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The Pygmy Dipole Resonance – status and new developments

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Abstract. At energies well below the isovector electric Giant Dipole Resonance, a concentration of electric dipole strength is observed in many stable and radioactive nuclei. This low-lying excitation mode is usually denoted as Pygmy Dipole Resonance (PDR). Different theoretical approaches can reproduce the gross features, like the energetic position and partly the excitation strength of the PDR, but they differ considerably in its underlying structural description. More sophisticated experiments looking for the isospin character, the detailed decay pattern, and the single-particle structure of the low-lying E1 excitations are therefore mandatory to gain a deeper understanding. This manuscript will give an overview about the most recent experimental results and present new experimental tools for the future.

Introduction

Atomic nuclei irradiated by photons in the MeV range can be excited to various electric and magnetic dipole modes (see figure 1). The electric dipole strength is dominated by the Giant Dipole Resonance (GDR) which was discovered already in 1937 by Bothe and Gentner [1]. Baldwin and Klaiber continued with systematic studies on various nuclei which enabled to derive the main parameters of the GDR [2].



Figure 1: Schematic distribution of dipole strength in an atomic nucleus showing electric dipole modes (E1) in the upper part and magnetic dipole modes (M1) in the lower part. The two-quasi-particle (2QP) strength is often denoted "scissors mode" in deformed nuclei.

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The GDR exhausts about 100% of the energy-weighted sum rule (EWSR) for isovector E1 strength. However, the last decades showed that an additional concentration of E1 strength exhausting about one to a few percent of the EWSR (i.e., a few percent of the strength found in the GDR) can be detected at lower energies. These excitations are commonly denoted as Pygmy Dipole Resonance (PDR); its properties are summarized in a recent review [3]. Different experimental probes have been used to determine the distribution of B(E1) strength including Nuclear Resonance Fluorescence (NRF) using photons from bremsstrahlung, see, e.g., refs. [4,5,6], Coulomb excitation of stable isotopes in (p,p') experiments at proton energies of around 400 MeV [7], and Coulomb excitation using relativistic beams in inverse kinematics [8]. The precise knowledge of the E1 strength distribution in atomic nuclei can help to get a better understanding of the neutron skin of nuclei and of the slope of the symmetry energy in the Equation of State [9-13].

Systematics of E1 strength distribution

An overview of most available data on E1 strength in the region below and around the particle threshold derived from electromagnetic excitation experiments is displayed in figure 2. Here, the summed E1 strengths are given as the exhaustion of the isovector E1 EWSR. The strength is plotted versus the Coulomb corrected Fermi energy Δ_{CCF} which is a good measure for the exoticity of a nucleus [3]. Studies on radioactive nuclei usually result in larger error bars. In an often discussed simplified picture of the PDR as an oscillation of excess neutrons against an isospin saturated core one would expect a correlation between the PDR strength and Δ_{CCF} . The figure shows quite obviously that the existing data are far from being consistent, different methods give different values for the summed B(E1) strength [3]. One of the reasons is different approaches how to treat the unresolved background in the region of the PDR. Another important reason is the difference in the definitions, which energy range and excitations have to be included in the summed strength, i.e., which states represent the PDR. We note that the data for radioactive nuclei usually stem from excitations above the neutron threshold (because the neutron is observed in the exit channel). This is in contrast to the situation for stable nuclei. The typical observables derived from electromagnetic excitation make it difficult to distinguish the structural differences in E1 excitation modes. Therefore, alternative probes are necessary to learn more about the E1 excitations.



Figure 2: Summed electric dipole strength in the region of the PDR versus the Coulomb corrected Fermi energy Δ_{CCF} . This parameter is a good measure for the exoticity of a nucleus. (adapted from [3].)

Isospin splitting of the E1 strength

The scattering of α particles at energies of around 35 MeV/u under forward angles favors isoscalar $\Delta T=0$ excitations at the surface of a nucleus. Coulomb excitation is strongly suppressed under these kinematical conditions. Therefore, they represent a complementary probe to photons which interact only with the protons in the nucleus and induce $\Delta T=1$ E1 transitions. Figure 3 exhibits as an example the situation in the nucleus ¹²⁴Sn: α scattering can only populate states with the same isospin T=12 as the groundstate, whereas the excitation by isovector photons can populate T=12 as well as T=13 states [14].



Figure 3: From the T_{gs} =12 ground state in ¹²⁴Sn, an excited state with T=12 can either be reached by an isoscalar ΔT =0 transition or by an isovector ΔT =1 transition. In addition, the ΔT =1 transition can populate a T=13 state (e.g. belonging to the GDR) which is at higher energies.

In pioneering experiments at the KVI Groningen, a group around M.N. Harakeh combined medium resolution spectroscopy of scattered α particles at the QMG/2 spectrometer with NaI detectors to measure the subsequent γ decay in coincidence [15]. This technique allows to select low-multipolarity groundstate transitions (as, e.g., E1 transitions) from the data. One could identify isoscalar E1 strength around 5-7 MeV in four nuclei with rather low level densities, namely ⁴⁰Ca, ⁵⁸Ni, ⁹⁰Zr, and ²⁰⁸Pb. Low level density was a prerequisite due to the limited energy resolution of the NaI detectors. About one decade later, an improved setup, using the Big-Bite Spectrometer (BBS) for α spectroscopy and an array of HPGe detectors for high-resolution γ spectroscopy allowed to extend the studies to nuclei with higher level densities as well [16]. Systematic studies on various isotopes followed, which revealed a surprising structural splitting of the E1 strength below the particle threshold. Figure 4 shows as an example the results for the Z=50 nucleus 124 Sn. The lower part gives the B(E1) strength distribution measured in real-photon scattering experiments, the upper part the cross sections measured in the α scattering experiment. Below about 7 MeV, the excitation pattern seems to be quite similar in $(\alpha, \alpha' \gamma)$ and (γ, γ') whereas nearly all excitations above about 7 MeV could not be excited with the isoscalar probe. Similar results have been obtained for all other heavy nuclei investigated in $(\alpha, \alpha' \gamma)$ and in a very recent study using ¹⁷O as a projectile by the Milano group [17]. Therefore, one can conclude that the low-lying E1 strength splits into a part below about 7 MeV which can be excited with α particles and γ rays and a higher lying part which can only be excited by γ rays. This observation was reproduced qualitatively by a number of theoretical calculations [see, e.g., 18-21]. A systematic comparison of PDR strength should therefore take into account possible structural differences of the E1 excitations.



Figure 4: Cross section for E1 excitations observed in the $(\alpha, \alpha' \gamma)$ experiment (upper part) in comparison with the E1 strength observed in (γ, γ') . Whereas all low lying states are populated in both experiments, the α particles do not populate the majority of the higher lying states (data taken from ref. [19]).

Outlook

The main challenges that need to be addressed to to obtain a better understanding of the PDR can be summarized as follows:

- What is the systematics of the E1 strength in light nuclei, in nuclei away from shell closures and in exotic nuclei?
- What are the decay properties of the E1 excitations into other low-lying states and do the theoretical models predict the decay pattern correctly?
- Is the observed difference in the excitation pattern using isoscalar and isovector probes a general phenomenon?
- What is the single-particle structure of the E1 excitations?

Ambitious experimental programs have been initiated and partly started at several stable and radioactive beam facilities and photon beam facilities worldwide to answer the questions above. An incomplete list includes experiments using photons at HI γ S, Duke University; at the S-DALINAC at Darmstadt University; ELBE at FZ Dresden; and in the future at the ELI-NP facility in Bukarest. The PDR in exotic nuclei will be studied at GSI Darmstadt using the virtual photon bath at relativistic beam energies; and at RIKEN, Tokyo using a He target to study the response to an isoscalar probe. Finally, stable ion beams are used, e.g., at INFN Legnaro, at iThembaLABS Cape Town, at RCNP Osaka, at MLL Munich, and at the IKP Cologne. One very recent result from the latter facility is shown in figure 5. A (d,p γ) reaction on ¹¹⁹Sn has been performed to populate states in ¹²⁰Sn. Due to the coincident spectroscopy of the proton and the emitted γ rays, this represents a very efficient tool for selecting the desired reaction and decay channels in the data analysis. The first preliminary results show that a strong excitation of the PDR in this one-neutron transfer reaction, tentative parities have been assigned by comparison with existing data. A more detailed analysis may allow an insight into the single-particle structure of the excitations.



Figure 5: γ spectrum from a (d,p γ) reaction at E_d =8.5 MeV measured at the Cologne Tandem accelerator using the particle detector array SONIC and the HORUS γ spectroscopy array.

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