ fission reaction cross section as reference. The excitation energy was scaled down to the equivalent neutron energy range by subtracting the neutron separation energy of ^{235}Pa(S_n=6.01 MeV). The experimental ^{234}Pa(n,f) cross sections as a function of equivalent neutron energy along with the Empire 2.19 predictions are shown in Fig.1. The inner and outer fission barriers for ^{235}Pa are 5.5 MeV and 6.1 MeV respectively as obtained from barrier formula(BF)[1]. For the second and third chance fission cross section calculations the fission barrier heights corresponding to various Pa isotopes were same as required to fit ^{234}Pa(n,f) data[1]. The Empire 2.19 predictions on ^{234}Pa(n,f) cross section values are lower in comparison to experimental cross section values corresponding to BF fission barrier heights. The calculations slightly improve by using RIPL-2 fission barriers of 5.1 MeV and 5.7 MeV for ^{235}Pa isotope but still underpredicts the experimental cross section values except at the lowest neutron energy. The Empire 2.19 predictions do not change much by further reducing the ^{235}Pa fission barrier heights. The sensitivity of Empire 2.19 specific parameters are being investigated and the detailed results of the analysis will be presented.

Acknowledgments

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References

[1] B.K. Nayak *et al.*, Phys. Rev.C78, 061602 (2008) and references there in.

[2] J.M. Allmond *et al.*, Phys. Rev. C79, 054610 (2009).

[3] S. R. Lesher *et al.*, Phys. Rev. C 424, 1 (2009).

[4] M.S. Basunia *et al.*, Nucl. Instr. and Meth., B267, 1988 (2009).