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Colloquia: COMEX7

Study of the Pygmy Dipole Resonance via (d, p) reactions

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Summary. — The low-lying $E1$ strength below, around, and partially above the neutron-separation threshold, S_n, is often referred to as Pygmy Dipole Resonance (PDR). At the moment, it is not clear whether the PDR is a collective excitation mode and whether it is a general feature of the γ-ray strength function, which needs to be answered to reliably calculate capture rates for nucleosynthesis processes when using statistical Hauser-Feshbach approaches. To further understand the microscopic origin of the PDR and possible cancellation effects between isovector $E1$ matrix elements, which appear to be strongly model-dependant, an experimental program studying the neutron one-particle-one-hole (1p-1h) structure of the PDR via (d, p) and $(d, p\gamma)$ reactions was started. Some results of the already published work will be discussed and additional remarks, including future plans, are made.

1. – Introduction

The low-lying $E1$ strength below, around, and partially above the neutron-separation threshold, S_n, is often referred to as Pygmy Dipole Resonance (PDR) (see the review articles [1-5]). At the moment, it is not clear whether the PDR is a collective excitation mode and whether it is a general feature of the γ-ray strength function, which needs to be answered to reliably calculate capture rates for nucleosynthesis processes when using statistical Hauser-Feshbach approaches.

Often, the collectivity of an excitation mode is evaluated in terms of the number of one-particle-one-hole (1p-1h) excitations which contribute, and by whether these act coherently and, therefore, generate enhanced transition strength. For the isovector $B(E1)$ strength below and around the neutron-separation threshold, significant cancellation effects have been predicted (see, *e.g.*, refs. [4-7]). At least in the isovector channel, these theoretical studies question the collective nature of the PDR. Coherence between the different 1p-1h matrix elements is expected in the isoscalar channel though, where the PDR appears to be a collective excitation mode. Still, it is the isovector $B(E1)$ strength which contributes to the γ-ray strength function and, consequently, influences reaction rates in statistical Hauser-Feshbach calculations.

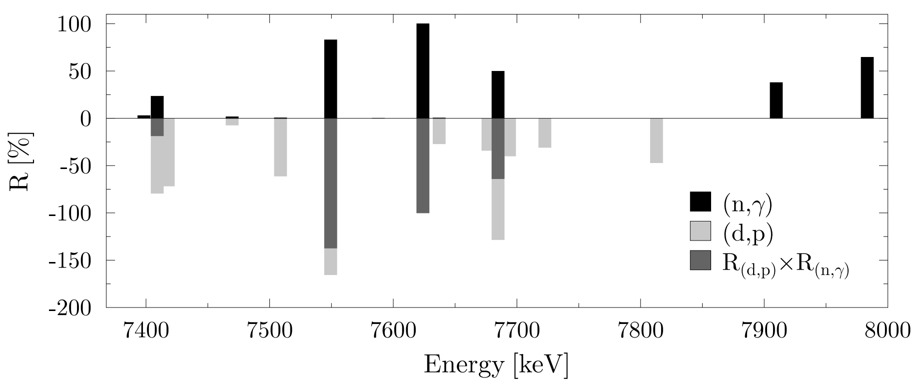

Fig. 1. – Comparison of resonant (n, γ) and (d, p) data for $J^\pi = 1^-$ states above the neutron-separation threshold $S_n = 7368\,\text{keV}$ and up to the proton-separation threshold $S_p = 8004\,\text{keV}$ in ^{208}Pb. For the ^{207}Pb(n, γ) data [8], the ratio R corresponds to the measured γ widths Γ_γ of the observed 1^- states normalized to the width of the 7624-keV state (black bars), which has the largest γ width. For the ^{207}Pb(d, p) data [9], the ratio R corresponds to the integrated $\sigma_{(d,p)}$ cross section for a specific excited state normalized to the integrated $\sigma_{(d,p)}$ cross section of the 7624-keV state (light gray bars). Note that the 7624-keV state is not the most strongly populated 1^- state in (d, p) for states with $E_x > S_n$. The (n, γ) and (d, p) ratios have been multiplied and again been normalized to the ratio of the 7624-keV states to highlight that the (d, p) ratios only take the population but not decay of the states into account (dark gray bars).

To further understand the microscopic origin of the PDR and possible cancellation effects between isovector $E1$ matrix elements, which appear to be strongly model-dependant [4-7], an experimental program studying the neutron one-particle-one-hole (1p-1h) structure of the PDR via (d, p) and $(d, p\gamma)$ reactions was started. Results for ^{208}Pb, ^{120}Sn, and ^{62}Ni following the (d, p) reaction on the corresponding odd-A targets, and in collaboration with colleagues from theory to gain a deeper understanding, have already been published [9-11]. For ^{120}Sn [10], the γ decay of $J^\pi = 1^-$ states to the ground state was selectively studied using the particle-γ coincidence capabilities of the combined SONIC@HORUS setup [12] at the University of Cologne. The experimentally determined γ-ray yields were compared to the predicted ones obtained from combined nuclear structure and reaction calculations. For ^{208}Pb and ^{62}Ni, experiments were performed with high-resolution magnetic spectrographs. While ^{208}Pb was studied at the since decommissioned Q3D spectrograph of the Maier-Leibnitz Laboratory in Garching, the ^{61}Ni$(d, p)^{62}$Ni experiment was performed with the recently commissioned Super-Enge Split-Pole Spectrograph (SE-SPS) at Florida State University. In both cases, angular distributions were measured to determine the angular momentum, l, transfer in the (d, p) reaction [9, 11]. By comparing these experimentally measured angular distributions to theoretical predictions made with the Distorted Wave Born Approximation (DWBA) or Adiabatic Distorted Wave Approximation (ADWA), the populated neutron 1p-1h configurations and model-dependent spectroscopic factors could be determined as well. Specifically for ^{208}Pb and ^{120}Sn, the comparison to theoretical predictions showed that states, which were populated via (d, p), were predominantly of neutron one-particle-one-hole (1p-1h) character with transition densities, which had a more pronounced contribution of neutrons at the surface [9, 10]. For the limited number of nuclei studied so far, 1^- states closer and above the threshold appear to have a more complex structure with two-

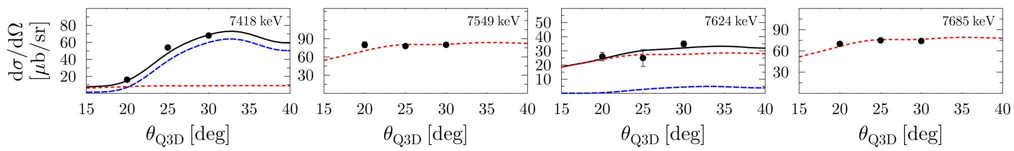

Fig. 2. – (d,p) angular distributions for the 7549-, 7624-, and 7685-keV states mentioned in the text. The angular distribution for the 7418-keV was added to highlight that some 1^- states above S_n were predominantly populated through $l=0$ angular momentum transfer in ^{207}Pb(d,p) [9]. Apparently, this state was not observed in (n,γ) though [8]. Blue lines correspond to $l=0$ and red lines to $l=2$ transfer calculated as described in ref. [9].

particle-two-hole (2p-2h) and three-particle-three-hole (3p-3h) excitations contributing to the wavefunctions [9, 10]. In contrast to ^{120}Sn, 1^- states with excitation energies larger than the neutron-separation energy were populated in ^{207}Pb$(d,p)^{208}$Pb, which are known to still decay via γ-ray emission.

In this conference proceeding, some additional aspects will be highlighted which were not necessarily part of the previous publications. Detailed discussions can, however, be found in refs. [9-11] and will not be repeated here. It should be pointed out though that (d,p) is a very selective reaction. Typically, only neutron 1p-1h configurations can be populated, which can be directly reached from the ground-state configuration of the target nucleus; meaning from the last active neutron single-particle orbit (unpaired neutron). Therefore, not all neutron 1p-1h components which might contribute to the wave functions of 1^- states of a specific nucleus can be probed within one experiment.

2. – Some additional remarks on the ^{207}Pb$(d,p)^{208}$Pb experiment to study PDR states

In ^{207}Pb$(d,p)^{208}$Pb, 1^- states are populated, starting from the $J^\pi = 1/2^-$ ground state of ^{207}Pb, if the $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$ ($l=0$ transfer) or $(3p_{1/2})^{-1}(3d_{3/2})^{+1}$ ($l=2$ transfer) neutron 1p-1h configurations are part of their wave function. Even though there are two major fragments for each configuration – observed at 5292 and 5947 keV, respectively – the majority of the previously known 1^- states was also populated in (d,p) [9]. These included states with excitation energies larger than the neutron-separation threshold S_n. Earlier, A.M. Lane had argued that these 1^- states could act as doorway states shared between neutron and γ channels in (n,γ) and that one could possibly probe the neutron entrance channel through (d,p) since data suggested a (d,p)-(n,γ) correlation [13]. The latter was problematic at the time because of a tension between the compound-nucleus reaction and direct capture discussion for (n,γ). In his discussion on the general existence of doorway states, he specifically highlighted the example of ^{208}Pb as, because of their $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$ neutron 1p-1h structure, 1^- states could be populated through s-wave capture in (n,γ) while also being populated in (d,p) through $l=0$ angular momentum transfers. Interestingly, he already stated in 1971 that "the $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$, $(3p_{1/2})^{-1}(3d_{3/2})^{+1}$ and $(2f_{5/2})^{-1}(3d_{5/2})^{+1}$ neutron states are virtually uncoupled from the giant resonance and interact to form the pygmy resonance at 5.49 MeV", which was based on theoretical calculations that had been performed at the time. Recent, state-of-the-art calculations with the QPM support indeed that the states with significant $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$, $(3p_{1/2})^{-1}(3d_{3/2})^{+1}$, and $(2f_{5/2})^{-1}(3d_{5/2})^{+1}$ amplitudes have transition densities which have been associated with the PDR [9]. These 1^-

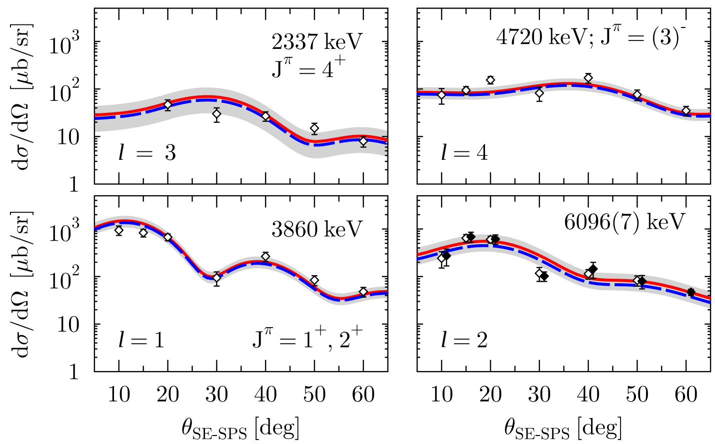

Fig. 3. – Examples for angular distributions measured with the FSU SE-SPS for ^{61}Ni$(d,p)^{62}$Ni. Different angular momentum, l, transfers are shown. See ref. [11] for more details.

states were, however, not populated in neutron capture as they are below S_n [8]; neutron energies up to 1 MeV were used in the measurement. We note that the interest to use (d,p) and $(d,p\gamma)$ as surrogates for (n,γ) has been revived with the advent of modern rare isotope beam facilities, which allow the study of very neutron-rich nuclei relevant for r-process nucleosynthesis (see, *e.g.*, refs. [14-16]). The critical interplay between compound, direct and semi-direct processes for neutron capture and implications for the r process were for instance discussed in refs. [16, 17].

To put a more up-to-date spin on the (d,p)-(n,γ) correlation discussion based on a state-to-state basis, the (n,γ) data from ref. [8] and the recent (d,p) data [9] have been compiled in fig. 1 for excited states of ^{208}Pb above S_n and up to S_p. As can be seen, more 1^- states are observed in (d,p) than have been identified through their γ decays after neutron capture. Interestingly though, the three most strongly populated 1^- states in (d,p), which are observed at 7549, 7624 and 7685 keV, are also the states with the largest γ widths. However, they are not populated through $l=0$ but through $l=2$ transfers in (d,p) (see fig. 2). Consequently, they might be populated through d-wave rather than s-wave capture in (n,γ) as for all but one state of these three states a significant $(3p_{1/2})^{-1}(4s_{1/2})^{+1}$ amplitude was not detectable. As all states shown in fig. 1 are above S_n, they can in principle decay via neutron emission and less so through γ-ray emission. Therefore, the $R_{(d,p)}$ and $R_{(n,\gamma)}$ ratios were multiplied and the resulting values again normalized to the one of the 7624-keV state. The resulting "intensity" pattern in fig. 1 is indeed closer to what has been observed in (n,γ). Ultimately, this comparison only highlights that understanding both the entrance and exit channel is essential to correctly model (n,γ) and that the 1^- states of the PDR can indeed act as doorway states.

3. – (d,p) and $(d,p\gamma)$ experiments at the FSU SE-SPS to study the PDR and γ-ray strength function

Recently, Ries *et al.* have suggested the onset of the PDR beyond $N=28$ based on the observation of a significant $E1$ strength increase in the Cr isotopes and proposed that the PDR has its origin in a few-nucleon effect [18]. Earlier, Inakura *et al.* had

Fig. 4. – The CeBrA demonstrator for particle-γ coincidence experiments in front of the SE-SPS. The entrance to the SE-SPS is to the right of the photo; after the green gate valve.

predicted by performing systematic calculations using the random-phase approximation (RPA) with the Skyrme functional SkM* that the $E1$ strength of the PDR strongly depends on the position of the Fermi level and that it displays a clear correlation with the occupation of orbits with orbital angular momenta less than $3\hbar$ $(l \leq 2)$ [19]. The strong $E1$ strength increase, suggested by (γ, γ') data available for nuclei just beyond $N = 28$ [18, 20-22], was indeed predicted by Inakura *et al.* [19].

To investigate the microscopic structures causing the possible formation of a PDR and the $E1$ strength increase beyond the $N = 28$ neutron shell closure, we performed a ^{61}Ni$(d, p)^{62}$Ni experiment at the John D. Fox Superconducting Linear Accelerator Laboratory of Florida State University. Angular distributions and associated single-neutron transfer cross sections were measured with the Super-Enge Split-Pole Spectrograph to determine the angular momentum transfers populating possible $J^{\pi} = 1^{-}$ states and other excited states of ^{62}Ni. Examples for these angular distributions are shown in fig. 3 and clearly highlight that the different l transfers can be distinguished. The results of the experiment were already published [11].

Several $J^{\pi} = 1^{-}$ states were observed below the neutron-separation threshold after being populated through $l = 2$ angular momentum transfers. The (d, p) data clearly proved that $l = 0$ strength, *i.e.*, the neutron $(2p_{3/2})^{-1}(3s_{1/2})^{+1}$ 1p-1h configuration plays only a minor role for 1^{-} states below the neutron-separation threshold in ^{62}Ni. Thus, any strength increase would need to be attributed to either the $(2p_{3/2})^{-1}(2d_{5/2})^{+1}$ or $(2p_{3/2})^{-1}(2d_{3/2})^{+1}$ neutron 1p-1h configuration if the predictions of Inakura *et al.* were correct. Experiments at the FSU SE-SPS are under way to further test the wave functions of 1^{-} states of nuclei around and beyond $N = 28$.

As mentioned in the previous section, understanding both the entrance and exit channels is essential in order to use information from (d, p) and $(d, p\gamma)$ experiments for (n, γ). Therefore, the CeBrA (for CeBr$_3$ Array) demonstrator has been designed at FSU for particle-γ coincidence experiments at the SE-SPS (see fig. 4). The first commissioning runs at the SE-SPS concluded successfully. As an example, fig. 5 shows the proton-γ coincidence matrix measured for the ^{49}Ti$(d, p\gamma)^{50}$Ti reaction. The inset shows the coincident γ-ray spectrum, measured with the CeBrA demonstrator, when an excitation energy gate is set on the 4880-keV state of ^{50}Ti. Selective excitation energy gates are possible due to the very good energy resolution of the SE-SPS, which is around 30-50 keV

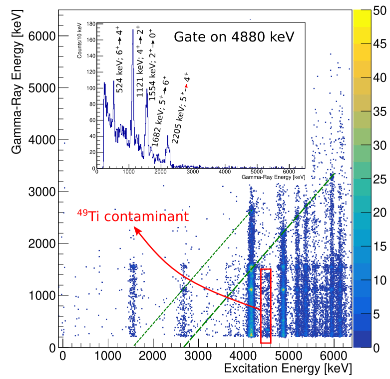

Fig. 5. – Particle-γ coincidence matrix measured for the ^{49}Ti$(d, p\gamma)^{50}$Ti reaction with the CeBrA demonstrator and the SE-SPS. The coincident γ-ray spectrum when gated on the 4880-keV state of ^{50}Ti is shown in the inset.

over the entire length of the focal plane of the spectrograph. Full scans of the excitation spectrum up to and beyond S_n will allow to study the γ-ray strength function via $(d, p\gamma)$ with the CeBrA demonstrator at the FSU SE-SPS using, *e.g.*, the method presented in ref. [15]. The addition of more large-volume CeBr$_3$ detectors would allow to investigate the γ decay of states around and beyond S_n directly.

4. – Conclusions

To further understand the microscopic origin of the PDR and possible cancellation effects between isovector $E1$ matrix elements, which need to be understood to reliably predict the γ-ray strength function far off stability and which appear to be strongly model-dependant, an experimental program studying the neutron one-particle-one-hole (1p-1h) structure of $J^\pi = 1^-$ states around and below S_n via (d, p) and $(d, p\gamma)$ reactions was started [9-11]. Using the examples of the recently measured ^{207}Pb$(d, p)^{208}$Pb [9] and ^{61}Ni$(d, p)^{62}$Ni [11] reactions, it was pointed out that understanding both the entrance and exit channels is essential in order to use information from (d, p) and $(d, p\gamma)$ experiments for (n, γ) reactions, which themselves are relevant for nucleosynthesis processes. Further (d, p) and $(d, p\gamma)$ experiments are planned at the FSU Super-Enge Split-Pole Spectrograph of the John D. Fox Laboratory for which the newly developed CeBrA demonstrator will be used for coincident γ-ray detection.

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