BARC–TIFR Pelletron Linac Facility Beam Time Request @2024

Title of the Experiment: Measurement of short-lived fission products in $^{6}Li+^{232}Th$ reaction to investigate the role of neutron and proton shells.

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Local Collaborator / Spokesperson: NA

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Motivation of the experiment: To achieve a comprehensive understanding of the role of neutron and proton shell closure in the region from sub-lead to the actinide region.

Beam details: ^{6}Li, 39.9 MeV, >8 pnA, Scattering chamber, Hall 1, and 0^{0}, Hall 2 Irradiation Chamber.

Buncher requirement: No

Number of shifts (1 shifts=8 hr.) required: 9

Experiment details:

1. **Objective of Experiment:**

There has been a renewed interest in investigating the role of neutron and proton shell closure as well as of the excitation energy in governing the fission mass distribution [1-3]. The recent studies have been aimed towards achieving a comprehensive understanding from sub-lead region to actinide region. These studies show that shell effects persist up to several tens of MeV of energy in the actinide and pre-actinide region [2-4], particularly more pronounced for higher chance fission. In our recent study of the fission product mass distribution of $^{12}C+^{232}Th$ reaction, a clear deviation from single Gaussian was observed at compound nucleus excitation energy of 37.6 MeV due to the presence of asymmetric fission. The experimental mass distribution was observed to be in good agreement with the GEF (v2021) [5,6] calculations, which attributed the asymmetric contribution mainly to the standard asymmetric mode S2 (corresponding to Z~55) and asymmetric mode S1 (corresponding to Z~52) [7]. Measurement of angular distribution of fission products also clearly showed the role of shell effects [8]. In another study, a detailed comparison of the fission product yields from $^{235}U(n_{th},f)$ reaction was carried out with those calculated using the GEF code, which showed inadequacy of the S2 mode (Z~55) to explain the yield of asymmetric fission products [9]. In this study, a systematic underestimation was observed around N~88 by the GEF calculations. These recent observations, suggest that it is required to measure the yield of fission fragments / products with information about both mass and atomic number to investigate the role of neutron and proton shells closure. Therefore, it is proposed to measure the fission product mass distribution in $^{6}Li+^{232}Th$ reaction using recoil catcher technique for the detection of mass and charge identified fission products using high resolution gamma-ray spectrometry. In addition to the measurement of overall mass distribution, the focus of the proposed study will be on the measurement of short-lived fission product having half-lives in the range of ~s to avoid the loss of information on the yields of a large number of fission products to the beta decay prior to the measurement, in general.

The ^{6}Li beam has been chosen for the proposed experiment to avoid the formation of very different fissioning systems in complete fusion fission and transfer channels. Also, a weakly bound projectile has been deliberately chosen so that there will be only three dominant fission channels, namely, i) complete fusion forming ^{238}Np, ii) ^{2}H transfer forming ^{234}Pa and iii) ^{4}He transfer forming ^{236}U. It should be mentioned here that same nucleon shells would be governing the fission product yields in transfer as well as complete fusion channels due to the very similar nature of the fissioning systems. Thus, here, the focus wouldn't be the segregation of fission from different reaction channels, which have mainly been the focus of fusion-fission studies with ^{6}Li so far. Rather, the primary objective of the proposed study would be to measure the yields of as many product isotopes as possible with different Z, particularly in the Z region ~52-56 dominated by S1 and S2 asymmetric fission modes. This would also help in clearly looking into additional neutron shells if present. This would require measurement of large number of short-lived fission products.

It is proposed to carryout detailed measurement of fission product yields in $^{6}Li+^{232}Th$ reaction at beam energy of 37 MeV. The choice of beam energy is based on a compromise of achieving low excitation energy and high fission cross section. Typical mass distributions for the complete fusion and transfer channels as calculated using the GEF code at 37 MeV beam energy are shown in Figs. 1(a-c). For the transfer channels, the excitation energy of the fissioning nuclei ^{234}Pa and ^{236}U were calculated assuming that the corresponding out-going PLF keeps on moving with the beam velocity after transfer. Strong role of shell effects, as predicted in the calculations for all the channels can be seen in these figures. As shown in ref [10], the contribution from complete fusion fission (CFF) in this reaction increases from nearly ~20% at the beam energy close the entrance channel Coulomb barrier to a nearly constant value of ~80% at beam at beam energy above ~1.25 times the entrance channel Coulomb barrier. Based on the interpolation from ref [10], contribution from CFF would be 70% at beam energy of 37 MeV. Thus, the overall average excitation energy, considering CFF as well as transfer induced fission (TF) would be about 32.3 MeV as given in Table I. The contribution from different fission modes (symmetric super long SL, standard asymmetric modes S1 and S2) after combining CFF and TF are also given in Table I. Contribution from these modes for individual fissioning nucleus were calculated using the GEF code [5,6]. As seen from the table, the contribution from asymmetric fission modes would be more than ~50%. Also, the total fission cross section at this beam energy (taken from ref [11]) is 511±51 mb. Thus, the proposed experiment would provide the opportunity to investigate the strong shell effects with good cross section.

(a) ^{6}Li+^{232}Th$\rightarrow$^{238}Np (38.2 MeV) (b) ^{6}Li+^{232}Th$\rightarrow$^{234}Pa+^{4}He (19.0 MeV) (c) ^{6}Li+^{232}Th$\rightarrow$^{236}U+^{2}H (18.2 MeV)

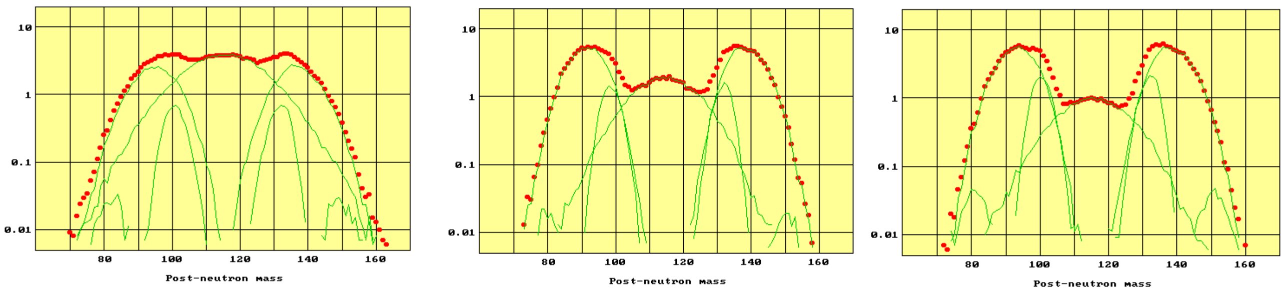

Fig. 1. Fission products mass distribution in ^{6}Li+^{232}Th reaction for complete fusion fission (a) and ^{2}H (b) ^{4}He (c) transfer fission as calculated using the GEF code [5,6] at beam energy of 37 MeV. Excitation energies of the fissioning nuclei are given inside parentheses.

2. Description of Experiment:

Charge and mass identified fission products will be measured using recoil catcher technique followed by off-line gamma-ray spectrometry. The experiment would be broadly divided into two parts. In the first part (set-up 1), a self-supporting ^{232}Th target having sufficient thickness of 2 mg/cm^2, sandwiched between two aluminium catcher foils of thickness 6.75 mg/cm^2 (Fig. 2) will be irradiated for short intervals to measure the short-lived fission products. Two HPGe detectors for high resolution gamma-ray spectrometry would be placed close to the target (~8-10 cm) at 120^0 to follow the decay of the fission products immediately after stopping the irradiation without removing the target. A schematic of the set-up is given in Fig. 2. This would enable the measurement of fission products having half-life in the range of ~s. The lowest half-life of fission product, for which yields can be measured, would be around ~5 s. This limit comes from the possibility of strong Compton background arising from the multiple gamma-rays arising from the decay of ^{30}S ($T_{1/2}$=1.18 s), a reaction product from ^{6}Li+^{27}Al reaction. Though, the neutron transfer product ^{28}Al has a half-life of 2.24 min, it has only one high energy gamma-ray of 1.78 MeV. Other reaction products arising from reaction with Al are not expected to significantly affect the present measurements, due to products being stable or having very low gamma intensities. After completing the short irradiation experiments, long irradiations of similar target catcher assembly (set-up 2) will be carried out to measure the yields of fission products with half-lives of several minutes to days. Beam current will be continuously monitored in both the set-up to accurately determine the irradiation start and stop time as well as any fluctuation in the beam intensity during irradiation. After completion of long irradiation, target-catcher assembly would be removed from the irradiation chamber and will be counted using a HPGe detector to follow the decay of fission products up to about 2 months.

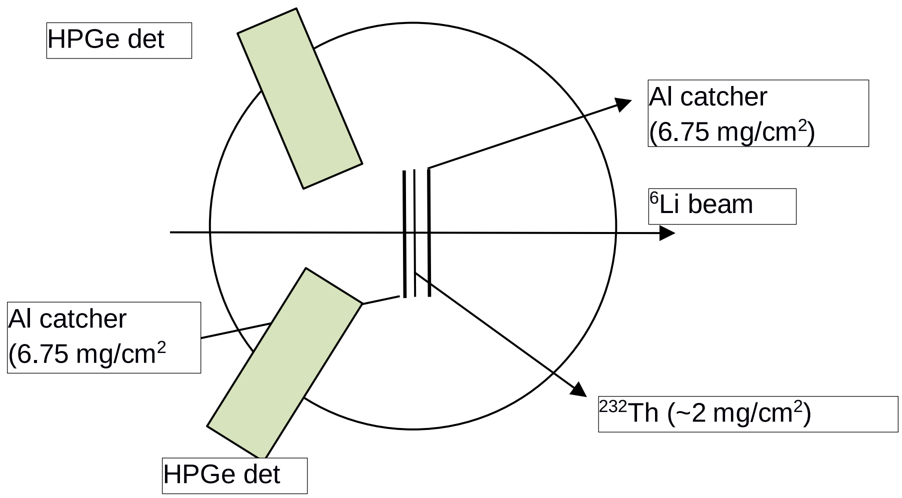

Fig. 2. Schematic of irradiation set-up 1 in scattering chamber

Details of required beam energy from the BARC-TIFR Pelletron-LINAC facility, beam energy incident at the target, excitation energy, fission cross sections and irradiation times are given in Table 1. The loss of beam energy in backward catcher foil was calculated using the code SRIM [12].

Table I:

Energy incident at irradiation assembly	Energy incident at ^{232}Th target	E^* (MeV)	$\sigma_{fission}$ (mb) [11]	$\langle E^* \rangle$ (MeV)	Contribution for different fission modes [5,6]	Irradiation time (hrs)	
39.9 MeV	37 MeV	38.2 (^{238}Np) 19.0 (^{234}Pa) 18.2 (^{236}U)	511±51	32.3	SL: 46.5% SA1: 8.4% SA2: 44.9%	Set-up 1 in scattering chamber of LINAC hall 1 for short-lived fission products 18	Set-up 2 in irradiation chamber in LINAC hall 2 for longer-lived fission products 36

- Time for setting up, irradiation assembly mounting, vacuum and beam-line switching: 18 hrs
- Total beam-time required: 72 hrs (9 shifts)

The irradiation time has been estimated based on the fusion cross section and experimentally measured activities of fission products in earlier experiments. Including the 18 hrs time required for setting up, target mounting and beam-line switching, the total beam time requirement is 72 hrs (9 shifts).

References

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- **Whether the experiment is part of PhD /Post Doc. Work:** No
- **Details of Beam time availed of in recent past on this experiment and / or by the PI:** NA
- **Details of papers published / presented in journals / symposia, etc. based on recent experiments:**

  1. Satyam kumar et al., Eur. Phys. J A (under review); S. Kumar et al., in Proceedings of DAE Symposium on Nuclear Physics, **67**, 401 (2023).

  2. Satyam Kumar et al., Phys. Rev. C (under review); S. Kumar et al., in Proceedings of DAE Symposium on Nuclear Physics, 67, 573 (2023).