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BARC - TIFR Pelletron LINAC Facility

Beam Time Proposal

Measurement of neutron capture reaction cross section on ^{88}Zr isotope using Surrogate Reaction Method

Neutron capture cross section data are of fundamental importance in nuclear science, such as the nuclear reactor performance, reactor waste management, nuclear security, stellar nucleosynthesis, nuclear medicine and defence applications. Obtaining the reliable neutron capture cross section data for radioactive targets remains a formidable challenge. In addition, understanding the formation of elements greater than iron, neutron capture reactions plays a crucial role. In recent years several indirect methods are developed to overcome in measuring the neutron induced reaction cross section for unstable isotopes [1, 2]. The accuracy of these reaction cross section data decides the safety assessment of the nuclear energy production. The presence of the neutron energy spectra above the traditional energy limits of fission reactors, for accelerator driven systems and advanced fusion reactors open up large number of threshold reaction channel such as (n, γ), (n, 2n), (n, p), (n, α), (n, np), (n, d), (n, 3n) and (n, nα) etc. [3].

The larger neutron capture reaction agent in nuclear reactor environment causes neutron poisons in fuel and lower the performance of the reactor. In the reactor Zirconium (Zr) is used as cladding materials for PHWR. The transmutation reactions on the stable Zr materials may produces radioactive isotopes, such as ^{88}Zr (half-life $t_{1/2}$= 83.4 days) for neutron energies above 21 MeV in spallation or ADS. However, the nuclear reaction model codes predictions on these radioactive isotopes rely on the cross section information, but there are limited or no data which is making it challenging. In addition, ^{88}Zr isotope is used as a tracer in radio-pharmaceutical research and for diagnostic nuclear weapons. It may also contribute to the nucleosynthesis of rare neutron deficient nuclides, which is of interest in nuclear astrophysics [4] . For ^{88}Zr, there is only one measurement for (n, 2n) reaction at 14.8 MeV neutron energy, while for (n, γ) reaction at 25 meV neutron energy by Shusterman et al. in 2019 [5] which shows a surprisingly large thermal neutron capture cross section of ^{88}Zr around 861,000 ± 69000 barns (1σ uncertainty). Gamma spectroscopy method was used to extract the cross section of ^{88}Zr(n, γ), where ^{88}Zr radio active target was prepared by ^{89}Y(p, 2n) reaction. In recent years, SRM became major tool in extracting neutron induced reaction cross section of unstable nuclei [2].

In the proposed experiment, it is proposed to measure the cross section of ^{88}Zr(n, γ) via surrogate reaction method at proton beam of 19.5-21.5 MeV energies. The compound nucleus is produced via p + ^{90}Zr → d + ^{89}Zr* and the outgoing deuteron

(d) is detected in coincidence with γ rays. The deuteron angle θ_d and energy E_d determine the excitation energy E_{ex} at which ^{89}Zr was produced. A range of energies, with $E_{ex} > E_n$, must be populated, so that the competition between γ-emission, neutron emission, and other decay channels can be studied in coincidence with the deuteron. The schematic representation of the surrogate reaction method shown in Fig.1.

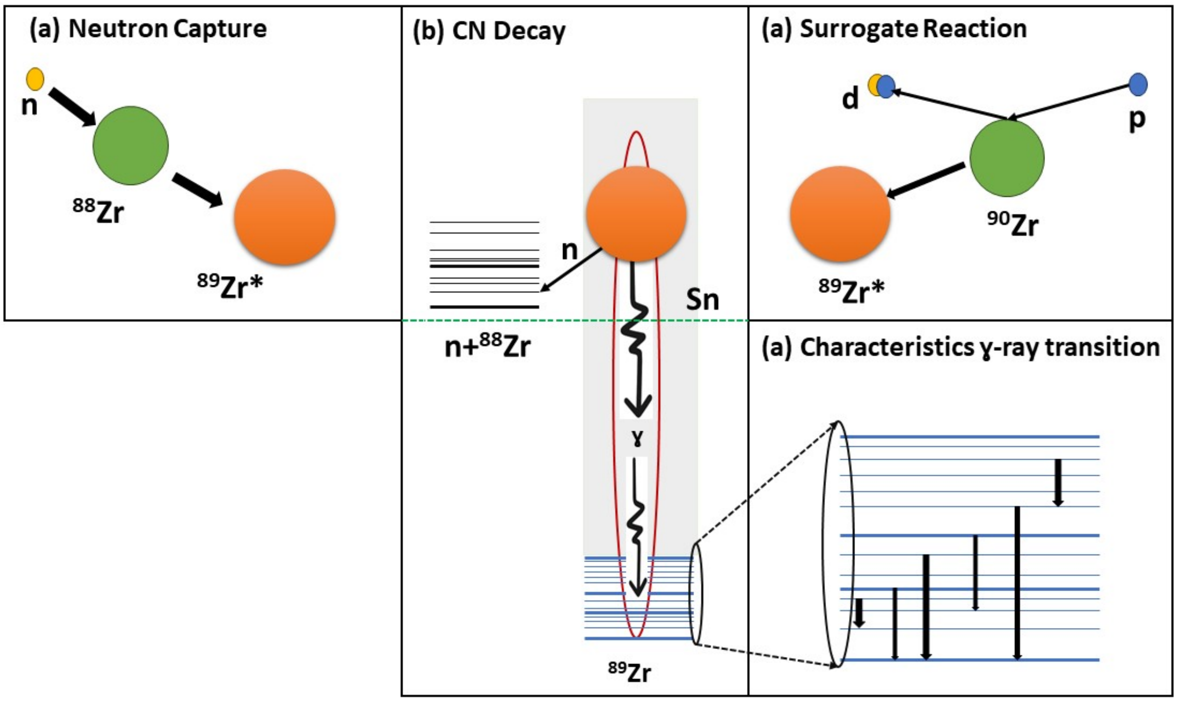

Fig. 1. Surrogate measurement of the ^{88}Zr(n, γ) cross section. Because of the short lifetime of ^{88}Zr, the reaction is difficult to measure directly. In the surrogate experiment, the first step of the capture reaction n + ^{88}Zr → ^{89}Zr* (a) is replaced by the p + ^{90}Zr→ d + ^{89}Zr* reaction (c), which produces the same CN, ^{89}Zr*. The subsequent decay of ^{89}Zr* (b) is then measured and used to extract the ^{88}Zr(n, γ) cross section. (d) γ-rays associated with transitions between known levels of ^{89}Zr are used to identify the decay path.

The **surrogate reaction method** is an indirect method which was first used in the 1970s for estimating neutron-induced fission cross-sections. In recent years, this method has been recognized as a potentially powerful tool for a wide range of applications that involve compound nuclear reactions. The experimentally constrained calculations yield desired capture cross-sections. In Bohr's hypothesis, the decay of compound nucleus is independent of its formations and this is exploited in the surrogate reaction approach by constraining decay probabilities, experimentally and by proper accounting for the spin-parity dependence. The spin parity dependence will be constrained by DWBA calculation and measured pickup reaction. The compound nucleus (B^*) formed in the reaction of interest ($a + A \rightarrow B^* \rightarrow c + C$) that involves difficult-to-produce targets is produced via an alternative reaction, called a surrogate reaction ($d + D \rightarrow B^* + b$), which involves a stable projectile–target combination (d + D) that is experimentally more feasible. The decay of B^* is observed in coincidence with the outgoing direct reaction particle 'b'. In this study, we plan to measure the $^{88}Zr(n, \gamma)^{89}Zr$ reaction cross-section by the $^{90}Zr(^{1}H, d)^{89}Zr^*$ as surrogate of the n + ^{88}Zr reaction. Similar studies are being reported earlier [6-10].

For the present experiment, the surrogate reaction of interest, the ground-state Q-values, the compound nuclei (CN) formed, neutron separation energies (S_n), and corresponding equivalent neutron capture reaction are listed in Table 1.

Table 1. Surrogate reaction investigated in the present experiment, the ground-state Q-value (Q_{gg}), the CN formed, neutron separation energie (S_n), and corresponding equivalent neutron induced reaction.

E^{1H}_{beam} (MeV)	Surrogate Reactions	Q_{gg} (MeV)	S_n (MeV)	Equivalent neutron Capture reaction
19.5-21.5	$^{90}Zr(^{1}H, d)^{89}Zr^*$	-9.74 MeV	9.320	$^{88}Zr(n, \gamma)^{89}Zr$

References:

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2. J. E. Escher *et al.*, Phys. Rev. Lett. 121, 052501 (2018).
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4. Matyskin A.V. *et al. Sci Rep* 13, 1736 (2023).
5. Shusterman et al. *Nature* **565**, 328–330 (2019).
6. Jutta E. Escher *et al.* Rev. Mod. Phys. **84**, 353 (2020).
7. Jutta E. Escher *et al.*, Phys. Rev. C 74, 054601 (2006).
8. J. D. Cramer and H. C. Britt, Phys. Rev. C 2, 2350 (1970).
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Experimental Setup

Target: ^{90}Zr of thickness ~ 500 µg/cm^2

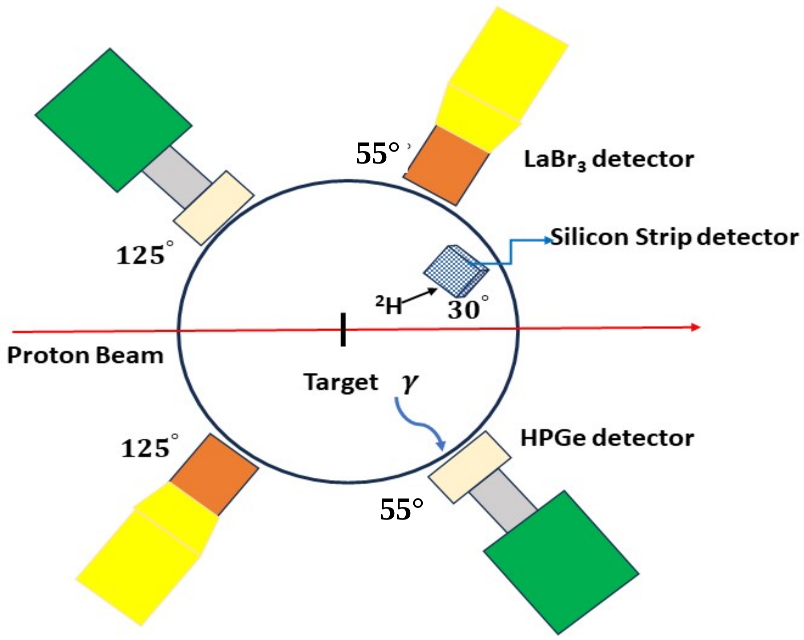
Beam: ^{1}H

Energy: 19.5, 20, 20.5, 21, & 21.5 MeV

Detector: One Double Sided Silicon Strip detector, two HPGe detectors, and two LaBr3 detectors.

Experimental Details:

Proton beam of energies ranges from 19.5-21.5 MeV will be used to bombard the targets of ^{90}Zr. CASCADE Hall-15N beam line will be used for this experiment. The deuteron which is a projectile like fragment (PLF) will be identified by the Silicon Strip Detector placing inside the scattering chamber at 30°. Two HPGe detectors and two LaBr3 detectors will placed an angle of 55° and 125° alternatively to measure the coincidence of gamma rays. The schematic representation of the proposed experiment shown below.



Beam time estimation:

Reaction	Energy(MeV)	Cross section(mb)	No of shifts required
^{90}Zr(^{1}H,d)^{89}Zr*	19.5, 20, 20.5, 21& 21.5	~10 for neutron pickup reaction	**14**
Setup			**1**
Total			**15**