The Pygmy Dipole Resonance – experimental studies of its structure and new developments

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Abstract. Several experimental studies using electromagnetic probes have found an enhancement of electric dipole strength between about 5 and 10 MeV. This phenomenon is usually denoted as Pygmy Dipole Resonance (PDR). The detailed structure of these excitations is still under debate. This manuscript will concentrate on the results of complementary experiments using hadronic probes to populate the PDR. These studies allow a first insight into the origin of the PDR. Finally, the manuscript will shortly discuss plans for future experiments.

Introduction

In a macroscopic picture, electric dipole (E1) moments of atomic nuclei are always connected to a breaking of the symmetry between protons and neutrons. The most prominent example is the Giant Dipole Resonance (GDR) which is visualized in a macroscopic picture as an out-of-phase oscillation of the proton and neutron fluids leading to an electric dipole excitation at energies of about $E_x = 31\ A^{-1/3} + 21\ A^{-1/6}$ MeV [1,2]. The GDR exhausts about 100% of the Energy Weighted Sum Rule (EWSR) for E1 transitions, which is approximately given by:

$$\int_0^\infty \sigma(E)dE = 60\frac{NZ}{A}MeV \cdot mb$$

Already in 1971 it has been proposed by Mohan, Danos, and Biedenharn that in a three-fluid hydrodynamical model a second collective E1 mode is generated by the oscillation of excess neutrons against an isospin-saturated proton-neutron core [3]. This mode would be located at lower energies and would carry less E1 strength compared to the GDR. First evidence for the existence of such a Pygmy Dipole Resonance (PDR) came from the observation of an enhancement of γ-ray emission after neutron capture [4]. The resulting schematic distribution of E1 strength is depicted in Figure 1 which already shows the difficulties of clearly distinguishing the PDR and GDR due to the fragmentation and fine structure. It is currently under debate if the precise knowledge of the properties of the PDR or of the complete distribution of the E1 strength has implications on the symmetry parameter in the equation of state [5-9].

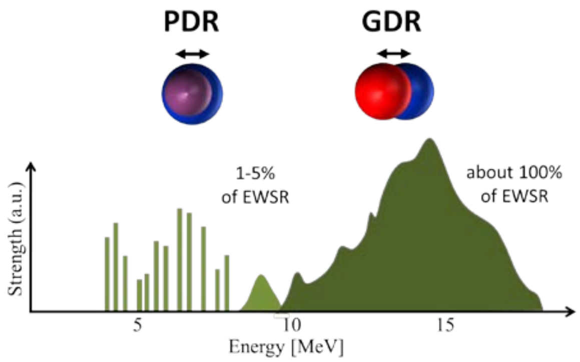

Figure 1: Schematic distribution of E1 strength in an atomic nucleus showing the splitting into a Pygmy Dipole Resonance (PDR) and a Giant Dipole Resonance (GDR). Octupole-coupled modes which can generate E1 strength at even lower energies are not shown.

The advent of bremsstrahlung photon sources with endpoint energies up to the particle thresholds from cw electron accelerators and the improvement of γ detector setups in the last two decades allowed high precision studies of the photoresponse of stable atomic nuclei in Nuclear Resonance Fluorescence (NRF) (γ,γ') experiments [10,11]. In these experiments, mainly dipole transitions are induced from the ground state of the nucleus and the subsequent γ decay is observed with high-resolution HPGe detectors. The final result is the detailed dipole strength distribution up to the particle threshold. Quasi-monoenergetic γ-ray beams from Laser Compton backscattering facilities can yield additional observables like parities and branching ratios of the excited states (see the contribution of Deniz Savran to these proceedings). More recently, the exchange of virtual photons between stable targets and a proton beam at energies of about 300 MeV has been used to study the dipole response below and above the particle threshold in a single experiment. This was achieved by high-resolution spectroscopy of the scattered protons using the Grand Raiden spectrometer at RCNP Osaka [12].

In very neutron-rich, unstable isotopes, one expects an enhancement of PDR-like excitations due to the larger neutron skin. A pioneering study has been performed at a setup at GSI Darmstadt. Radioactive ^{130,132}Sn nuclei were selected by the Fragment Separator (FRS) and exchanged virtual photons with a high-Z target. A magnet (ALADIN) behind the target chamber selected the ion of interest. Neutrons stemming from the (γ,xn) reaction were analyzed by the Large Area Neutron Detector LAND in coincidence with γ rays detected by scintillators from Crystal Ball surrounding the target chamber. These experiments showed an enhancement of E1 strength in the low energy tail of the GDR at about 10 MeV which exhausts several percent of the EWSR [13]. In a different approach, the radioactive neutron rich nucleus ^{68}Ni has been studied at the FRS by detecting the γ decays with the HECTOR and RISING array [14]. Again an enhancement of the E1 strength at energies of about 11 MeV is observed.

In summary, the studies using electromagnetic interaction observe an enhancement of E1 excitations at energies well below the GDR or on top of the tail of the GDR [15]. In stable nuclei, this strength exhausts about 1% of the isovector EWSR and is found below the neutron separation energy. In the few cases where radioactive nuclei have been investigated, the strength is found at higher energies and exhausts up to 5% of the isovector EWSR. Whether both observations belong to the same excitation mode, i.e., the PDR, is unclear. Obviously, more systematic studies on stable and radioactive species are mandatory to get a better understanding.

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Hadronic probes

One main problem in the interpretation of the data is how to distinguish between excitations belonging to the GDR (having wave functions representing the typical out-of-phase oscillation of protons and neutrons) and excitations belonging to a different type of excitation, i.e., the PDR. One way to answer this question is to use hadronic probes as an alternative excitation mechanism for the dipole modes. Table 1 compares the two experimental approaches. One big advantage of electromagnetic probes is the selective excitation of the lowest spin modes and – if one can use HPGe detectors for the γ decay channel – the excellent energy resolution. These two advantages are lost in typical hadron scattering experiments. However, in 1992, Poelhekken, Harakeh *et al.* complemented the QMG/2 particle spectrometer at KVI Groningen by an array of NaI detectors to detect the γ rays from the decay in coincidence with the scattered α particles [16]. This coincidence requirement restores the selectivity to low-spin excitations which decay to the groundstate via E1, M1, or E2 transitions. However, due to the limited energy resolution of the NaI detectors, this setup allowed to study only a few selected nuclei with rather low level density.

	(γ,γ') or Coulex	(α,α') @ 30 MeV/A
Interaction	**electromagnetic**	**strong**
Location of interaction	**whole** nucleus	**surface**
Isospin	**isovector** E1 excitations	dominant **isoscalar**
Multipolarity	E1, M1, E2	E0, E1, E2, E3, ...
ΔE	3-500 keV	50-200 keV

Table 1: Comparison of electromagnetic and hadronic excitation. At energies of 30 MeV/A, α scattering is strongly dominated by hadronic interaction for the excitations under investigation. Detecting the γ decay in coincidence restores the selectivity to low spin excitations.

This limitation was overcome a decade later when we replaced the NaI detectors by an array of HPGe detectors which provided an excellent energy resolution [17]. In these experiments, the scattered α particles were analyzed by the new Big Bite Spectrometer. The coincidence data can be sorted into a matrix where one axis represents the energy loss of the α particle during the scattering process (which yields the excitation energy) and the other axis represents the energy of the γ ray measured in coincidence, see Fig. 2.

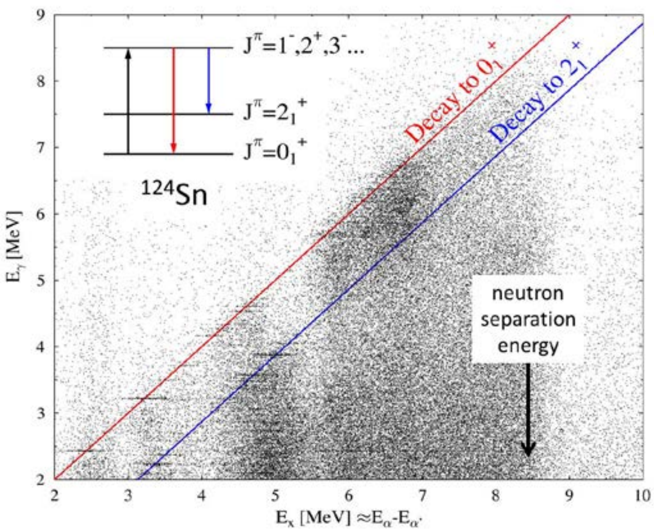

Figure 2: α-γ coincidence matrix of the (α,α'γ) experiment on ^{124}Sn (adapted from [18]). Thin horizontal lines represent excitations in ^{124}Sn, mainly γ decays to the ground state or first excited state have been observed. The neutron separation energy lies at about 8.5 MeV, above this energy, γ-ray transitions are strongly suppressed.

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Such experiments allow a detailed state by state analysis of the α scattering cross section even in nuclei where the level density is rather high. The result was quite surprising: Whereas below about 7 MeV all E1 excitations seen in (γ,γ') are observed also in (α,α'), this is not the case for the E1 excitations at slightly higher energies [19-22], see Fig. 3. Referring to Table 1, this points to a different underlying nuclear structure: The E1 strength splits into a surface mode with a strong isoscalar component at lower energies and a more isovector mode at higher energies.

Very recently, a group around Angela Bracco at Milano performed ^{17}O scattering experiments at energies of about 20 MeV/A on ^{208}Pb and ^{124}Sn [23,24] at the Tandem-ALPI accelerator complex at INFN Legnaro. Again, the dominantly isocalar hadronic interaction can populate the states of interest. These studies reproduce the observations we made earlier in the (α,α'γ) experiments, i.e., a splitting of the E1 strength into a lower and higher lying part.

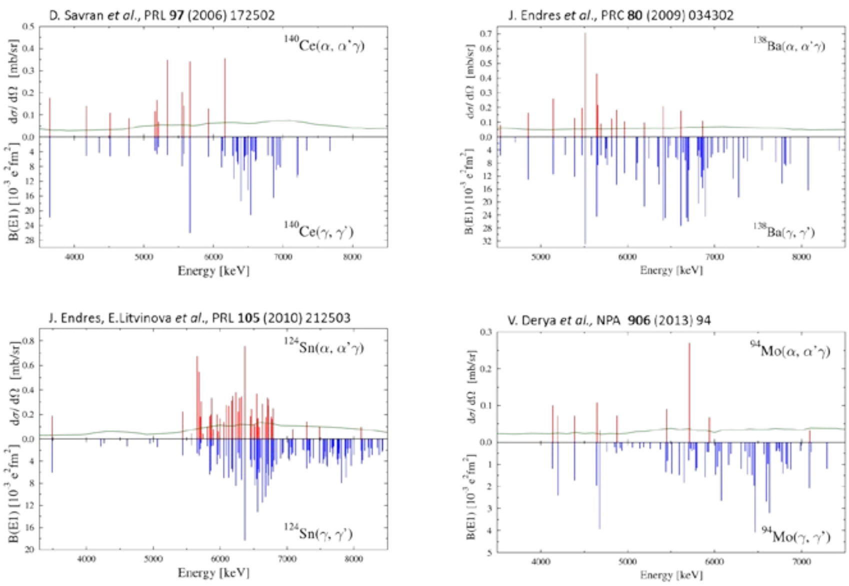

Figure 3: Cross sections for E1 excitations observed in the (α,α'γ) experiments (upper parts) in comparison with the E1 strength observed in (γ,γ') (lower parts) for the nuclei ^{140}Ce, ^{138}Ba, ^{124}Sn, and ^{94}Mo.

These experimental observations are supported by various theoretical calculations, which predict distinctly different transition charge densities for typical 1^- states at lower and higher energies: Whereas the former resemble the macroscopic picture of surface neutrons oscillating against an isoscalar core, the latter have charge densities more typical for states belonging to the GDR, see, e.g., Refs [18,25,26].

Future experiments

Various theoretical models (also the simplified geometrical picture of a neutron skin oscillating against an isospin saturated core) predict a strong enhancement of the PDR with neutron excess. Therefore, it is interesting to study the isospin character of E1 strength in exotic neutron-rich nuclei as well. One way to do this would be to perform α scattering experiments in inverse kinematics using a radioactive ion beam. A European-Japanese collaboration is currently investigating the Sn isotopic chain from stable proton-magic ^{124}Sn to the doubly-magic radioactive nucleus ^{132}Sn in experiments at RIKEN. The large acceptance radioactive ion separator BigRIPS is used to select the isotopes of interest. The beam interacts with a liquid He target, the scattered heavy ions are analyzed by the ZeroDegree spectrometer which is set to collect ions without charge and mass change (i.e., elastic α scattering). The trigger is determined by the detection of coincident γ rays with NaI detectors (DALI2) and additional LaBr detectors in forward direction (see Fig. 4).

Figure 4: Setup at RIKEN to study α scattering on neutron rich nuclei. The DALI2 array plus additional LaBr detectors measure the γ decay from the beam after hitting the liquid He target. The scattered beam particles are measured in the ZeroDegree particle spectrometer.

Further experiments using α or proton scattering as an experimental tool to study the PDR in stable nuclei are planned at iThembaLABS Cape Town and at RCNP Osaka, studies on unstable nuclei will be continued or are planned at GSI/FAIR Darmstadt and at RIKEN.

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