Concentration of electric dipole strength below the neutron separation energy in N=82 nuclei

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Abstract

The semi-magic nuclei $^{138}$Ba, $^{140}$Ce, and $^{144}$Sm have been investigated in photon scattering experiments up to an excitation energy of about 10 MeV. The distribution of the electric dipole strength shows a resonance like structure at energies between 5.5 and 8 MeV exhausting up to 1 % of the isovector E1 Energy Weighted Sum Rule.

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Collective electric dipole excitations (E1) are common phenomena in very different finite fermion systems. They were first discovered in atomic nuclei where they can be interpreted as out of phase oscillations of protons versus neutrons and are characterized as Giant Dipole Resonance (GDR) \[1,2\]. In recent years they have also been observed in metallic clusters where compounds of typically 2-40 positively charged ions are oscillating versus its electron cloud leading to an E1 resonance like structure, see e.g. \[3–5\]. Very recently a similar mode has been predicted to occur in quantum dots where the fermions are the electrons and holes confined to a tiny space \[6,7\].

The mean energy of the GDR in nuclei lies around 14 MeV in heavy nuclei and around 20 MeV in light nuclei. The GDR exhausts about 100\% of the Energy Weighted Sum Rule (EWSR) for isovector E1 strength. Microscopically the GDR consists of particle–hole excitations across one major shell. The residual interaction shifts the energy to the GDR region. In the past there has been some experimental evidence, that a considerable part of the E1 strength remains around the $1\hbar\omega$ region \[8–14\]. This strength is usually specified as Pygmy Dipole Resonance (PDR). However, no systematic study on a number of nuclides in the energy range up to the particle threshold has been performed so far. In addition, very different and sometimes contradictory, collective pictures have been proposed to account for this low lying E1 strength.

A nonstatistical distribution of E1 strength close to the neutron threshold has important implications for ($\gamma,n$) reaction rates in hot stellar scenarios important for nucleosynthesis \[15,16\]. Please note that this is true even for E1 strength below the threshold because of finite population of low lying excited states in thermal equilibrium shifting the collective E1 strength (Brink hypothesis).

Detailed experimental knowledge about E1 excitations below the GDR is typically limited to the energy region below 4.5 MeV. High resolution photon scattering experiments (Nuclear Resonance Fluorescence – NRF) have yielded a wealth of information, especially for deformed nuclei well away from shell closures \[17,18\].

In most spherical nuclei only the lowest $1^-$ state has been studied. Systematic ($\gamma,\gamma'$) studies together with complementary experiments with hadronic probes have established this lowest E1 excitation as a two phonon quadrupole–octupole $2^+ \otimes 3^-$ mode \[19\]. It has a dominant isoscalar character \[20\].

For the energy range above the two phonon state up to the neutron threshold the advent of experimental facilities for high precision photon scattering at higher energies enables now a detailed determination of the E1 strength pattern. Photon scattering is an ideal tool to investigate collective low spin modes because it selectively populates dipole (and to less extent quadrupole) excitations from the ground state. The well known electromagnetic excitation mechanism allows a model independent determination of absolute transition strengths (or of dynamic dipole moments). Using a continuous bremsstrahlung spectrum allows a scan of a wide energy region with a single measurement \[17\].

We have performed photon scattering experiments on the semi–magic N=82 nuclei $^{138}$Ba, $^{140}$Ce, and $^{144}$Sm at the real photon facility of the superconducting Darmstadt electron accelerator S–DALINAC which allows experiments up to $E_{\text{max}}=9.9$ MeV \[21\]. Table I lists the parameters of the experiments: Target composition, isotopic enrichment, mass, neutron separation energy, maximum energy of the bremsstrahlung beam, and the total measuring time. To distinguish direct decays to the ground state from decays to excited states one
has to perform measurements with at least two different endpoint energies. For $^{138}$Ba and $^{140}$Ce data is available from older $(\gamma, \gamma')$ experiments up to 6.7 MeV \cite{12,14}. For $^{144}$Sm we performed an additional experiment with a maximum energy of 7.6 MeV.

The raw photon scattering spectrum of $^{138}$Ba recorded with a Ge(HP) detector positioned at 90° with respect to the incoming photon beam is shown in Fig. 1. It shows a number of lines mainly stemming from the decay of excited states in $^{138}$Ba to the ground state. In addition one can identify lines from transitions in the photon flux calibration target $^{11}$B measured simultaneously. The lines are sitting on a background of mostly nonresonantly scattered photons which rises exponentially with decreasing energy. Already from the raw spectrum the nonstatistical structure of the excitations in $^{138}$Ba can be guessed: Besides the strong transition at 4025 keV stemming from the decay of the $2^+ \otimes 3^-$ mode discussed above, a concentration of lines is observed between 5.5 and 7 MeV.

A measurement of the angular distribution yielded the spin of the excitations. Measurements at only two angles (90° and 130°) allow for distinguishing the two possible $\gamma$ ray spin cascades starting from the groundstate, populating a $J=1$ or 2 state and decaying back to the groundstate ($0 \rightarrow 1 \rightarrow 0$ and $0 \rightarrow 2 \rightarrow 0$) unambiguously. A recent parity measurement using a monoenergetic photon beam has already verified negative parity for all dipole excitations below 6.7 MeV (the higher energy range has not been measured so far) in $^{138}$Ba \cite{22}. From this result and based on systematic grounds we assume that all observed dipole excitations have electric character, i.e. our summed strength are an upper limit for the E1 strength.

Figure 2 gives the deduced $B(E1)^\uparrow$ strength distribution for the three investigated N=82 isotones. A very similar pattern is observed in these nuclei: One isolated E1 excitation at 4026, 3644, and 3226 keV in $^{138}$Ba, $^{140}$Ce and $^{144}$Sm, respectively, followed by a resonance like structure of E1 strength between 5.5 and 8 MeV. Please note that no strength is observed above approx. 8 MeV. This shows that the observed states are not just statistical E1 excitations sitting on the tail of the GDR but represent a fundamental nuclear structure effect. A similar concentration of E1 strength has been observed in $^{116}$Sn and $^{124}$Sn at slightly higher energies \cite{13}. In the doubly magic nuclei $^{48}$Ca \cite{23} and $^{208}$Pb \cite{24} the E1 strength is much less fragmented. However, again a concentration of strength is found around $\hbar \omega$ in both nuclei. Folding the B(E1) strength distribution with a Lorentzian with a width of $\Gamma=250$ keV shows, that there may be certain substructures in the resonance region. Bumps appear at energies of 5.5, 6.7, and 7.8 MeV in $^{138}$Ba and at slightly lower values in the other two nuclides \cite{25}.

Elastic photon scattering using tagged photons between 4.5 and 9 MeV with an energy resolution between about 40 keV and 100 keV have been performed by Laszewski on Ba and Ce targets with natural isotopic composition \cite{9}. Whereas our integrated cross sections for $^{138}$Ba are in agreement with Laszewski’s measurement, the results for $^{140}$Ce differ considerably in the energy region above 6.5 MeV \cite{25}.

The E1 strength for the lowest lying excitation (the two phonon mode) and the summed strength for the remaining states (belonging to the resonance mode) up to the endpoint energy $E_{\text{max}}$ are listed in Table II. One can see that the B(E1) value for the two phonon $2^+ \otimes 3^-$ state is nearly identical for the three nuclei. We note that these strengths agree well with the values measured in the pioneering works by Metzger \cite{26} and Swann \cite{27}. Recently it has been shown that the dynamic dipole moments determined experimentally for one class
of nuclei (either semi-magic, non-magic or strongly deformed) scale with the dipole moment calculated from the dynamic quadrupole and octupole deformations $\beta_2$ and $\beta_3$ [28,29]. The systematics of these $B(E1)$ strengths have been discussed in ref. [30].

The remaining $E1$ strength up to the endpoint energy of the bremsstrahlung varies much more. In $^{138}$Ba the weighted mean energy is 6.5 MeV and 0.78(15)\% of the EWSR is exhausted. The weighted mean energy in $^{140}$Ce and $^{144}$Sm is 6.4 MeV and 6.0 MeV, respectively. The strengths exhaust 0.33(5)\% and 0.24(4)\% of the EWSR in these two nuclides.

Figure 3 gives the summed $B(E1)$ strengths above the two phonon excitation up to the neutron threshold for the three investigated $N$=82 nuclei. From the available data points it is impossible to decide if there is a systematic decrease of the summed strength with proton number and/or a minimum around $Z$=60 as expected from some models (see below). Therefore photon scattering experiments on the two remaining stable $N$=82 nuclei $^{136}$Xe and $^{142}$Nd in the same energy range are mandatory. Nuclei away from the valley of stability could be investigated in Coulomb scattering in inverse kinematics at radioactive beam facilities.

What could be the origin of the observed $E1$ strength? One possible explanation would be a breaking of the symmetry of the proton and neutron distributions in the nucleus due to the formation of a neutron or proton skin. Such a skin may oscillate versus the core leading to an isovector $E1$ mode [31–34]. It would be the analogon to the so called Soft Dipole Mode (SDM) in exotic light nuclei with extreme neutron excess where one or two neutrons form a halo at great distance to the core. This SDM has been observed at energies of a few hundred keV with $B(E1)$ values in the order of one Weisskopf unit [35,36]. In some stable nuclei an enrichment of neutrons or protons in the periphery is predicted and observed as well: Elastic proton scattering experiments have shown that the rms radius of the neutrons is slightly larger than that of the protons in many neutron rich stable nuclei [37]. In addition recent antiproton absorption experiments at the LEAR facility at CERN have shown, that nuclei with neutron separation energies of less than about 10 MeV (i.e. nuclei on the more neutron rich side of the valley of stability) possess a neutron rich nuclear periphery [38]. On the other hand, for certain stable nuclei with a closed neutron shell like e.g. $^{144}$Sm a proton rich nuclear periphery has been observed [38]. Calculations in a self consistent HFB theory have yielded a similar result for $N$=82 nuclei: A neutron skin for the neutron rich nuclei and a proton skin for the nuclei on the more proton rich side [39]. Such a skin excitation mode is predicted at energies between 6 and 10 MeV and with a $B(E1)$ strength in the order of one percent of the EWSR, strongly depending on the $N/Z$ ratio [31,32]. The studies mentioned above would predict a minimum of the $E1$ strength resulting from skin excitations for $^{142}$Nd and a very high value for $^{136}$Xe. Measurements on the isotopes $^{142}$Nd and $^{136}$Xe planned for the near future will therefore allow a more concise statement about the origin of the $E1$ strength.

The so called Toroidal Dipole Resonances (TDR) have been predicted as a completely different $E1$ excitation mode in the same energy region. Here a vortex collective motion of the nucleons inside the nucleus leads to isoscalar transversal $E1$ excitations [40]. Recent calculations in the relativistic random phase approximation predict such a mode to occur in stable nuclei around 10 MeV [41,42]. A similar mode has been predicted by Colò et al. [43] at slightly higher energies and has been observed in $\alpha$ scattering experiments by Clark et al. [44]. If the resonance between 5.5 and 8 MeV observed in our experiments is really an
isoscalar mode it should be strongly populated in α–scattering experiments under extreme forward angles which can be performed e.g. at KVI in Groningen and RCNP in Osaka. The transversal character of the mode could be checked with electron scattering experiments with small momentum transfer at the S–DALINAC.

Another possibility of generating E1 strength in the energy region below the GDR is a local breaking of the isospin symmetry due to a clustering mechanism. Here it is assumed that in certain heavy nuclei a cluster with a different neutron to proton ratio than the remaining nucleus may form. An oscillation of this cluster would lead to a relatively narrow isovector resonance mode which should be concentrated around 6 MeV in heavy nuclei [45,46].

In conclusion we have performed for the first time a high resolution study of the electric dipole strength distribution in $^{138}$Ba, $^{140}$Ce, and $^{144}$Sm up to the neutron threshold. A resonance like concentration of strength has been observed in all three nuclei between 5.5 and 8 MeV. Besides a study of the two remaining stable N=82 nuclei in ($\gamma$, $\gamma'$) studies, complementary experiments with hadronic probes and electrons are necessary to understand the structure of the excitations. Measurements with monoenergetic polarized photons from laser back scattering could help to clarify the parities and detailed decay patterns of the states [22].

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| Target      | Enrichment (%) | Target mass (mg) | $S_n$ (MeV) | $E_{max}$ (MeV) | $t_{meas}$ (h) |
|-------------|----------------|------------------|-------------|----------------|----------------|
| $^{138}\text{Ba}_2\text{CO}_3$ | 99.5           | 3011             | 8.6         | 9.2            | 40             |
| $^{140}\text{CeO}_2$         | 88.5           | 3160             | 9.2         | 9.9            | 40             |
| $^{144}\text{Sm}_2\text{O}_3$ | 96.5           | 726              | 10.5        | 9.9            | 80             |
|             |                |                  |             | 7.6            | 40             |

**TABLE I.** Properties of the examined targets and parameters of the photon scattering experiments: Target, isotopic enrichments, target mass, neutron separation energy $S_n$, maximum bremsstrahlung energy $E_{max}$, and measuring time $t_{meas}$.

| Nucleus | $E_{twph}$ (MeV) | $B$(E1)$↑_{twph}$ ($10^{-3}e^2fm^2$) | $E_{res}$ (MeV) | $\sum B$(E1)$↑_{res}$ ($10^{-3}e^2fm^2$) | EWSR (%) |
|---------|------------------|------------------------------------|-----------------|---------------------------------|----------|
| $^{138}\text{Ba}$ | 4.026            | 17(3)                               | 6.5(13)         | 579(111)                        | 0.78(15) |
| $^{140}\text{Ce}$ | 3.644            | 19(2)                               | 6.4(10)         | 247(40)                         | 0.33(5)  |
| $^{144}\text{Sm}$ | 3.226            | 19(3)                               | 6.0(11)         | 201(36)                         | 0.24(4)  |

**TABLE II.** Energies $E_{twph}$ and strengths $B$(E1)$↑_{twph}$ of the two phonon $2^+ \otimes 3^-$ states, mean energies $E_{res}$ and summed E1 strengths $\sum B$(E1)$↑_{res}$ of $1^-$ states above the two phonon states up to the neutron threshold, and exhaustions of the isovector energy weighted sum rule.
FIG. 1. Photon scattering spectrum of $^{138}$Ba measured with an bremsstrahlung endpoint energy of 9.2 MeV. Almost all lines stem from the decay of states populated in $^{138}$Ba. Lines stemming from the decay of the $^{11}$B calibration target are labelled.

FIG. 2. Electric dipole $B(E1)↑$ strength distributions below 10 MeV in the three investigated isotopes $^{138}$Ba, $^{140}$Ce, and $^{144}$Sm.
FIG. 3. Measured summed B(E1)↑ strengths above the two phonon state up to the neutron separation threshold.