Transfer reactions to populate the Pygmy Dipole Resonance (PDR) in ^{96}Mo

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Abstract. This paper presents a study that attempts to probe the nature of the pygmy dipole resonance (PDR). In particular, the single-particle or the collective nature of these dipole states by exploiting the sensitivity of one-particle transfer reactions to excite single-particle states. The measurements on transfer reactions (p,d) and (d,p) were performed on two different targets ^{97}Mo and ^{95}Mo, respectively to populate the ^{96}Mo residual nucleus. The proton and deuteron beam energies used were 25 MeV and 10 MeV for the (p,d) and (d,p) reaction channels, respectively. The ejectiles were detected, identified and momentum-analyzed by the MAGNEX spectrometer and its focal-plane detector. The data reduction process of the (p,d) reaction will be presented together with some preliminary results.

1. Introduction

The Pygmy Dipole Resonance (PDR), is widely described as a concentration of electric dipole states (1^-) around the neutron separation energy (S_n), has thus far only been observed in neutron-rich nuclei. Bracco *et al*. [1] and Savran *et a*l. [2] recently conducted detailed reviews on the PDR, outlining the progress made in the study of dipole excitation. Macroscopically, the PDR was interpreted using the hydrodynamical model as an oscillation of a neutron skin against a proton-neutron core.

In an attempt to describe the PDR microscopically and, among the different models used, the quasi-particle random phase approximation (QRPA), the relativistic quasi-particle random phase approximation (RQRPA) and the quasi-particle phonon model (QPM) have been found to best describe the PDR when compared to available experimental results. Significant amount of work has also been done experimentally to study the PDR in order to understand its nature. Previous studies show that the PDR is very probe sensitive and, therefore, two different types of experiments conducted on the same nucleus might give complimentary information on the nature of the PDR. The interpretation of this excitation mode is not yet clear and lately the collectivity of these states has also been put under scrutiny. At an attempt to interpret this dipole excitation mode some theoretical studies [3, 4] found that although the low-lying states cannot be considered as collective as the Giant Dipole Resonance states, they also cannot be described as a single p-h configuration. The response of the PDR to an isovector operator calculated using RPA theoretical models, does not show a clear collective nature since the several particle-hole configurations do not contribute coherently to the pygmy state wave function. Contrarily, there are other studies

[5,6] where single-particle behaviour of the PDR strength is predicted due to an observed strong fragmentation which could be influenced by single-particle shell effects.

Experimentally, inelastic scattering of high-energy protons (p,p') [7] and real photons (γ,γ')[8] have been used as probes for PDR studies on ^{96}Mo. However, these are not selective thus to investigate properly the single-particle(hole) nature of this dipole response a more selective probe is required. Direct reactions, specifically stripping and pickup transfer reactions, owing to their selectivity for exciting single-particle (hole) states, were thus considered in this work.

2. Experimental Method

Stripping (d,p) and pickup (p,d) reactions were performed on ^{95}Mo and ^{97}Mo targets respectively, in order to examine the single-particle/hole configurations of ^{96}Mo. The targets used had aerial density of 0.6 mg/cm^2 and 0.4 mg/cm^2 for the (d,p) and (p,d) reactions, respectively. The 10-MeV deuteron and 25-MeV proton beams were delivered by the 14MV- Tandem accelerator which is installed at the INFN-LNS in Catania, Italy. The beams impinged on the ^{95}Mo and ^{97}Mo targets, respectively, to excite ^{96}Mo. The choice of the beam energies was influenced by the enhanced single-particle selectivity of direct reactions at this energy range [9]. The data were collected for approximately 234 hours at a beam current ranging between 0.9 nA and 5 nA for both reactions. The MAGNEX magnetic spectrometer and its focal-plane detection system was used to detect the reaction products [10]. The data were collected at three different angular settings, namely 10^o, 17^o and 24^o in order to allow the measurement of the angular distribution of the scattered particles and deduce the spin/parity of the excited states. The magnetic field settings were adjusted to measure a wide excitation-energy region, up to 8 MeV.

3. The data reduction process

The data reduction process for the three angular settings has been completed for the pickup reaction on the ^{97}Mo target. The initial step was to identify the deuterons and this information was obtained through the combination of the energy loss (ΔE) measurement by the deuterons in the gaseous region of the detector and the focal-plane horizontal position (X_f) with the residual energy (E_{res}) in the silicon detectors. Once the deuterons were selected, the quality of the PID process was checked using the horizontal angle (Θ_f) and the focal-plane horizontal position (X_f) measurement as seen in Figure 2 for the low-energy regions of the focal- plane. The vertical position calibration of the focal plane was performed which allowed accurate extraction of the vertical position (Y_f) and the vertical angle (Φ_f) for the events of interest. Since MAGNEX is a large-acceptance spectrometer with a vertical acceptance of ±125mrad [10] and a horizontal acceptance -90 − 110 mrad [10], ray-reconstruction is important to correct for high-order aberrations.

To initiate the reconstruction process, a direct transport 10th-order matrix was created using COSY-INFINITY [11] with the final phase space parameters as input (X_f , Y_f , Θ_f , Φ_f). A correction of the rigidity (Bρ), quadrupole field (BQ) and the boundary coefficients of the entrance of the dipole magnet was also included. A set of events was then created using Monte Carlo-based techniques which are included in the COSY-INFINITY as to test the quality of the reconstruction. These events were compared to the experimental data as seen Figure 2. The obtained transport matrix was then inverted and applied to the experimental data to extract the initial phase space parameters such as the excitation energy (E_x) and the scattering angle (Θ_{lab}). Once extracted, the next step was to analyze the ^{96}Mo excitation-energy spectrum to identify peaks and compare with data from Cochavi *et al*. [12] so as to ensure that the energy-calibration was correct and to compare the cross-section angular distributions of the lower-energy region states before extending to the PDR region which is our region of interest. The MAGNEX magnetic spectrometer allows particle identification with energy resolution of ($\Delta E/E \sim 1/1000$) [10]. However, the energy loss in the target can also affect the final energy resolution. The preliminary estimation of the energy resolution for the pickup reaction (p,d) is ~40-keV FWHM for the 17^{o} angular setting dataset.

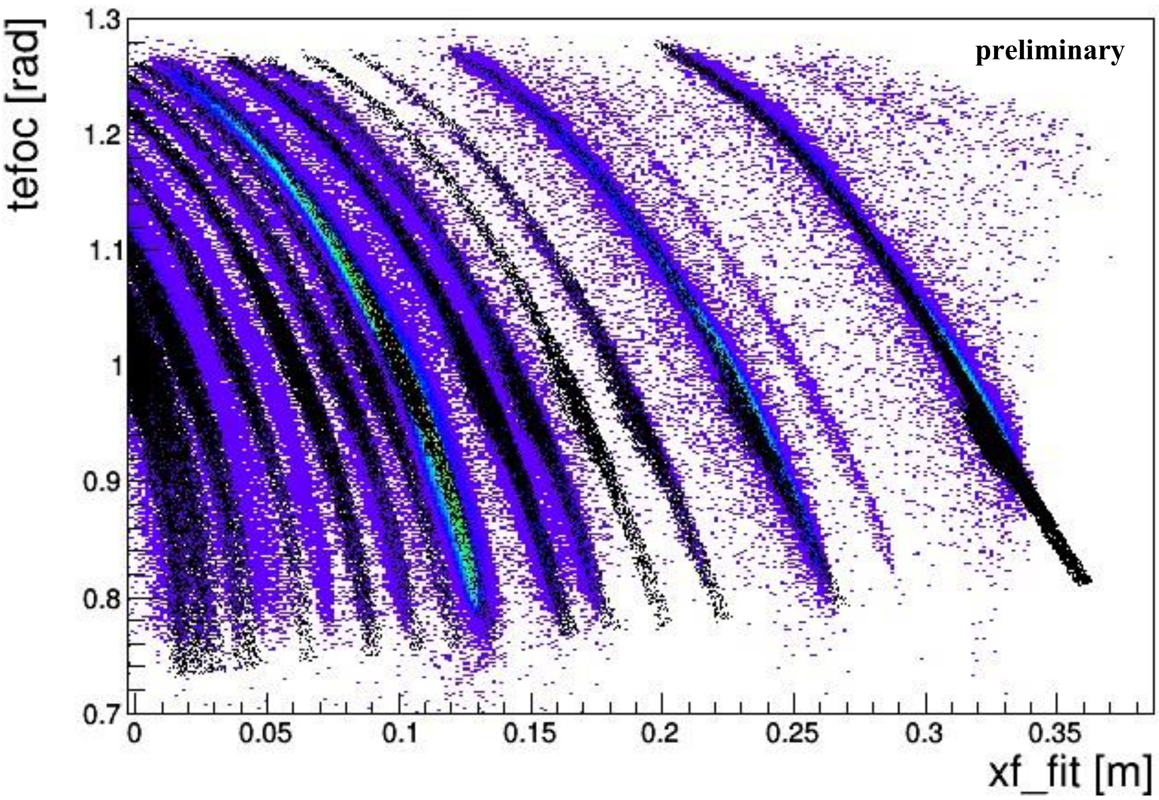

Figure 2: The horizontal angle (Θ_f) versus horizontal focal-plane position representation (X_f) where the 10^{o} experimental data is represented in blue and the COSY INFINITY [11] simulations are represented in black. For the low-energy region of the focal plane, the experimental data and the simulations overlay. This representation is also used as quality check for the ray-reconstruction procedure.

4. Conclusion & future work

A study that seeks to examine the collective/ single-particle nature of the PDR was presented. Where the experimental setup and data optimization were presented. The current status of the study was also discussed. For future work and currently underway, the differential cross section for all the states identified will be calculated. Angular distributions of the scattered particles will be used to determine the spin and parity of the observed states. The results will be compared to theoretical predictions and other experimental data available for ^{96}Mo.

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