BARC–TIFR Pelletron Linac Facility Beam Time Request @2024

Title of the Experiment: Exploring E1 transitions at particle-emission threshold near $N = 50$ shell closure through neutron pickup reaction

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Motivation of the experiment:

There is a significant focus on unraveling the characteristics of low-lying E1 strength at particle-emission thresholds or close to neutron-separation energies after Bartholomew et al. observed an enhanced strength of γ rays around 5 – 8 MeV while studying thermal neutron-capture reactions. The E1 transitions near the particle separation energy are termed Pygmy Dipole Resonance (PDR). They exhaust a tiny fraction of the Thomas–Reiche–Kuhn (TRK) sum rule contrary to the Giant Dipole Resonance (GDR) which exhausts a large fraction of this sum rule. The study of PDR strength distribution significantly contributes to our insights into the EoS for isospin-asymmetric environments, such as neutron stars [1,2]. Moreover, since PDR represents the 1^- states close to the neutron-separation energy, understanding its nature will also aid in understanding neutron capture and r-process nucleosynthesis [3].

Following its discovery, numerous theoretical and experimental endeavors have been undertaken to unravel the microscopic structure of the Pygmy Dipole Resonance (PDR) [4,5]. However, despite these efforts, several unresolved questions persist, impeding a systematic understanding of the underlying microscopic structures of the PDR. These inquiries include whether there exists an onset of single-particle characteristics within the PDR, discerning how nuclear level densities contribute to the fragmentation observed in the PDR strength, and investigating how the distribution of strength within the PDR is influenced by the deformed shapes of nuclei in their ground states.

Beam details:

Beam species: Proton

Beam energy in (MeV): 20 MeV

Beam current in (pnA): 1 pnA

Beam Port: Cascade Hall port 30 Deg South

Buncher requirement: No

Number of shifts (1 shifts=8 hr.) required: 18 shifts (Experiment/Data taking), 6 shifts (Setting up/Calibration) (Please see below for the estimation).

Experiment details:

1. **Objective of Experiment:**

In PDR, the excess neutron fluid oscillates against the isospin-symmetric core of the nucleus ($N = Z$), giving rise to low-lying electric dipole modes with weak transition strengths near the particle-emission threshold or close to neutron-separation energies (around 5 – 8 MeV). There are debates regarding the collective nature of PDR. Collectivity in a nucleus is perceived as the coherent excitation of one particle and one hole (1p-1h). The 1p-1h components contribute to the overall structure of the $1-$ state of the PDR. Recent theoretical works have found collectiveness in the isoscalar mode, however, they question the collectiveness in the isovector part of the PDR strength distribution [6,7], as the particle-hole configurations do not contribute coherently to the pygmy state wave functions. J. Piekarewicz [1] showed that the high-angular momentum orbitals play a passive role in the transition strength of the low-lying dipole states. In another study, it was observed that the transition strength increases (following the TRK sum rule) while crossing the neutron shell closure in Cr isotopes [8]. The single-particle behaviour of the PDR strength could be a consequence of strong fragmentation influenced by single-particle shell effects [9].

Among different experimental methods, the particle-gamma coincidence technique helps to select the 1^- states that have PDR characteristics. A new approach has been developed to study the underlying microscopic structure of the PDR and to access its single-particle states via the (d,p) neutron transfer reaction to populate the 1^- states in ^{208}Pb [10] and in ^{120}Sn [11]. The neutron-pickup reaction (p,d) has also been studied recently at the INFN Laboratori Nazionali del Sud (LNS) in Catania, to populate the 1^- states in ^{96}Mo from ^{97}Mo [12].

We propose to study the low-lying 1^- states in ^{90}Zr, which are populated by the ^{91}Zr(p,d) reaction. The ground-state spin parity of ^{91}Zr is $5/2^+$, similar to ^{97}Mo. In this reaction, the most probable scenario involves the pick-up of a single neutron from the $2d_{5/2}$ level in the ground state of ^{91}Zr, leading to the population of the ground state in ^{90}Zr. Any other low-lying excitation in ^{90}Zr will be due to the coupling of a proton pair or core excitation [13]. This reaction was explored at a proton bombarding energy of 22 MeV, with outgoing deuterons detected via a charge-particle detector, yielding observations of excitation energy around 5 MeV [13]. Additionally, the ^{91}Zr(p,d) reaction was performed previously at Oak Ridge Cyclotron, where the outgoing deuterons were momentum analyzed in a magnetic spectrograph, and excitation energies up to 5.95 MeV were observed [14].

Experimentally, a variety of probes have been employed for probing the PDR in ^{90}Zr, including inelastic scattering of high-energy protons (p,p') [15], alphas (α,α') [15,16], ^{17}O [17], and real photons (γ,γ') [18,19]. The one neutron separation energy of ^{90}Zr is around 12 MeV. Therefore, the low-lying 1^- states around or below 12 MeV will be of particular interest. With ^{17}O as a probe, excitation energies up to 7 MeV were observed, with a strong E1 transition from the 6.424 MeV state, which showed isoscalar character [17]. However, with the real photon experiment, dipole-strength distributions up to the neutron separation energy were observed [19]. In Fig. 1, the dipole strength distributions in ^{90}Zr obtained from the various means are shown, where the data obtained via inelastic alpha and proton scattering show some unresolved strengths up to 12 MeV.

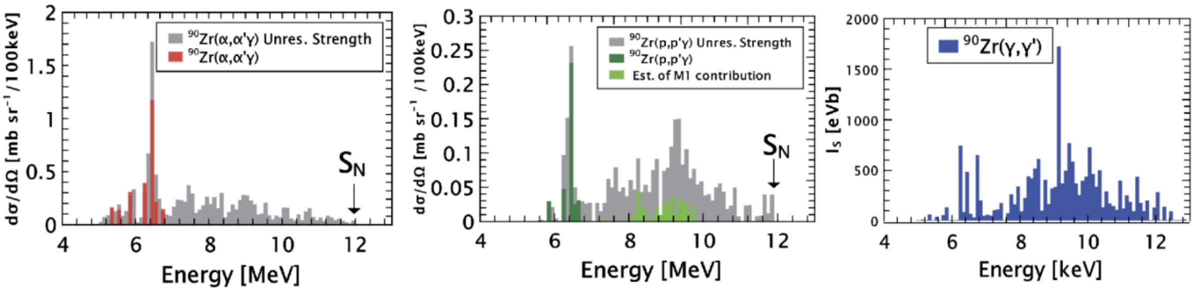

Figure 1: The dipole strength distribution in ^{90}Zr, obtained from inelastic alpha scattering, is shown in the left figure; from inelastic proton scattering, it is shown in the middle figure; and from the real photon scattering, it is shown in the right figure. The gray areas represent the unresolved strength, and the light green portion in the middle figure corresponds to a possible M1 transition. The figure has been taken from Ref. [15].

The Quasi-particle Phonon Model (QPM) predicted the transition strength of the E1 states to be directly proportional to the amount of excess neutron in the energy range up to 7.5 MeV in ^{90}Zr [19]. This prediction suggests the collectiveness of the strength distribution and also refers to the isoscalar nature of the PDR. However, the strength above 7.5 MeV is fragmented, suggesting the onset of possible single-particle strengths, lacking a reliable description [19]. Therefore, it is of utmost importance to study the gamma decay from discrete dipole states in ^{90}Zr. Microscopic calculations are found to suitably predict the experimental observations and a typical transition density for the PDR for ^{90}Zr, employed with the SGII interaction in Random Phase Approximation (RPA), is shown in Fig. 2. It represents the neutron contribution at the nuclear surface [15].

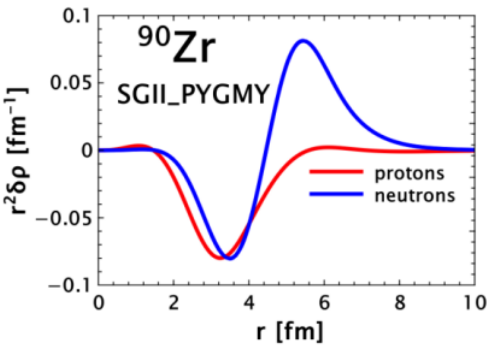

Figure 2: The transition density for ^{90}Zr corresponding to a pygmy dipole state, calculated with SGII interaction, is shown. The figure is taken from Ref. [15].

Although microscopic calculations are better suited for describing the PDR states, there are some mismatches between experimental observations with inelastic proton scattering and theoretical calculations for certain states around 7 MeV and above 11.5 MeV [15], suggesting that there could be different intrinsic underlying structures of the 1^- states. Additionally, the gamma strength function below the photo-neutron threshold was not estimated correctly [19]. Furthermore, there is a demand to study the dipole states above 6.5 MeV with much larger statistics [17].

Therefore, in order to address the aforementioned problems, we have considered the pickup reaction ^{91}Zr(p,d), due to its selectivity for exciting single-particle (hole) states. The methods described above for populating the 1^- states in ^{90}Zr are not state-selective. Our aim is to populate the 1^- states in ^{90}Zr through the ^{91}Zr(p,d) reaction up to the particle-emission threshold. Since the ground-state spin-parity of ^{91}Zr is $5/2^+$ ($2d_{5/2}$), then to populate 1^- negative parity states the neutrons from the lower deep shells $1f_{7/2}$, $1f_{5/2}$, and $2p_{3/2}$ will be picked up and this will populate the higher energy end of the PDR. Since in ^{90}Zr there is an onset of proton sub-shell closure and neutron shell closure, it also offers a benchmark for improving available microscopic calculations. Furthermore, we aim to measure the gamma-strength function in ^{90}Zr and also possible M1 transitions at and above 9 MeV [18].

2. Description of Experiment:

The choice of the proton beam energy (20 MeV) is suitable for enhanced single-particle selectivity within this energy range. In a previous study, the proton beam energy was 25 MeV for populating the 1^- states in ^{96}Mo from ^{97}Mo via the (p,d) reaction [12]. We will employ a ^{91}Zr self-supporting target with an areal density of 2 mg/cm^2. Utilizing a particle-gamma coincidence setup will enhance sensitivity for detection of 1^- excited states due to their E1 transition to the ground state. This can be achieved by selecting a gate condition where the excitation energy (E_{ex}) is approximately equal to the energy of the γ-transition (E_γ). Moreover, this method is beneficial for suppressing the background by several orders of magnitude, ensuring an unambiguous determination of 1^- states in ^{90}Zr. In addition to that, the angular correlation between the emitted deuteron and the gamma should be checked.

The Charged Particle Detector Array (CPDA) installed at TIFR will be utilized for particle identification through ΔE (energy loss)-E (total energy deposited) measurements. It consists of CsI detectors as well as Si Surface Barrier detectors. The thicknesses of the detectors should be such that the ejected deuterons are stopped inside the detector, enabling a complete kinematic reconstruction. The charged particle detectors will be installed at backward angles.

To access the γ-strength distribution of the PDR states (1^- states), the state-of-the-art Indian National Gamma Array (INGA) consists of Compton-suppressed clover High-Purity Germanium (HPGe) detectors [20]. The photo-peak efficiency of a single HPGe detector for 1 MeV γ-ray is estimated to be around 0.2%. Additionally, a new active collimator detector has been developed [21]. Its integration with the existing Compton-suppressed clover HPGe and $LaBr_3$(Ce) detectors establishes a highly effective γ-ray multiplicity filter for angular momentum selection. Angular correlation is essential to achieve spin alignments of the observed states. In total, 20 gamma-ray detectors will be arranged surrounding the target chamber.

A justification is given below for Beam Time Requirement based on the count rate estimation and statistics.

We have estimated the integrated cross section of the 1- state at 6.424 MeV to be around 0.1 mb. The efficiency of a charged-particle detector has been estimated to be 50%. The total efficiency of 20 gamma detectors (INGA array) at 6 MeV has been estimated to be around 0.6%.

With a beam intensity of 1 pnA and a target thickness of 2 mg/cm^2, our estimated yield at 6.424 MeV is approximately 0.025 counts per second (cps). To maintain a statistical error of the integrated cross section at the level of 1%, we request 6 days (excluding setup time) of beam time for reliable data collection. The background level is estimated to be around 10-15%, although a particle-gamma coincidence mechanism can significantly reduce this background by several orders of magnitude.

References:

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- **Whether the experiment is part of PhD /Post Doc. work:** Yes (Ph.D. student: Ms. Shinjini Pal, IIT ISM Dhanbad)

- **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:**

Journal

1. Accurate simultaneous lead stopping power and charge-state measurements in gases and solids: Benchmark data for basic atomic theory and nuclear applications, S. Ishikawa **(S. Bagchi)** et al., Phys. Lett. B 846, 138220 (2023).
2. Matter radius of the doubly-magic ^{56}Ni measured in a storage ring, M. von Schmid **(S. Bagchi)** et al., Eur. Phys. Jour. A 59(4), 83 (2023).
3. Studying Gamow-Teller transitions and the assignment of isomeric and ground states at N = 50, A. Mollaebrahimi **(S. Bagchi)** et al., Phys. Lett. B 839, 127833 (2023).

Conference Proceedings

1. Effect of ground-state shape deformation on the Isoscalar Giant Monopole Resonance in Nd isotopes, M. Abdullah, **S. Bagchi**, M. N. Harakeh., Proceedings of the DAE-BRNS Symposium on Nuclear Physics, 66, 94-95 (2022).
2. Extraction of Optical-Model Parameters from α elastic scattering of highly-deformed ^{172}Yb, K. Khokhar, **S. Bagchi**, M.N. Harakeh et al., Proceedings of the DAE-BRNS Symposium on Nuclear Physics, 67, 709-710 (2023).
3. Geant4 simulation on Gamma-Neutron detection with CLYC: An Elpasolite Detector, Debodyuti Kar, **S. Bagchi**, Proceedings of the DAE-BRNS Symposium on Nuclear Physics, 67, 1297-1298 (2023).