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Reactions induced by real photons for nuclear structure and nuclear astrophysics☆

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Abstract

This contribution presents examples for recent experimental studies with real photons. Topics include the electric dipole response below the particle separation energy (pygmy resonance), the magnetic scissors mode in deformed nuclei, an analysis of low-lying electric quadrupole strength and astrophysical applications. Results of reactions induced by real photons are compared to those obtained from virtual photons (electron scattering, Coulomb excitation).

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1. Introduction

Photon-induced reactions have been used to study atomic nuclei since more than seven decades. A first theoretical analysis of resonance effects by Bethe and Placzek [1] already indicated two important reactions types, photodisintegration of nuclei and photon scattering. Bethe and Placzek stated that cross section σ for a particular reaction channel f depends on the photon energy - as expressed by the reduced wavelength $\lambda/2\pi$ - statistical terms that depend on the spin of the excited state J and of the ground state J_0, a Breit-Wigner resonance shape around the resonance energy E_x and resonance widths. In a notation slightly more convenient than the one used by Bethe and Placzek, one needs the partial decay width Γ_0 for a radiative transition into the ground state, the total width Γ (including radiative width and possible particle widths) and the partial width for decay into the observed channel f. The relation

$$\sigma_f(E) = \frac{\pi}{2}\frac{\lambda^2}{4\pi^2}\frac{2J+1}{2J_0+1}\frac{\Gamma_0\Gamma_f}{(E-E_x)^2+\Gamma^2/4} \tag{1}$$

demonstrates that only those resonances are excited by photons that have a significant partial branch into the ground state. In many nuclear resonance fluorescence (NRF, resonant photon scattering, see, *e.g.*, [2]) experiments one therefore even assumes that all other decay branches are weak and that $\Gamma_0 \approx \Gamma$ as the only observed decay of the excited level is the decay back to the ground state ($f = 0$).

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In the same year as Ref. [1], Bothe and Gentner carried out experiments with photons produced in a proton-capture reaction [3]. The gamma ray with energies of about 17 MeV was used to irradiate various materials. Following photodisintegration reactions in the targets, radiochemical analyses allowed them to deduce the lifetimes of the unstable nuclides. For the case of copper, where the photodisintegration rate was highest, they were capable of estimating a cross section of about 50 mb for the process. Today we know that the resonance maximum of the giant dipole resonance in copper is close to 17 MeV and has a peak cross section of about 67 mb (cf., *e.g.*, Ref. [4]).

The characteristic resonance shape of the giant dipole resonance, however, was first identified in 1947 by Baldwin and Klaiber [5]. They identified the resonance shape in a photo-fission experiment from actinide nuclei following a subtraction and unfolding procedure which they applied to the yield curve they had obtained from a series of measurements with bremsstrahlung.

The electric giant dipole resonance is prototypical for an entire class of excitation modes in nuclei. Within a macroscopic, geometrical description, we assume that giant resonances are excitation modes of the nucleus where many nucleons contribute to shape oscillations. Microscopically giant resonances are formed by the coherent superposition of one-particle-one-hole configurations across at least one major shell. Prominent examples are the isoscalar giant quadrupole resonance (cf. [6, 7]) and the isoscalar giant monopole resonance (breathing mode, see [8, 9]). One has to distinguish isoscalar excitations, where protons and neutrons move in phase, and isovector excitations (such as the isovector giant dipole resonance) with the the protons and neutrons oscillating out of phase.

In open-shell nuclei, valence nucleons produce excitation modes that may be visualized as surface vibrations. A textbook example is given by the low-lying quadrupole excitation [10] that constitutes a fundamental vibrational mode. With collective and single-particle degrees of freedom, a plethora of excitations are generated through coupling.

The interaction mechanism in photo-induced reactions are well understood. This allows one to extract nuclear structure information from the experimental observable, *e.g.*, a cross section. Beyond processes with real photons, the electromagnetic interaction dominates also electron scattering and - at low energies or large impact parameters - ion scattering. Electron scattering data [11] as well as Coulomb excitation [12] are therefore well suited to complement the information available with real photons. Real photons probe excitations of low multipolarity, hence I will discuss – after some brief remarks on recent technical and methodological improvements – few selected current examples of results on electric dipole (E1), magnetic dipole (M1), and electric quadrupole (E2) excitations.

2. Experimental matters

2.1. Photon sources

There are various sources of photons. Besides gamma rays from capture reactions, numerous other techniques have been employed. In the early years of photonuclear reactions, radioactive sources - in particular on centrifuges - were used [13, 14]. When working with sources, intensity is clearly an issue. In addition, the energy range of sources is limited, and the gamma-ray spectrum is so narrow that there are rather few other nuclei that feature a level whose energy coincides with the transition energy of the source. Broadening the spectrum through Compton scattering usually creates difficult spectral distributions and enhances the problems concerning intensity.

Bremsstrahlung provides a continuous spectrum that allows one to excite all suitable levels in the target nucleus in one experiment. This gives rise to experimental challenges, *e.g.*, how to disentangle transitions into the ground state and those to lower-lying excited states and possible feeding of lower-lying levels. While earlier bremsstrahlung sources suffered from low count rates due to the pulsed operation of the driver linacs, high repetition rates are available from either electrostatic accelerators (*e.g.*, [15]) or superconducting linacs (*e.g.*, the setup at the Darmstadt superconducting electron accelerator S–DALINAC [16] or the one at the Dresden-Rossendorf ELBE facility [17]). Off-axis bremsstrahlung has been used for producing partial linear polarization of the bremsstrahlung [18].

Tagged bremsstrahlung overcomes part of these problems by measuring the energy of the slowed-down electron in coincidence with the reaction channel so that the excitation energy is measured independently from the decay branch. Due to the limited count rates of the electron detectors, however, the maximum photon flux is reduced by several orders of magnitude as compared to the untagged bremsstrahlung. An example for a dedicated tagger setup for nuclear spectroscopy aiming at high resolution and high count rates is given by the photon tagger NEPTUN that was recently installed at the S-DALINAC [19].

Most of the data on photo-neutron production cross sections have been measured using positron annihilation in flight [20]. By subtracting the cross section obtained from bremsstrahlung produced by electrons from those produced by positrons, an effective excitation region is selected that is rather monochromatic. As these experiments were usually carried out at pulsed linear accelerators, data taking rates were limited by the duty cycle of the accelerators.

In recent years, laser Compton-backscattering facilities providing high gamma-ray intensities have come into operation. The flagship laboratory concerned with nuclear structure and astrophysics in this context is the Duke University free-electron laser laboratory with its high-intensity gamma-ray source HIγS [21]. Here, particularly high intensities are reached through intra-cavity backscattering of a free-electron laser. Laser Compton-backscattering provides gamma beams with a narrow spectrum and high degrees of polarization close to 100%.

2.2. Detectors

Furthermore, significant increase in efficiency was obtained during the past decades through new detector types and/or advances in detector fabrication. Germanium crystals have more than tripled in size since the mid-1980s thereby allowing gamma-rays to be efficiently detected with excellent resolution. By introducing segmentation of the detector, it is possible to either determine the polarization of the incident gamma-rays by using the detector as an active scatterer [22] or extract the first interaction point (*e.g.*, see Ref. [23, 24]). The latter is important for Coulomb excitation experiments on radioactive nuclei in inverse kinematics.

Radioactive ion beams from post-accelerated ISOL beams or in-flight facilities have become available in the past twenty years only. In addition to Coulomb-excitation experiments in inverse kinematics [25], plans exist to use stored rare ions also for electron-scattering experiments [26, 27].

Further improvements are imminent as the current progress in electronics allows entire pulse shapes to be digitized. This is utilized for a fast pre-analysis from which, *e.g.*, pile-up effects can be deconvoluted [28], and the data can be transferred with high throughput.

3. Electric dipole excitations

3.1. Pygmy electric dipole resonance

For the isovector giant dipole resonance (IVGDR) the gross features - centroid energies, widths, and strengths - have been established throughout the valley of stability [20]. The IVGDR exhausts about 100% of the energy-weighted Thomas-Reiche-Kuhn (TRK) sum rule. In addition, neutron-capture reactions identified E1 strength also below the IVGDR [29]. As the effect is much weaker than the IVGDR, the structure has been dubbed Pygmy Resonance (PR). Its structural origin was first proposed to arise from the oscillation of excess neutrons against a proton-neutron saturated core within a three-fluid model by Mohan, Danos, and Biedenharn [30]. Similarly, Iachello [31] suggested modes of isospin-zero clusters (*e.g.*, alpha particles) inside the nucleus as possible origin for additional E1 strength at low energies. If these assumptions held true, the PR would be structurally different from the IVGDR, and it would strongly emerge in nuclei with an exotic neutron-to-proton ratio.

I have summarized the status of the field in a conference report [32] several years ago to which I refer the reader for details. Here basic results are summarized only, and recent results are added. (Note the list of references is far from complete.)

- NRF experiments on semi-magic or doubly magic nuclei show a resonance-like structure with many individual states between about 5 MeV excitation energy and the particle separation threshold. This PR strength contributes usually 1% or less to the TRK sum rule.
- At even lower energies one finds single E1 excitations that are thought to arise from the coupling of the lowest quadrupole surface vibration mode with the octupole surface vibration [33]. As the structure of these states is very peculiar, they are left out of the considerations for the PR.
- Mass regions where the PR was studied include the $Z = 20$ shell closure [34–36], the $N = 50$ shell closure [37–40], the tin isotopes ($Z = 50$, [41, 42]), the $N = 82$ isotones [43–46], and the Pb region ($Z = 82$, [47–51]).
- In nearly all cases, the vast majority of the dipole excitations has electric multipole character [52].
- Different microscopic nuclear structure models are capable of explaining - at least on a qualitative level - gross features and fragmentation of the PR. The calculations suggest that these E1 excitations can indeed be explained by an out-of-phase oscillation of excess neutrons against a proton-neutron core [49, 50].

- A statistical analysis of the fine structure (for the example of the $N = 82$ isotones) shows level repulsion at short distances that are a signature of large mixing matrix elements [53].

- Coulomb excitation or Coulomb dissociation experiments on radioactive isotopes provide insight into nuclides with particularly large N/Z ratios. One finds evidence for particularly strong E1 excitations at low energies. Examples include ^{6}He [54], oxygen isotopes [55, 56], ^{68}Ni [57], and the ^{132}Sn region [58]. The Coulomb dissociation experiments probe the nucleus above the neutron separation threshold and therefore yield higher average excitation energies and higher TRK sum-rule depletions for the PR in comparison to Coulomb excitation and NRF.

- There is an ongoing discussion about the comparison of the PR if excited by photons from the ground state with the gamma-ray strength function from light-ion scattering ("Oslo method", see, *e.g.* [59–61] and Refs. therein).

- In recent years, the group at the Helmholtz research centre Dresden-Rossendorf has proposed an analysis to correct NRF spectra at high excitation energies for unresolved states [62, 63]. It is based on a simulation of the background shape, correction of the detector response, and a statistical model to correct for both feeding of lower-lying states and unobserved decay branches. The correction factors obtained within this method are substantial and indicate that the PR region is smoothly linked to the IVGDR region. At the same time, the Dresden-Rossendorf group suggested a new parameterization of the IVGDR [64] to include possible triaxial shapes of the nucleus. Following this ansatz, they find that most of the E1 strength below the neutron separation energy is likely due to the tail of the IVGDR, however, a small fraction of the E1 strength in the PR usually is unaccounted for by the extrapolation.

- Other recent studies have investigated the PR by inelastic alpha scattering in coincidence with gamma-ray detection. Due to the isoscalar nature of the alpha particle, the experiments probe isoscalar excitations in contrast to the photons from which both isoscalar and isovector modes can be excited. In these experiments one finds that at lower energies significant isoscalar E1 strength is found, whereas there is no or very little signal above approx. 6.7 MeV [65]. Microscopic models suggest the trend that the low-lying fraction of the PR region is mainly due to an "isoscalar" motion (*e.g.*, excess neutrons vs. $N \approx Z$ core), whereas the higher-lying part reflects the transition to the tail of the IVGDR [66].

- Intermediate-energy forward-angle proton scattering was suggested as a tool to extract the full E1 strength [67].

3.2. Photodisintegration: an astrophysical example

Knowing the details of the E1 strength distribution around the particle separation energy is an important input for nuclear astrophysics. In a seminal analysis, Goriely has studied for the example of the r process of nucleosynthesis how strongly predicted abundance patterns may vary if one introduces PR strength close to the particle threshold [68]. This holds basically for all nucleosynthesis processes that take place in particularly hot environments as photodisintegration is directly competing with capture reactions.

Bremsstrahlung experiments at the S-DALINAC have been used to study reaction rates in a p- (or γ-) process environment. Due to the exponential decrease of the Planck spectrum with energy, only an energy interval of about 1 MeV above the particle separation energy is of relevance for the astrophysical rate. This can be sampled by a series of measurements with different endpoint energies. An appropriate weighting of the bremsstrahlung spectra allows one to extract the astrophysical rate more or less directly from the measured data [69, 70].

However, one caveat is in order: The experiments of Refs. [69, 70] determine the disintegration rates for nuclei in their ground states only. In hot environments above 1 GK in temperature, nuclear levels other than the ground state are populated, according to the Boltzmann distribution. Hence photo-activation serves first and foremost to benchmark statistical model calculations used as input for astrophysical network calculations [71].

4. Magnetic dipole excitations

M1 modes in nuclei arise due to orbital motion or spin-flip transitions. A recent review by Heyde, von Neumann-Cosel, and Richter [72] has collected all important details on this issue with particular emphasis on the low-lying collective orbital M1 scissors mode that occurs most prominently in heavy deformed nuclei.

4.1. Orbital M1 strength: the scissors mode

The scissors mode was first discovered in electron scattering in the heavy deformed nucleus ^{156}Gd [73], following predictions within a semi-classical two-rotor model [74] and the interacting-boson approximation [75]. From the form factor [73], an orbital motion was suggested, and proton-scattering experiments revealed little influence of the spin on the total strength [76]. Subsequent systematic NRF experiments [77] in many nuclei throughout the $N = 82 - 126$ major shell produced an impressive data set [78] whose results may be summarized as follows:

- The scissors mode occurs in this mass region in an energy window of approximately 2.5 - 4 MeV. The average excitation energy of about 3 MeV is independent from the deformation and varies slowly with mass.
- The summed M1 strength strongly depends on the deformation parameter δ. Like the rotational first 2^+ state in deformed nuclei, its strength is proportional to δ^2, cf. Ref. [79], and it saturates at mid-shell at about 3 μ_N^2.
- A phenomenological sum-rule analysis leads to a good description of the experimental data with no free parameters, but using experimental data on, *e.g.*, g factors and deformation parameters as an input [80, 81].
- Outside the above mentioned mass region deviations are observed. However, in these cases the identification of scissors-mode fragments is not as unambiguous as in the case of the $N = 82$ - 126 major shell [81].
- An analysis of the level-spacing distribution supports the assumption that the mode's underlying structure is collective and that the level density in the even-even nuclei is not too high [82].
- In odd-mass nuclei, fragmentation is much higher due to the very high level density. Part of the total strength therefore remains unresolved in the experimental background of an NRF spectrum. The full strength information may be restored using a statistical fluctuation analysis of the spectra [83–85].

4.2. An example for spin-M1 strength: photo-disintegration of the deuteron

The deuterons structure features important information on the nucleon-nucleon force. We know very well about the ground state of the deuteron, which is an isospin-singlet, spin-triplet state. The spin-singlet isospin-triplet states include the ground-state configurations of the di-neutron and the di-neutron that are unbound. Hence - due to the charge-independence of the nuclear force - also the isospin-triplet member in the deuteron is unbound, and it is excited from the deuterons ground state by a spin-flip M1 transition. The inverse reaction is the neutron capture on a proton, which was the very first nuclear reaction to take place in the universe after the big bang. The formation of the deuteron represented the first step in the so-called big-bang (or primordial) nucleosynthesis (BBN, [86, 87]) producing the lightest nuclides, *i. e.* d, ^{3}He, ^{4}He, and ^{7}Li. About one second through five minutes after the big bang, the universe was cool enough so that the capture reaction rate could outweigh photo-dissociation. Yet it was dense enough so that a sufficient reaction rate could be achieved.

Astronomical observations are capable of extracting the abundances of the nuclides produced in the BBN from the spectra of old stars. On the other hand, the abundances are calculated using the so-called cosmological standard model (CSM). In the latter, the abundances depend on a parameter, the baryon-to-photon ratio which is related to the density of the universe. Hence by means of the CSM, the measured BBN abundances yield values for the baryon-to-photon ratio. However, the results are inconsistent. While the ^{4}He mass fraction and the ^{7}Li abundance agree with each other, the D abundance is significantly different, although it appears to agree with the observations of the WMAP satellite on the cosmic microwave background [88].

Among the largest uncertainties to the nuclear-physics input for the CSM predictions is the capture rate in the p + n $\rightarrow$ d + γ reaction [89]. As again the direct modelling of the conditions in the early universe is difficult, it is more instructive to benchmark the theoretical models that are used for the calculations. To this end, one must carefully disentangle the M1 spin strength close to the threshold from E1 contributions at higher energies. Hence, experiments were carried out at the HIγS facility at Duke University with monochromatic polarized photons [90] and at the S-DALINAC using electron scattering [91] at 180°. At 180°, the longitudinal contributions in the electron scattering cross section are suppressed, and M1 dominates the cross section for low momentum transfers. The results show that the potential models currently employed for BBN abundance predictions within the CSM describe the data very well. Hence, the observed inconsistencies must originate from other sources than this nuclear-physics input.

5. Electric quadrupole excitations

5.1. Mixed-symmetry states

In addition to a quadrupole surface vibration originating from an in-phase motion of the protons and the neutrons, an out-of-phase surface vibration is also possible. These modes represent the low-energy counterparts of the isoscalar giant quadrupole resonance (ISGQR) and the isovector giant quadrupole resonance (IVGQR). The low-energy electric quadrupole (E2) excitation with proton-neutron mixed symmetry has been proposed within the interacting boson approximation [92], and first experimental evidence [93] was reported by Hamilton, Irbäck, and Elliott in 1984. Research on mixed-symmetry states intensified when it became possible to reproduce these structures also in microscopic models such as the Quasiparticle Phonon Nuclear Model [94] and when first investigations started searching for multi-phonon configurations involving the mixed-symmetry quadrupole mode [95]. As the mixed-symmetry 2^+ state in vibrational or gamma-soft nuclei is characterized by a strong M1 transition to the fully symmetric 2^+ level and a weakly collective E2 excitation, it still can be populated in NRF [96] and also from Coulomb excitation [97]. The 1^+ member of the expected quintuplet of states arising from the coupling of the fully symmetric quadrupole phonon and the mixed-symmetry phonon can also well be characterized from NRF; it is the analog of the scissors mode in a vibrational nucleus. In order to gain more insight into the decay pattern, NRF is often combined with other spectroscopic techniques [98].

A fairly recent overview is given by Refs. [33, 99]. Among the achievements in the past years are the experimental investigation of the mixed-symmetry state through electron and hadron scattering [100] as well as establishing a link between the low-energy mixed-symmetry mode and the quadrupole giant resonances [101].

5.2. Low-lying E2 strength in magic nuclei: How strong is the giant quadrupole resonance?

Even-mass nuclei usually feature a strong E2 excitation at low energy [10]. It arises either from vibrational or rotational motion in collective nuclei or from very distinct particle-hole excitations near shell closures. A large amount of data exists [102] that shows the influence of shell structure, but at the shell closures one cannot conclude on how “magic” a nucleus is, neither from the E2 strength nor from the depletion of the energy-weighted sum rule (EWSR) for isoscalar E2 excitations

$$m_1(\mathrm{E2}) = \sum E_{\mathrm{x},i} B(\mathrm{E2})_i = 30\frac{Z^2}{A^2}\frac{(\hbar c)^2}{8\pi m_p c^2} A e^2 R_0^2 = 71,3\frac{Z^2}{A^{1/3}} e^2 \mathrm{fm}^4\,\mathrm{MeV} \qquad (2)$$

with proton mass m_p, and nuclear radius parameter R_0. At high energies, one expects the isoscalar giant quadrupole resonance. Intuitively, one has the notion that a giant resonance should be strong and exhaust a large fraction of the sum rule, if not of the total (non-energy-weighted) strength, just as in the case of the IVGDR.

An NRF experiment on ^{40,48}Ca [34, 103] revealed also significant E2 strength below the particle separation energy, *i. e.*, about 8 MeV below the expected maximum of the ISGQR. In fact, 25 - 40% of the EWSR are exhausted at these low energies. This means that the share of the low-energy strength on the total non-energy-weighted E2 strength is even larger. In the neighboring semi-magic ^{52}Cr no significant E2 strength above the 2^+_1 was uncovered [104]. From the systematics of the ISGQR one finds, in fact, a strong variation of the EWSR depletion factors, ranging from about 40% to 130%, see Ref. [105].

The analysis of Ref. [104] took data for the 2^+_1 from literature [102] and compiled data from various NRF experiments and electromagnetic excitations on magic nuclei. If one includes E2 strength beyond the excitation of the first level from the ground state, one finds that in all doubly magic nuclei the exhaustion of the EWSR below the particle threshold is particularly large.

From the measured depletion of the EWSR below the particle threshold and the assumption that the EWSR m_1 is fully depleted if the E2 strength is summed from zero to infinity, one can extract the fraction of the non-energy-weighted total E2 strength that is exhausted below the particle threshold if one takes for the probable energy of the residual E2 strength the centroid of the ISGQR, $E_{\mathrm{x,ISGQR}}$. To this end, we introduce a non-energy-weighted “sum rule” (NEWSR) from the experimental data

$$m_0 = \sum B(\mathrm{E2})_i + \frac{m_1 - \sum E_{\mathrm{x},i} B(\mathrm{E2})_i}{E_{\mathrm{x,ISGQR}}}\,. \qquad (3)$$

The finding is [104] that in all (semi-)magic nuclei included in the analysis the NEWSR depletion at energies below the particle threshold amounts to about 50% of the total strength, decreasing slightly towards heavier masses.

6. Summary and outlook

The present contribution listed a number of recent examples in the investigation of E1, M1, and E2 excitations with electromagnetic probes, in particular with real photons. The advances in accelerator and detector technology have enhanced the sensitivity limits significantly during the past decades so that many high-quality data sets have been acquired. Studying fundamental modes of low multipolarity experimentally allows important benchmark tests for nuclear structure models and has impact on astrophysical processes.

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