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The Pygmy Dipole Resonance – past, presence, and future

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Abstract. The advent of improved experimental and theoretical techniques has brought a lot of attention to the electric dipole (E1) response of atomic nuclei in the last decade. The extensive studies have led to the observation and interpretation of a concentration of E1 strength energetically below the Giant Dipole Resonance in many nuclei. This phenomenon is commonly denoted as Pygmy Dipole Resonance (PDR). This contribution will summarize the most important results obtained using different experimental probes, define the challenges to gain a deeper understanding of the excitations, and discuss the newest experimental developments.

1 Introduction

The dipole response of atomic nuclei is full of interesting and surprising phenomena. The experimental study of these dipole modes started already more than 75 years ago, but especially the advent of new powerful photon beams in the MeV range in the entrance channel and new high resolution efficient detectors in the exit channel revived the field some years ago. In the field of magnetic dipole excitations these developments helped to understand the nature of the orbital scissors mode [1]. For electric dipole excitations one could establish systematically low-lying octupole coupled modes [2,3], the isovector Giant Dipole Resonances (GDR) and the so called Pygmy Dipole Resonances (PDR) [4,5]. It is discussed, that the detailed knowledge of the E1 strength distribution in atomic nuclei can shed light on the slope of the symmetry parameter in the equation of state (see, e.g., Refs. [6,7]) and may have implications for the synthesis of heavy nuclei [8,9].

This manuscript will concentrate on electric dipole strength observed in the energy range between the lowest-lying octupole coupled modes (about 3-4 MeV in spherical nuclei) and the energy range where the low energy tail of the GDR dominates the photoresponse (about 10-12 MeV). The concentration of E1 strength found in this region is usually denoted as Pygmy Dipole Resonance (PDR) without referring to a certain structure.

2 Experimental status

2.1 Electromagnetic probes

Electromagnetic probes which excite the nucleus of interest by real or virtual photons are ideal tools to investigate the dipole response of atomic nuclei.

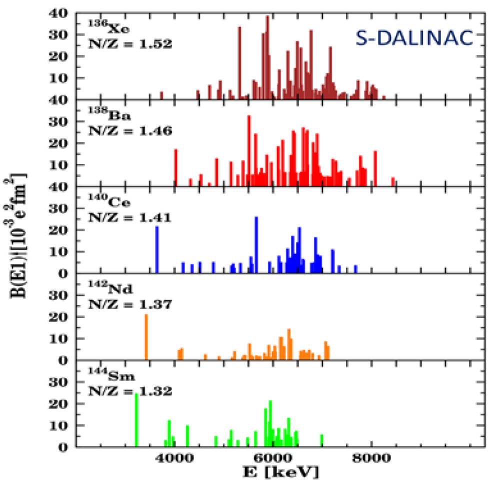

Figure 1: E1 strength distribution observed in discrete transitions to the groundstate in the stable even-even N=82 isotones (adapted from Refs. 14 and 15).

Many systematic studies using real photons have been performed at the former bremsstrahlung facilities in Ghent [10] and Stuttgart [11] and the present facilities at

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TU Darmstadt [12] and the Helmholtz-Zentrum Dresden-Rossendorf [13]. The continuous or "white" bremsstrahlung spectrum produced at these facilities allows one to study a wide energy range in a single experiment using the method of Nuclear Resonance Fluorescence (NRF) [11]. The excitation is proportional to the ground state decay width Γ_0, i.e., the strongest E1 and M1 excitations are easily identified. In addition the observables energy, spin, branching ratios, absolute transition strength and parity can be derived in a completely model independent way. In a more integral approach strength hidden in the background can be taken into account as well. Both data evaluation methods exhibit an enhancement of the E1 strength in the energy region between about 5 and 8 MeV (see Figs. 1 and 2).

Coulomb excitation studies with virtual photons have been performed at the RCNP Osaka in proton-scattering experiments at E_p about 300 MeV under extreme forward angles [17]. The scattered protons are measured with high resolution (ΔE about 25 keV) with the Grand Raiden magnetic spectrometer. Therefore this method is no longer restricted to excitations below the particle threshold (where γ decay dominates), but one can measure dipole strength distributions from the lowest to the highest energies and derive, e.g., integral parameters like the dipole polarizability α_D.

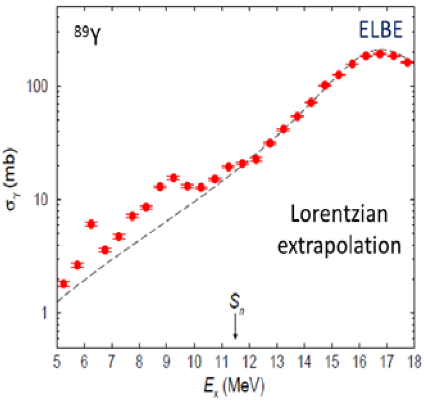

Figure 2: Total photoabsorption cross section in ^{89}Y (adapted from Ref. [16]).

The exchange of virtual photons is used as well in inverse kinematics experiment where the role of projectile and target are exchanged. This enables the study of the dipole response of radioactive species as well. One example are the Sn isotopes ^{130,132}Sn which have been studied at the LAND neutron detector setup at the fragment separator (FRS) at GSI [18]. However, these experiments can only identify strength above the threshold. The γ decay of radioactive nuclei after Coulomb excitation in the region of the PDR has been measured recently in the nucleus ^{68}Ni combining the FRS with the HECTOR BaF array and RISING HPGe array for γ ray detection [19].

The summed E1 strength detected by various experiments in the "region below the GDR" or "on top of the tail of the GDR" (which are somehow arbitrary or model dependent definitions) is shown in Figure 3. The strength is given in terms of the exhaustion of the isovector energy weighted sum rule (EWSR) which correlates with (N·Z)/A. The parameter Δ_{CCF} gives the differences in the Coulomb-corrected Fermi energies for protons and neutrons and is a good measure for the "exoticity" of a nucleus. The plot shows a wide scatter of the summed E1 strength. We think that this is partly due to a summation of E1 strengths which do not belong to the same excitation mode, i.e. a PDR with a structure distinct from the GDR. Therefore one needs experiments with complementary probes which test different observables connected to the structure of the excitations and can serve to identify the fraction belonging to the PDR.

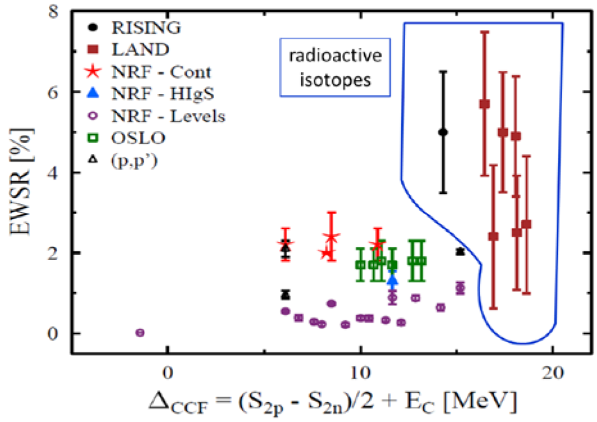

Figure 3: Summed E1 strength vs. Coulomb-corrected Fermi energy Δ_{CCF} (adapted from Ref. [4]). The plot includes as well data derived by the Oslo group [20].

2.2 Hadronic probes

Electromagnetic probes can yield the details of the E1 strength distribution, but one way to obtain additional information are proton- and α-scattering studies at, e.g., intermediate energies of 80 MeV and 120 MeV, respectively, where the hadronic interaction strongly dominates. Such experiments can help to investigate the isospin character and the spatial extension of the wave functions of the excitations. However, such scattering experiments are much less selective with respect to the spin of the excitation compared to the described studies using electromagnetic excitation. In addition, the energy resolution of typical particle spectrometers is much worse compared to HPGe detectors frequently used to study the de-excitation of the states forming the PDR after electromagnetic population.

The solution to these limitations came partly by an idea of M.N. Harakeh and T.D. Poelhekken who combined a particle spectrometer positioned under forward angles to detect the scattered particles with NaI detectors for the coincident spectroscopy of the γ rays emitted after excitation [21]. In a second step our group replaced the NaI detectors by high-resolution HPGe detectors which allowed performing the particle-γ coincidence experiments even in nuclei and energy regions with higher level densities [22].

The results from systematic (α,α'γ) studies on different closed neutron- and proton-shell nuclei and the open shell nucleus ^{94}Mo were quite surprising [23-26]: whereas the E1 strength below about 6-7 MeV could be populated in both, photon scattering and alpha scattering, the higher lying strength was not excited by the alpha particles. Just from this experimental result the E1 strength below the GDR has to be divided into two groups: One low-lying part below about 6-7 MeV with a strong isoscalar component and a surface-peaked wave function. And a higher-lying part with a dominant isovector character. This result has been confirmed recently in ^{17}O scattering experiments by the Milano group [27].

The splitting has been supported by a number of theroretical calculations as well, see e.g. Refs. [28,29]. Therefore, we propose that only the lower-lying part should be attributed to "the real PDR", an excitation mode clearly distinct from the GDR, whereas the higher lying part is E1 strength with transition charge densities on the way to the GDR.

On basis of the interpretation of the splitting of the E1 strength, a summation should be carried out only by taking into account those excitations, which are populated in both, (γ,γ') and (α,α') experiments. The result of this new summation for the five isotopes where complete data sets are currently available is exhibited in Figure 4 [30]. One can see that the original summed E1 strength (the blue squares) is reduced (leading to the red triangles). The new summed E1 strength seems to follow nicely a linear correlation with the parameter Δ_{CCF} as predicted in various theoretical calculations, see, e.g., Ref. [31].

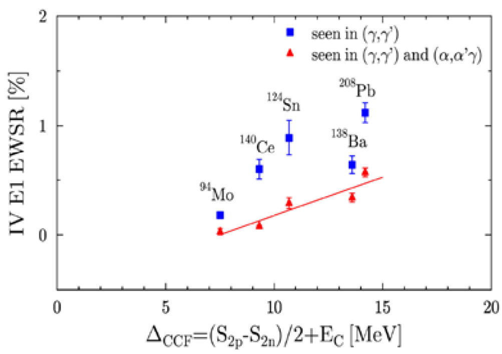

Figure 4: Summed E1 strength in the PDR region (blue squares) and summed E1 strength in the PDR region excited in photon- and α-scattering experiments (red triangles) [30].

3 The future

The present status described above defines a number of key questions which should be addressed to allow for a better understanding of the low-lying E1 strength and to establish the PDR as a new distinct general phenomenon in atomic nuclei:

- What is the evolution of the E1 strength distribution with respect to mass, deformation and neutron excess?
- What can we learn from the γ-decay pattern of the 1^- states?
- What is the isospin structure of the excitations? Does it allow to distinguish the PDR from the GDR?
- What is the single-particle structure of the excitations building the PDR?

A number of experiments are already under way or have been proposed. We refer to the contributions by V. Derya, J. Isaak, R. Massarczyk, P. von Neumann-Cosel, S.G. Pickstone, D. Symochko, A. Tonchev, and V. Werner to the CGS 15 conference. In the following we will discuss two approaches which are under way to look into the isospin structure and the single-particle structure of the PDR, respectively.

3.1 Isospin structure and the splitting of the low-lying E1 strength

One crucial step in the study of E1 excitations were the first experiments using hadronic probes at intermediate energies. However, the Big-Bite Spectrometer at KVI is no longer operational, therefore we had to stop the (α,α'γ) and (p,p'γ) experiments at Groningen. Fortunately, two other facilities provide the opportunity to continue the high-precision scattering experiments with coincident detection of γ-rays on stable nuclei:
During beamtimes planned for the next future at RCNP Osaka, the CAGRA array, a setup consisting of 16 Compton-suppressed HPGe detectors will be installed at the Grand Raiden spectrometer. This will allow to perform (α,α'γ) and (p,p'γ) experiments with parameters similar to those at the Big-Bite Spectrometer at KVI Groningen, but with a much higher efficiency to detect γ rays and a considerable improved detection probability in the spectrometer. A number of experiments have been proposed by a group of researchers from Darmstadt, Milano, Osaka, and Cologne.
The K600 spectrometer at iThemba Labs in Faure, South Africa, provides another opportunity to continue the hadron-scattering experiments with coincident detection of γ rays. First test experiments have been performed successfully, presently modifications to the spectrometer and an integration of HPGe detectors from the AFRODITE array are planned to optimize the setup.
First α-scattering experiments in inverse kinematics to study the PDR also in radioactive nuclei will be performed in October 2014 at the BigRIPS spectrometer at RIKEN by a collaboration including working groups from GSI, TU Darmstadt, INFN Milano, RIKEN, University of Tokyo, and University of Cologne. Here different Sn beams ranging from stable ^{124}Sn to radioactive ^{132}Sn will be scattered on a liquid He target, γ-rays are detected by means of the extended DALI 2 array consisting of NaI and LaBr detectors [32].

3.2 Single-particle structure of the PDR

Proton- and neutron-transfer experiments allow to study the single-particle character of the excitations. At high-resolution spectrometers, like the Q3D at the MLL in Munich, this can be done quantitatively in a very efficient way if the level density is not too high [33].

Recently we have complemented the HORUS array for γ spectroscopy at the Cologne FN Tandem accelerator consisting of 14 HPGe detectors by the newly developed particle-detection array SONIC. This array consists of eight ΔE-E Silicon detectors for particle identification and particle-energy determination with high resolution. The target-detector distance can be varied for each telescope detector separately to optimize count rates (see Fig. 5). The first preliminary results are quite promising: in a ^{119}Sn(d,p) neutron-transfer reaction PDR states in ^{120}Sn could be populated. More details can be found in the contribution by S.G. Pickstone *et al.* to these proceedings.

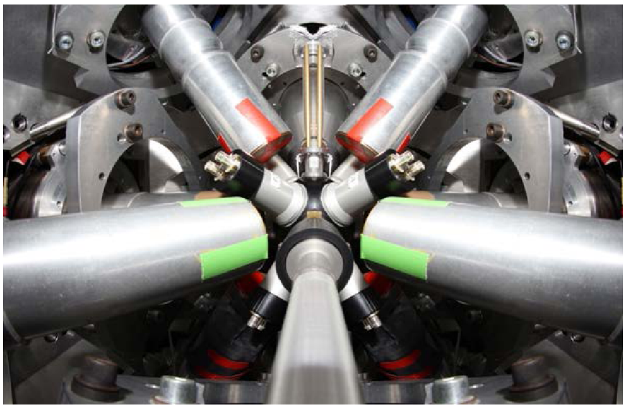

Figure 5: The SONIC particle identification and spectroscopy array mounted in the HPGe array HORUS (the beam is coming from the back side).

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