

Recent results on the Pygmy Dipole Resonance

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Abstract. Beside the well-known Giant Dipole Resonance in most nuclei an additional structure has been identified in the low-energy part of the electric dipole strength, which is usually denoted as Pygmy Dipole Resonance (PDR). The PDR has attracted strong interest in the last years in nuclear physics and has been experimentally studied using different approaches in the last decade. Among the other experiments the nuclear resonance fluorescence (NRF) method has played a pioneering role in the research on the PDR.

1. Introduction

The Isovector Electric Dipole Giant Resonance (IVGDR) is the dominant feature of the electric dipole (E1) strength in atomic nuclei. This collective excitation mode is understood in a macroscopic interpretation as an out-of-phase oscillation of the protons and neutrons and has been studied in the past in various experiments, see e.g. [1] and references therein.

In many nuclei an additional structure in the low-energy tail of the IVGDR has been observed, which exhausts only a few percent of the total E1 strength and, therefore, is denoted as Pygmy Dipole Resonance (PDR) or Pygmy Dipole Strength. Even though the strength of the PDR is small compared to the IVGDR, its location at low energies around the particle threshold makes it particular interesting from the nuclear structure point of view, since it allows to study details of modern microscopic models which describe the E1 response of atomic nuclei [2]. In addition it has gained interest in the last decade due to its possible connections to the neutron skin of atomic nuclei and properties of nuclear matter [3, 4, 5, 6, 7] as well as reaction rates in the synthesis of heavy elements [8, 9, 10]. However, the microscopic structure of the PDR, its collectivity and the robustness of the connections to other properties mentioned above are a matter of ongoing discussions.

Experimentally no conclusive picture can be drawn so far on the systematic or structure of the PDR. We have recently presented the available experimental data on the PDR in our review [11] describing in detail also the experimental approaches and their limitations. Special attention is made in this review also on the NRF method using different photon beams and its application to investigate low-lying E1 strength below the particle threshold. For a detailed discussion I thus refer to [11].



2. Systematics of the PDR

Photon (real or virtual) induced reactions are an ideal tool to investigate the (total) strength of the PDR. The well-known reaction mechanism allows a model independent extraction of absolute transition strengths from the ground state into the PDR from the experimental observables. For stable nuclei the nuclear resonance fluorescence (NRF) method is used most widely to obtain information on the E1 strength distribution below the neutron separation energy. For these experiments photon beams produced via bremsstrahlung [12, 13] and laser Compton backscattering (LCB) [14] have been used. In the analysis of the data different approaches have been used taking into account either only the contribution of isolated peaks resulting in model-independent results but accepting a limited sensitivity (see e.g. [15]) or including the full spectra to extract the full strength but accepting the need of statistical model assumptions in the analysis and thus model dependent results (see e.g. [16]). For a detailed discussion of the different approaches used in NRF experiments including their individual advantages and drawbacks I refer to the review [11] and the references given above.

For excitation energies above the neutron emission threshold the NRF reaction is no longer suitable, since the decay is dominated by neutron evaporation. In this energy region information on the excitation energy thus has to be provided by the incoming photon beam. Consequently, LCB photons have been used to measure the (γ, n) cross section as a function of the excitation energy (see e.g. [17, 18]). Just recently a new approach has been proven to result in the extraction of the full E1 response independent of particle thresholds by the means of Coulomb excitation (i.e. virtual photons) in the (p, p') reaction [19, 20], which however requires a separation from the M1 response via a multipole decomposition analysis (see contribution of P. von Neumann-Cosel).

For unstable nuclei the available approaches are much more involved, since experiments have to be performed in inverse (and complete) kinematics including a clean isotope identification on an event-by-event basis, which requires complex experiment setups in addition to the facility producing and providing the exotic ion beam. So far the E1 response in medium-heavy to heavy nuclei has been studied via Coulomb excitation in inverse kinematics in the region of $^{130,132}\text{Sn}$ [21, 4] and in ^{68}Ni [22, 23]. The experiments were sensitive to excitation energies above the corresponding particle thresholds only. Thus, deriving a consistent systematic picture on the total strength of the PDR together with the results from stable nuclei is very difficult.

Figure 1 summarizes the fraction of the energy weighted sum rule (EWSR) exhausted by the PDR for a variety of nuclei of different masses as reported in the different corresponding publications (see [11] for details). It has to be stressed, that the EWSR values are not derived in a consistent way along the different experiments, i.e. in some cases contributions of the low energy IVGDR tail are subtracted in others not. Partly different energy regions have been chosen for the integration region. This summary therefore can only provide a first idea on the strength of the PDR.

The strength of the PDR is plotted in Fig. 1 as a function of the parameter Δ_{CCF} , which is defined by

$$\Delta_{CCF} = (S_{2p} - S_{2n})/2 + E_C \quad (1)$$

where S_{2p} and S_{2n} are the two proton and two neutron separation energies, respectively, and E_C is the height of the Coulomb barrier at the nuclear radius (CCF = Coulomb Corrected Fermi energy). The parameter therefore compares the Fermi energies of protons and neutrons corrected for the coulomb contribution, which seems to be a reasonable parameter for the neutron skin thickness (see [11] for details). Although the strength of the PDR seems to be enhanced in the more neutron rich isotopes a clear and conclusive statement on the dependence of the PDR on Δ_{CCF} cannot be drawn. Additional and especially more complete and consistent data is necessary in order to learn more on the systematics of the PDR. Also, experiments determining the E1 strength distribution alone are not sufficient in order to learn more on the underlying structure of the PDR.

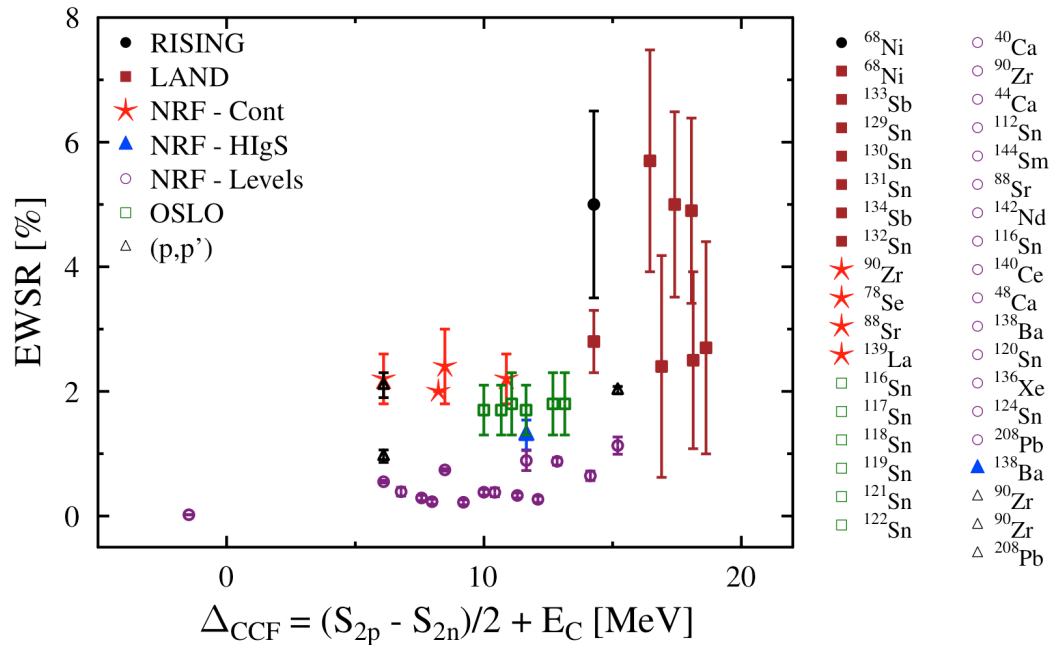


Figure 1. Reported exhaustion of the PDR in various nuclei extracted from experiments using different experimental approaches as a function of Δ_{CCF} (see [11] for details).

3. The decay properties of the PDR

A property which can provide further insight into the structure of the E1 strength at low energies is the decay pattern of the PDR. So far, this property could not be directly accessed, since the branching transitions to individual low-lying excited states are small and, therefore, a very sensitive experimental method is needed. On the other hand, information on the decay behavior of the PDR is of high interest since it is also directly connected to the concept of γ -ray strength functions, which are used within the statistical model to describe the decay of excited states in nuclear synthesis processes. Partly, this concept is also used in the analysis of experimental data to derive information on the total strength of the PDR [16]. An experimental determination of branching ratios and in general the decay pattern of the low-lying E1 strength is therefore of principle interest.

Again, photon-induced reactions can be used in order to address this topic. However, standard NRF experiments are not sensitive enough to investigate the weak branching transitions to low-lying excited states, even when using a mono-energetic LCB photon beam. At the same time these NRF experiments have shown indirectly that the integrated intensity going into these so-called inelastic transitions (i.e. any transition not going directly back to the ground state) cannot be neglected [24, 25, 26, 27]. The method of γ - γ coincidence experiments has been shown to be very sensitive even to very weak transitions. However, so far this method has only been used in particle-induced reactions, which do not sufficiently excite the $J^\pi = 1^-$ states of interest. Therefore, the combination of γ - γ coincidence spectroscopy and the NRF reaction using a mono-energetic photon beam from LCB offers the best possible experimental approach to access the branching pattern of the PDR.

This approach is realized in the newly installed γ^3 setup at the High Intensity γ -ray Source (HI γ S) at TUNL, Duke University [28]. In this setup high-efficiency large LaBr detectors are combined with high-resolution HPGe detectors. The concept is illustrated in the left part of Fig. 2. The high efficiency of the LaBr array allows to gate on the decay of the low-lying state (green)

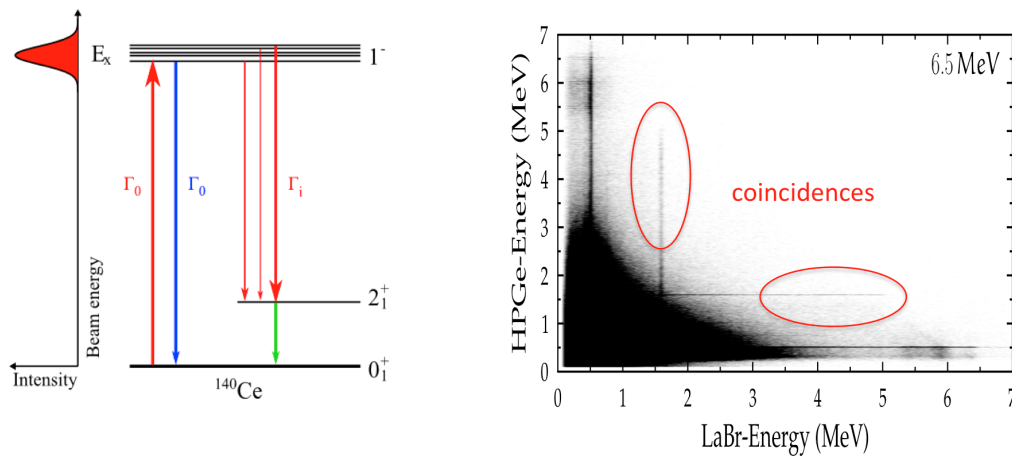


Figure 2. Left part: Concept of the γ - γ coincidence technique in combination with the mono-energetic photon beam at HI γ S. Right part: Measured γ - γ coincidence matrix using the combination of LaBr and HPGc detectors.

and investigate the feeding transitions (red) with high resolution using the HPGc array. Since the photon beam is mono-energetic all transition energies are uniquely defined in a two-step decay cascade. This strongly reduces the background and, therefore, provides the high sensitivity needed to investigate even weak branching transitions. In a first commissioning experiment this has been demonstrated for the case of ^{32}S , where an improvement of the peak-to-background ratio of about a factor of 50 was achieved [28].

As one of the first cases to investigate the decay pattern of the PDR with the new γ^3 setup the N=82 isotope ^{140}Ce has been chosen, since in this nucleus an interesting splitting of the low-lying E1 strength into two parts with different underlying structure has been reported using the $(\alpha, \alpha'\gamma)$ reaction (see contribution of A. Zilges and references [29, 30, 31]). The first results show that the sensitivity is high enough in order to investigate directly the branching ratios into the first excited states. In the right part of Fig 2 one example of a two-dimensional γ - γ coincidence matrix is shown for a beam energy of 6.5 MeV. The coincidence transitions into the first excited 2_1^+ state at 1596 keV are evident. One first result from this experiment is given in Fig. 3, which shows the determined mean branching ratio as a function of the excitation energy (see [32] for details). Calculations within the quasi-particle phonon model (QPM) are in excellent agreement to the data, which shows that the relevant couplings of the PDR to the 2_1^+ is described in the QPM in an accurate way [33].

These first results show, that the used approach is suitable and sensitive enough to study even very weak decay branchings to excited states of the nucleus, which will allow to investigate the decay pattern of photo-excited states in much greater detail.

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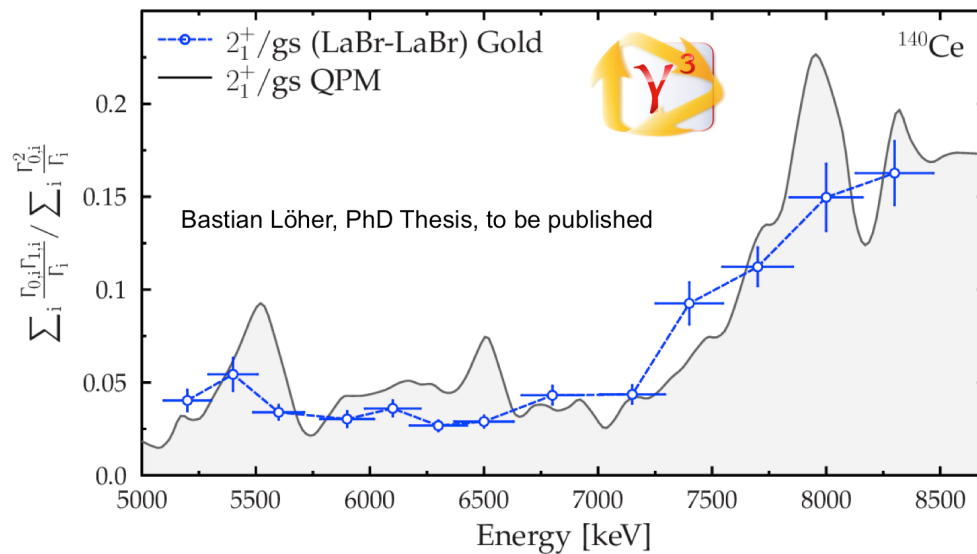


Figure 3. First results for the mean branching ratio to the first excited state in the nucleus ^{140}Ce as determined using the γ^3 setup and calculated within the QPM model [32].

References

- [1] Harakeh M N and van der Woude A 2001 *Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation*, Oxford University Press
- [2] Paar N, Vretenar D, Khan E and Colò G 2007 *Rep. Prog. Phys.* **70** 691
- [3] Piekarewicz J 2006 *Phys. Rev.* **C73** 044325
- [4] Klimkiewicz A, Paar N, Adrich P *et al.* 2007 *Phys. Rev.* **C76** 051603
- [5] Tsoneva N and Lenske H 2008 *Phys. Rev.* **C77** 024321
- [6] Piekarewicz J 2011 *Phys. Rev.* **C83** 034319
- [7] Vretenar D, Niu Y F, Paar N and Meng J 2012 *Phys. Rev.* **C85** 044317
- [8] Goriely S 1998 *Phys. Lett.* **B436** 10
- [9] Goriely S, Khan E and Samyn M 2004 *Nucl. Phys.* **A739** 331
- [10] Litvinova E, Loens H P, Langanke K, Martinez-Pinedo G, Rauscher T, Ring P, Thielemann F K and Tselyaev V 2009 *Nucl. Phys.* **823** 26
- [11] Savran D, Aumann T and Zilges A 2013 *Prog. Part. Nucl. Phys.* **70** 210
- [12] Schwengner R, Beyer R, Dönauf F *et al.* 2005 *Nucl. Instr. and Meth.* **A555**(1-2) 211
- [13] Sonnabend K, Savran D, Beller J 2011 *et al. Nucl. Instr. and Meth. Phys. Res.* **A640** 6
- [14] Weller H R, Ahmed M W, Gao H, Tornow W, Wu Y K, Gai M and Miskimen R 2009 *Prog. Part. Nucl. Phys.* **62** (1) 257
- [15] Savran D, Elvers M, Endres J *et al.* 2011 *Phys. Rev.* **C84** 024326
- [16] Schwengner R, Rusev G, Tsoneva N *et al.* 2008 *Phys. Rev.* **C78** 064314
- [17] Utsunomiya H, Goriely S, Akimune H *et al.* 2010 *Phys. Rev.* **C81** 035801
- [18] Utsunomiya H, Goriely S, Kamata M *et al.* 2011 *Phys. Rev.* **C84** 055805
- [19] Tamii A, Poltoratska I, von Neumann-Cosel P *et al.* 2011 *Phys. Rev. Lett.* **107** 062502
- [20] Iwamoto C, Utsunomiya H, Tamii A *et al.* 2012 *Phys. Rev. Lett.* **108** 262501
- [21] Adrich P, Klimkiewicz A, Fallot M *et al.* 2005 *Phys. Rev. Lett.* **95** 132501
- [22] Wieland O, Bracco A, Camera F *et al.* 2009 *Phys. Rev. Lett.* **102** 092502
- [23] Rossi D M, Adrich P, Aksouh F *et al.* 2013 *Phys. Rev. Lett.* **111** 242503
- [24] Tonchev A P, Hammond S L, Kelley J H, Kwan E, Lenske H, Rusev G, Tornow W and Tsoneva N 2010 *Phys. Rev. Lett.* **104** 072501
- [25] Angell C T, Hammond S L, Karwowski H J, Kelley J H, Krtićka M, Kwan E, Makinaga A and Rusev G 2012 *Phys. Rev.* **C86** 051302(R)
- [26] Isaak J, Savran D, Krtićka M *et al.* 2013 *Phys. Lett.* **B727** 361
- [27] Scheck M, Ponomarev V Y, Aumann T *et al.* 2013 *Phys. Rev.* **C87** 051304

- [28] Löher B, Derya V, Aumann T *et al.* 2013 *Nucl. Instr. and Meth. Phys. Res.* **A723** 136
- [29] Savran D, van den Berg A M, Harakeh M N, Hasper J, Matic A, Wörtche H J and Zilges A 2006 *Phys. Rev. Lett.* **97** 172502
- [30] Endres J, Savran D, van den Berg A M, Dendooven P, Fritzsche M, Harakeh M N, Hasper J, Wörtche H J and Zilges A 2009 *Phys. Rev.* **C80** 034302
- [31] Endres J, Litvinova E, Savran D *et al.* 2010 *Phys. Rev. Lett.* **105** 212503
- [32] Löher B 2014 *PhD thesis, University Mainz, to be published*
- [33] Ponomarev V 2014 *private communication*