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Gamma decay of pygmy states in ^{90,94}Zr from inelastic scattering of light ions

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Abstract. We performed experiments to study the low-energy part of the E1 response (Pygmy Dipole Resonance) in ^{90,94}Zr nuclei, by measuring the (*p*,*p*'γ) and (α,α'γ) inelastic scattering reactions at energies $E_{beam,p}$ = 80 MeV and $E_{beam,\alpha}$ =130 MeV respectively. The inelastically scattered particles were measured by employing the high-resolution spectrometer Grand Raiden. The gamma-rays emitted following the de-excitation of the Zr target nuclei were detected using both the clover type HPGe detectors of the CAGRA array and the large volume $LaBr_3$:Ce scintillation detectors from the HECTOR+ array. Some preliminary results are presented here.

1. Introduction

It is well known that the electric dipole strength in nuclei is dominated by the Giant Dipole Resonance. This collective mode is perceived as an oscillation of all the neutrons against all the protons. However, it is found the systematic presence of an accumulation of electric dipole strength, at energies around the particle threshold, in most of the studied neutron rich nuclei. To this accumulation of strength has been given the name of Pygmy Dipole Resonance [1,2]. The word pygmy was used due to the much smaller fraction of energy-weighted sum rule exhausted by this group of E1 states as compared to that exhausted by the GDR. The PDR is possibly associated to a new kind of collective mode arising from the oscillation of the N=Z core against the neutron skin in neutron rich nuclei. The properties of the PDR strength are connected to the properties of the neutron skin which in turn are used to constrain the equation of state of neutron rich matter [3,4,5]. In addition, the PDR strength plays a role for r-process nucleosynthesis [6].

From the experimental point of view an important finding concerns the observation of the structural splitting of the PDR states into two separated groups [7,8]. One higher-lying group of states has isovector nature and it is excited only in photon scattering experiments, these states are associated to the transition toward the GDR. One lower lying group of states of more isoscalar character is excited both in photon scattering and alpha scattering experiments. In addition experiments performed for the nuclei ^{208}Pb, ^{124}Sn, ^{90}Zr and ^{140}Ce [9-12] have shown that the (^{17}O,^{17}O'γ) reaction is a good tool to investigate the isospin properties of the pygmy states.

Although a large number of experimental and theoretical works have been devoted to this subject in the past decades, the nature of the PDR is not well understood yet. Key issues for the interpretation of the nature of the PDR states are the determination of their characteristic transition density and the isospin character.

We proposed the experiments described here to study the low-energy part of the E1 response, by measuring the (*p*,*p*'γ) and (α,α'γ) inelastic scattering reactions with the CAGRA-Grand Raiden set-up. Our aim is to investigate the isospin character of the PDR states by comparing with high resolution data their population with the (α,α'γ) reaction (isoscalar character, surface-sensitive), (p,p'γ) reaction (mainly isoscalar character, better sensitivity to the inner transition density), and (γ,γ') (mainly isovector character).

The ^{90}Zr and ^{94}Zr nuclei were chosen because of their pronounced proton subshell closure and because they are rather well studied with the (γ, γ') reaction [13], [14]. The works with (γ,γ') reported in [13], [14] show clearly an excess of E1 yield at low energy as compared with the expectation using the Lorentzian tail of the GDR.

2. Experimental Technique and Setup

The experiments have been performed at the Research Center for Nuclear Physics (RCNP) of the Osaka University. The used beams of alpha particles and protons, at bombarding energy of respectively 130 MeV and 80 MeV, were provided by the AVF cyclotron. Inelastically scattered particles (alphas or protons) were detected by the high-resolution spectrometer Grand Raiden (GR) [15]. A schematic picture of the setup is shown in the Figure1. In the used forward scattering mode, the GR spectrometer was placed at the angles of 4.5 deg and 6.6 deg, for the case of the alpha and proton beams respectively. The Grand Raiden Forward-mode beam line (GRAF) was used to transport the beam to a beam dump placed at 20 m downstream of the target (see Figure 2). In this kind of experiment it is mandatory to stop the beam far from the target position and in a well-shielded beam dump, to decrease sufficiently the background in the gamma-ray coincidence measurements. The full solid angle of the Grand Raiden spectrometer is ~4 msr.

Two different target nuclei (^{90}Zr and ^{94}Zr) were studied using alpha and proton beams. The gamma-rays emitted following the de-excitation of these target nuclei were detected using both the clover type HPGe detectors of the CAGRA array [16] and the large volume $LaBr_3$:Ce scintillation detectors from the HECTOR+ array [17], placed in a 4π geometry around the target position (as can be seen in the inset of the Figure 1). The CAGRA array consisted of 12 clover detectors: 8 of them were placed at an angle of 90 deg. with respect to the beam direction, while the remaining 4 clovers were placed at backward (135 deg.) angles. The distance between the target and the front face of the HPGe detectors is 22.0 cm. The four $LaBr_3$:Ce scintillators (crystal dimensions 3.5”x8”) of the HECTOR+ array were placed at forward angles (45 deg.) at a distance of 16.0 cm from the target to the front face of the detectors.

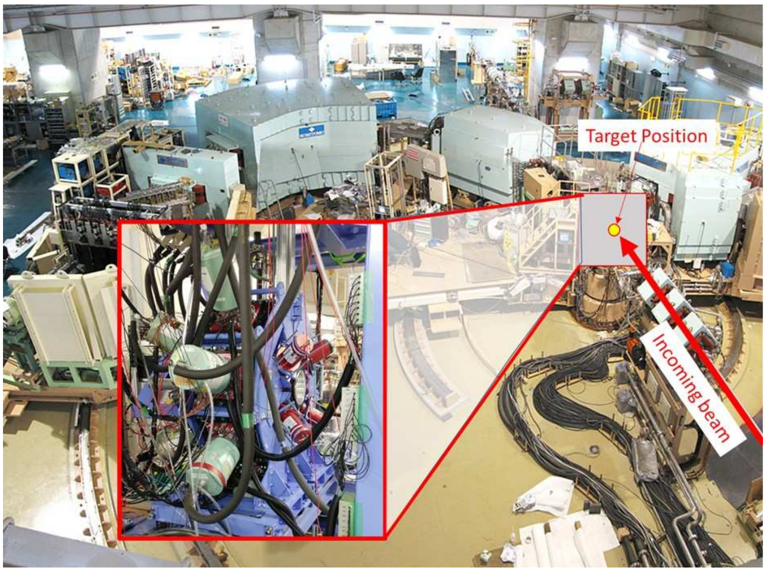

Figure 1. Picture of the Grand Raiden spectrometer in the west experimental hall of the RCNP, Osaka University. The inset show a picture of the gamma detectors placed around the target position: 12 HPGe clovers of the CAGRA array and 4 $LaBr_3$:Ce scintillation detectors of the HECTOR+ array.

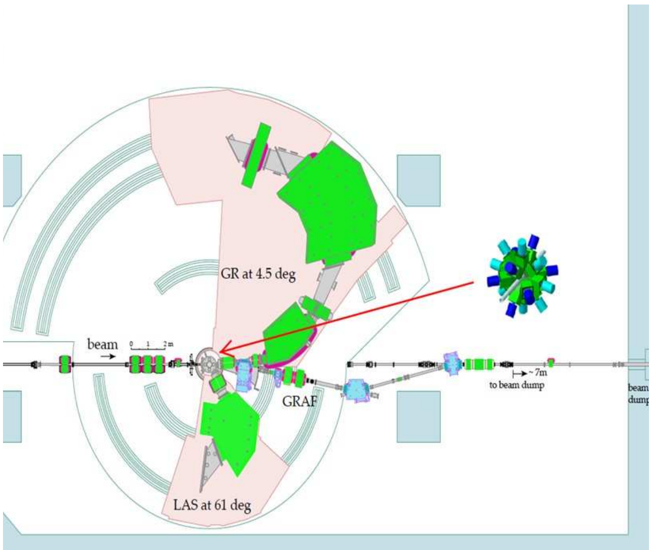

Figure 2. Schematic drawing of the Grand Raiden spectrometer used in forward scattering mode.

3. Preliminary Results

One important quantity in the analysis of the data is the correlation between E_x and E_{gamma}. E_x represents the excitation energy of the target nucleus, deduced from the measurement of the inelastically scattered particle (alpha or proton) in the Grand Raiden spectrometer. E_{gamma} is the energy of the gamma rays emitted following the de-excitation of the target nucleus, it is measured by the HPGe clover detectors of CAGRA or by the $LaBr_3$:Ce scintillation detectors of the HECTOR+ array. This correlation can be seen in the 2D-histogram shown in Figure 3. This refers to the case of the ^{90}Zr(α,α'γ) run (E_{beam}= 130 MeV) with E_{gamma} representing the gamma energy measured in the HPGe clover detectors. The events lying on the diagonal are those for which holds the condition E_x=E_{gamma}, they are associated to the direct decay to the ground state (this is shown in Figure 3 with the red dotted line). By applying different cuts in the the matrix E_x versus E_{gamma} it is possible to select events associated to different decay paths to the ground state. For example, the events lying along the black dotted diagonal line displayed in Figure 3 are associated to the decay to the first 2^+ excited state. In the matrix is also clearly visible the sudden decrease in the number of the events after an excitation energy E_x larger than the one neutron separation energy of ^{90}Zr (S_n =11.968 MeV) is reached, this is shown by the black vertical line in Figure 3. Background associated to random coincidences events has been subtracted in the matrix.

The E_x versus E_{gamma} 2D-histograms have been extracted for the four measurement runs associated to the different target-beam combinations used. In particular: for the case of the ^{90}Zr(α,α'γ) reaction with E_{beam} = 130 MeV; for the case of the ^{94}Zr(α,α'γ) reaction with E_{beam} = 130 MeV; for the case of the ^{90}Zr(p,p'γ) reaction with E_{beam} = 80 MeV and finally for the case of the ^{90}Zr(p,p'γ) reaction with E_{beam} = 80 MeV.

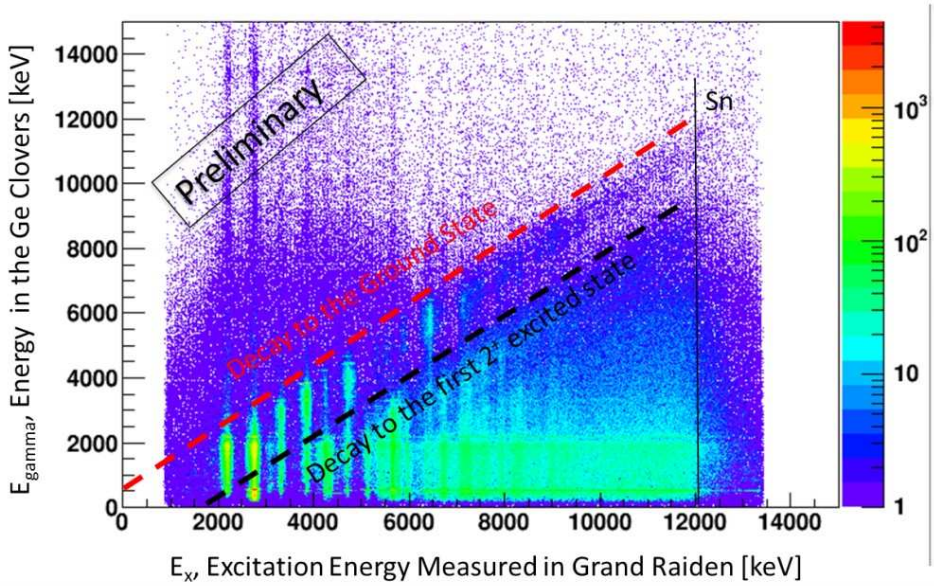

Figure 3. 2D-histogram showing the correlation between E_x (the excitation energy of the target nucleus) and E_{gamma} (energy of the gamma rays measured by the HPGe clover detectors of CAGRA**)** for the ^{90}Zr(α,α'γ) reaction at E_{beam} = 130 MeV.

These matrices show that states in the PDR energy region (below the neutron emission threshold) have been populated in ^{90,94}Zr for both the cases of alpha and proton beams.

The panel a) of figure 4 displays the comparison between the histograms of the excitation energy E_x (measured with Grand Raiden) of the ^{90}Zr target nuclei for the alpha inelastic reaction at E_{beam} = 130

MeV (red line histogram) and the proton inelastic scattering reaction at E_{beam} = 80 MeV (black line histogram). These histograms were obtained projecting on the X-axis the E_x vs E_{gamma} matrices and are associated to ground state gamma decay events. In fact in performing the projection only the events for which the following condition holds were considered: -40 keV < E_{diff} < 1100 keV; where E_{diff} corresponds to (E_x - E_{gamma}), that is the difference between the excitation energy of the target nuclei measured with Grand Raiden and the energy measured in the Ge gamma detectors. The two histograms are normalized in respect to the height of the prominent peak associated to the most intense 1^- state at 6425 keV, which is indicated in the figure. The panel b) of figure 4 show a similar comparison for the case of the measurements with the ^{94}Zr target nuclei. In this case the condition applied in performing the projection on the X-axis of the E_x vs E_{gamma} matrices is -30 keV < E_{diff} < 700 keV. The two histograms are normalized in respect to the height of the peak associated to the most intense 1^- state at 2846 keV, which is indicated in the figure. The neutron emission threshold is S_n=11.968 MeV for the ^{90}Zr and S_n=8.219 MeV for the ^{94}Zr. For both ^{90}Zr and ^{94}Zr there is clear similarity between the levels excited by protons and those excited by alpha particles in the lower energy part of the showed spectra (i.e. between 5.8 MeV and 7.6 MeV for the case of ^{90}Zr and between 2.8 keV and 5.0 MeV for the case of ^{94}Zr). In contrast, in the higher energy part the spectra appear to be significantly different. In particular for the case of ^{90}Zr the ratio of the counts in the higher energy region in the two spectra (alpha/proton) is 0.51 (in this case the higher energy region is considered from 7.6 MeV up to S_n=11.968 MeV). For the case of ^{94}Zr the same ratio (alpha/proton) is very different: 2.57 (in this case the higher energy region is considered from 5.0 MeV up to S_n=8.219 MeV).

These puzzling results are still preliminary and need further investigation, the data analysis is ongoing.

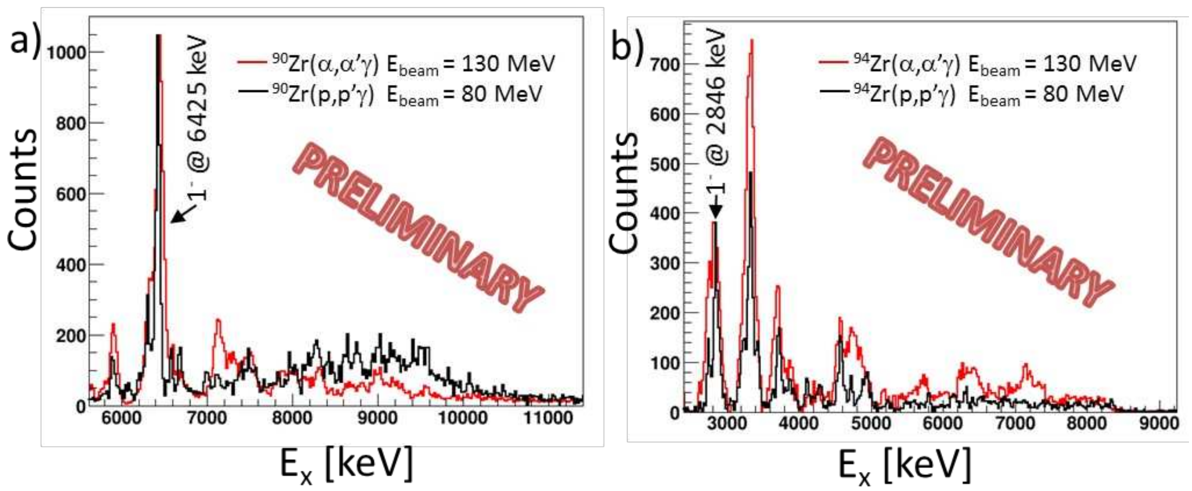

Figure 4. Panel a): Comparison between the histograms showing the excitation energy (measured with Grand Raiden) of the ^{90}Zr target nuclei for the alpha inelastic reaction at E_{beam} = 130 MeV (red line histogram) and the proton inelastic scattering reaction at E_{beam} = 80 MeV (black line histogram). These histograms are obtained as projections on the x-axis of the matrix E_x vs E_{gamma} (with the conditions described in the text) and are associated to ground state gamma decay events. The prominent peak associated to the most intense 1^- state at 6425 keV is indicated. Panel b): same comparison as in panel a) but this time the data are of the measurements with the ^{94}Zr target nucleus. The peak associated to the most intense 1^- state at 2846 keV is indicated.

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