Progress on $M1$ Research

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Abstract. Magnetic dipole transitions in nuclei can offer crucial information on nuclear structure, *e.g.*, on spin-flip processes or on nuclear charge currents. Driven by the need for more comprehensive or more precise data on $M1$ transitions in nuclei, we have recently tried to advance pre-existing experimental methods to meet the present needs. This contribution reports on the current status of our efforts on three aspects: (i) access of spin-flip $M1$ strength in radioactive nuclei, (ii) quadrupole-collectivity of the $M1$ scissors mode, and (iii) highest-precision measurements for strong ground-state $M1$ excitations.

1. Introduction

Magnetic dipole ($M1$) radiation provides crucial information on nuclear physics and insight into nuclear structure phenomena. An important example is the $M1$ excitation of the nucleon itself to its $J^\pi = 3/2^+$ Δ-resonance. It represents an isovector transition from the $T = 1/2$ isospin doublet of the nucleon to the Δ-resonance with isospin $T = 3/2$. Its matrix element amounts to about 3 nuclear magnetons ($\mu_N = e\hbar/2m_N c$). This transition corresponds to a quark spin-flip excitation in the schematic static quark model.

Also the simplest nucleus, the deuteron, features an isovector $M1$ excitation from its $J^\pi_T = 1^+_0$ ground state to its first excited $J^\pi_T = 0^+_1$ resonance. In a simplistic way, this transition can also be considered as a quark spin-flip transition, now flipping the spin of one nucleon versus that of the other. Consequently its $M1$ strength is comparable to that of the nucleon. This isovector $M1$ strength manifests itself most notably in the isovector $M1$ transition between the quasi-deuteron [1] partner states of ^{6}Li, its $J^\pi_T = 1^+_0$ ground state and its $J^\pi_T = 0^+_1$ state at 3.56 MeV excitation energy, which again has an $M1$ transition matrix element of about 4 μ_N in size.

Besides spin-flip dynamics between spin-orbit partner orbitals, $M1$ transitions are sensitive to changes in charge currents inside the nucleus, too. The electromagnetic charge distinguishes protons from neutrons in the nuclear environment. Hence, the investigation of $M1$ transitions between nuclear states [2] can provide us with information on the proton/neutron structure of nuclear states and on the local spin-orbit splitting of effective single-particle orbitals. Together these effects yield access to the dominant degrees of freedom in the formation of nuclear structures in the nuclear valence shell. The paramount importance of the evolution of effective single-particle energies as a function of nucleon numbers on the emerging nuclear structure has become apparent through the advent of spectroscopic information on exotic nuclei over the last two decades. The tensor force between nucleons [3] and effective three-body forces [4] have been shown to be essential ingredients for a global understanding of nuclear structure across the nuclear chart.

In this contribution we have addressed our recent progress on the investigation of nuclear structures that dominantly decay by $M1$ radiation: the new approach of relative γ-ray self-absorption for a precision measurement of the $M1$ excitation strength of ^{6}Li, the first attempt to access the electromagnetic quadrupole radiation strength of the proton/neutron mixed-symmetric orbital 1^+ scissors mode in a quadrupole-deformed nucleus, and a new approach for directly measuring the local spin-orbit splitting in neutron-rich radioactive nuclei by the two-target relativistic projectile-Coulomb excitation method. We have performed corresponding experiments at the Superconducting DArmstadt LINear electron ACcelerator (S-DALINAC) at TU Darmstadt, at the High Intensity γ-ray Source (HIγS) at Duke University, and at the FRagment Separator (FRS) at the GSI Helmholtz Center for Heavy Ion Research at Darmstadt in the scope of the PreSPEC/AGATA campaign.

2. Relativistic $M1$ Coulomb excitation experiment on ^{85}Br with PreSPEC/AGATA

Exotic nuclei with ratios of neutron to proton numbers differing considerably from what is encountered near the line of stability have been found to often feature hitherto unexpected structure, *e.g.*, strong collectivity at the conventional ”magic numbers” or aspects of closed shell nuclei even when the proton and neutron numbers do not coincide with them. These phenomena are attributed to an evolution of shell structure which itself arises from a systematic dependence of the effective single-particle energies on the nucleon numbers by weakening or strengthening the local spin-orbit splitting as a function of valence nucleons.

It is apparently desirable to experimentally measure the energy splitting of spin-orbit partner orbitals in exotic nuclei. Spin-flip transitions between spin-orbit partners correspond to $M1$ transitions with a size on the order of one Weisskopf unit, *i.e.*, $M1$ transitions that are comparatively strong. Therefore, the occurence of strong $M1$ transitions in the range of one nuclear magneton can serve as a unique signature for spin-orbit partner orbitals. The direct measurement of such large $M1$ transition rates for γ-ray energies of about one MeV or more is a difficult task, in particular, in heavy exotic nuclei. That is because such transition rates lead to half-lives below one hundred femtoseconds where techniques for direct lifetime measurements start to fail. Classical techniques for unique identication of spin-flip excitations, such as direct measurements of $M1$ radiative widths in photon scattering or electron scattering reactions, or high-resolution charge-exchange reactions, are not yet applicable to the investigation of radioactive isotopes. The measurement of $E2/M1$ mixing ratios δ from the analysis of angular distributions is significantly hindered at relativistic beam energies due to large Lorentz boost and by low statistics in experiments with radioactive ion beams. We have recently proposed that the method of relativistic $M1$ projectile-Coulomb excitation may offer a viable alternative.

The ratio of cross sections for magnetic and electric Coulomb excitation is in first order proportional to $(v/c)^2$ times the ratio of the corresponding matrix elements squared. For sufficiently large $M1$ matrix elements the magnetic contribution to the cross section can be detectable at relativistic velocities, while traditional sub-Coulomb barrier Coulomb excitation is dominated by far by electric excitations. Because of the different energy dependence for electric and magnetic multipoles in the Coulomb excitation process, the ratio of Coulomb-excitation cross-sections at different beam energies allows to extract the ratio of the excitation characters contributing to the respective excitation and, hence, the multipole mixing ratio of the transition and the total electromagnetic transition matrix elements. Exploiting these properties of the Coulomb-excitation process, the straightforward way to extract $E2$ and $M1$ matrix elements is to perform two Coulomb-excitation experiments at different beam energies and determine the ratio of measured cross-sections. This approach demands sufficient beam-time and two cross-sections measurements. In γ-ray spectroscopy experiments with detectors that have a sufficiently good

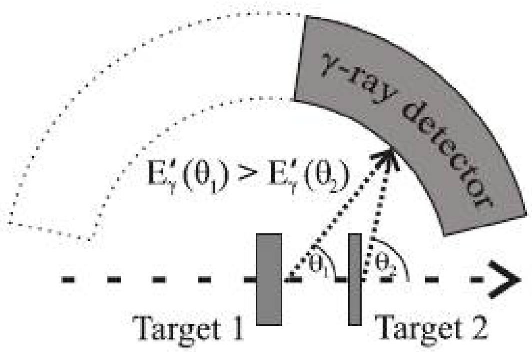

Figure 1. The relativistic ion beam impinges from the left on two targets that are spatially separated by about 10 cm. The first target is thick enough to slow down the beam such that $E2$ and $M1$ contributions to the Coulex cross sections are sufficiently different. Gamma-radiation from the two targets can be distinguished by the different Doppler-shifts due to the considerably different observation angles seen by the granular γ-ray detector array.

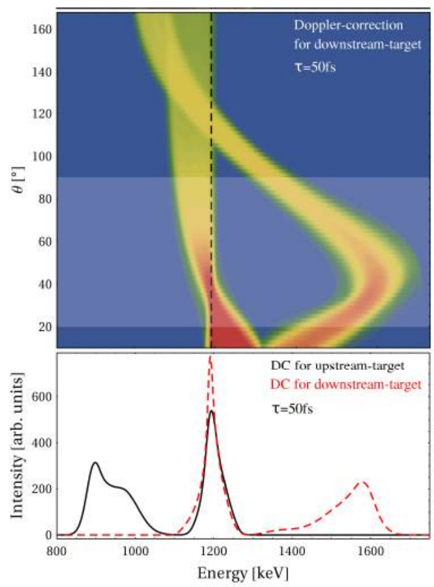

Figure 2. Simulation for the separation of γ-rays from relativistic ions that were Coulomb excited either in the first or in the second target. The ratio of the peak areas is sensitive to the $M1$ matrix element to be measured.

energy resolution, like HPGe detectors, the two cross-section measurements can be combined in one single experiment with two spatially separated targets and a sufficiently large energy-loss in the first target [5]. The principle of the two-target relativistic Coulex multipolarity is exemplified in Figs. 1 and 2.

We report here on the first experiment aiming at the measurement of a proton spin-flip $M1$ transition rate in a relativistic $M1$ projectile-Coulomb excitation reaction. It was carried out on a secondary ion beam of radioactive neutron-rich ^{85}Br$_{50}$ nuclei at the neutron shell closure $N = 50$ in the sequence of isotones from stable nuclei towards the neutron-rich doubly magic nucleus ^{78}Ni. Due to the crossing of effective proton single-particle energies of the $\pi(2p_{3/2})$ orbital

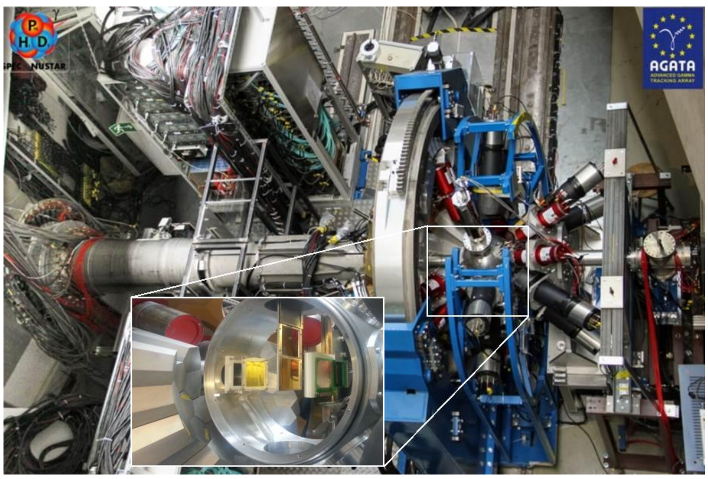

Figure 3. Photograph of the PreSPEC/AGATA set-up at the FRS at GSI. The radioactive-ion beam enters from the right. The secondary double target (inset) is surrounded by scintillators and HPGe-detectors of the Hector and AGATA arrays. The secondary reaction products are mass and charge analyzed event-by-event by the LYCCA device [10] to the left.

with the $\pi(1f_{5/2})$ orbital along the chain of heavy nickel isotopes it is interesting to study the evolution of the spin-orbit splitting between the $\pi(2p_{3/2})$ and the higher-lying $\pi(2p_{1/2})$ orbital in this region of the nuclear chart.

Relativistic beams of ^{85}Br with velocities of up to 70% of the speed of light have been abundantly provided by the FRS at GSI [6] following the primary one-proton knock-out reaction of a beam of fully stripped ^{86}Kr ions in a beryllium production target in March 2014. High-resolution in-flight γ-ray spectroscopy at relativistic energies requires precise Doppler-shift correction capabilities. Gamma-rays were measured in-beam with the highly-segmented novel PreSPEC/AGATA device [7, 8, 9]. We report on this new experimental technique, on our experiences with it, and on the status of the data analysis. Figure 3 shows a photograph of the set-up.

The two targets for secondary Coulomb excitation consisted of massive gold plates of about 1 mm thickness, each. The data analysis is currently underway. Calibrations for proper Doppler correction have not been completed, yet. Figure 4 shows a γ-ray spectrum from 5% of the data taken without Doppler correction. A γ-ray line at 547.5(3) keV corresponding to the Coulomb excitation of the ^{197}Au target nuclei is clearly visible. Its yield implies that the sought-after γ-ray line from relativistic $E2/M1$-Coulomb excitation of the $J^\pi = 1/2^-$ level of ^{85}Br at 1.191 MeV excitation energy should be detectable after Doppler corrections if that state would sufficiently purely correspond to the spin-flip excitation of the $\pi(2p_{3/2})$, $J^\pi = 3/2^-$ ground state.

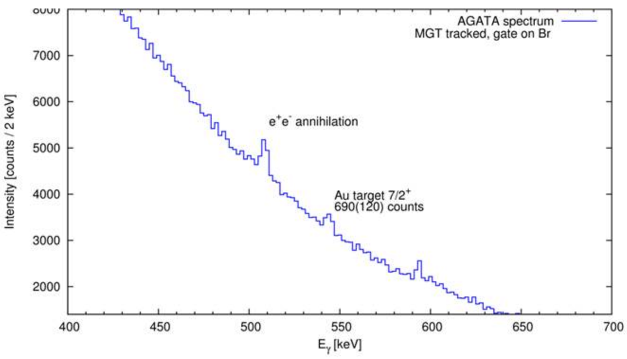

Figure 4. Gamma-ray spectrum without Doppler correction from a part of the data taken spring 2014 with the PreSPEC/AGATA array on the relativistic Coulomb excitation reaction of a beam of radioactive ^{85}Br ions on two gold targets. Coulomb excitation of gold is clearly visible and can serve for the determination of absolute $E2$ and $M1$ relativistic Coulomb-excitation cross sections for ^{85}Br. The data analysis is underway.

3. Quadrupole decay strength of the $M1$ scissors mode of ^{156}Gd

Orbital charge currents can be another source of nuclear $M1$ radiation besides spin-$M1$ modes as discussed above. The most prominent example of orbital $M1$ strength is given by the $J^\pi = 1^+$ nuclear scissors mode discovered in the deformed nucleus ^{156}Gd by Richter and collaborators at Darmstadt in the 1980s [11]. The orbital $M1$ excitation strength is proportional to the square of the quadrupole deformation of the ground state. While the $M1$ strength of the scissors mode has been studied in detail over the last 30 years, the electric quadrupole matrix element between the rotational band of the scissors mode and the ground band is still unknown. It can be obtained from the measurement of the $E2/M1$ multipole mixing ratio of the $1^+_{\text{sc}} \to 2^+_1$ transition. We have measured this multipole mixing ratio for the first time in a deformed nucleus.

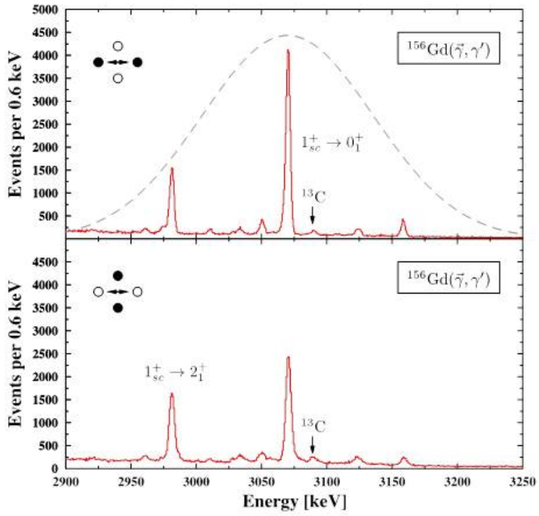

Figure 5. Gamma-ray spectroscopy of the scissors mode of ^{156}Gd excited by the quasi-monoenergetic linearly-polarized photon beam of the HIγS facility at Duke University, Durham, NC. The beam's energy-profile is indicated by the dashed curve. The $1^+_{\mathrm{sc}} \to 0^+_1$ $M1$ transition to the ground state at 3070 keV and the $E2/M1$ mixed transition to the 2^+_1 state of the ground state rotational band are dominantly observed. The relative azimuthal distribution about the (horizontal) polarization plane of the incident γ-ray beam is sensitive to the $E2$ contribution of the $1^+_{\mathrm{sc}} \to 2^+_1$ transition.

The experiment has been performed on the nuclide ^{156}Gd using the quasi-monoenergetic linearly-polarized photon beam of the High-Intensity γ-ray Source (HIγS) at Duke University, Durham, NC [12]. Figure 5 shows a relevant part of the data. The $E2$ matrix element between the scissors mode and the ground state band of ^{156}Gd is appreciably smaller than 1 W.u. The data and results are currently being prepared for publication.

4. Relative self-absorption experiment on the quasi-deuteron $M1$ excitation of ^{6}Li

The first excited 0^+ state of ^{6}Li with isospin $T = 1$ is the first nuclear state in the chart of nuclides that predominantly decays electromagnetically. Its $M1$ decay width provides a sensitive test for

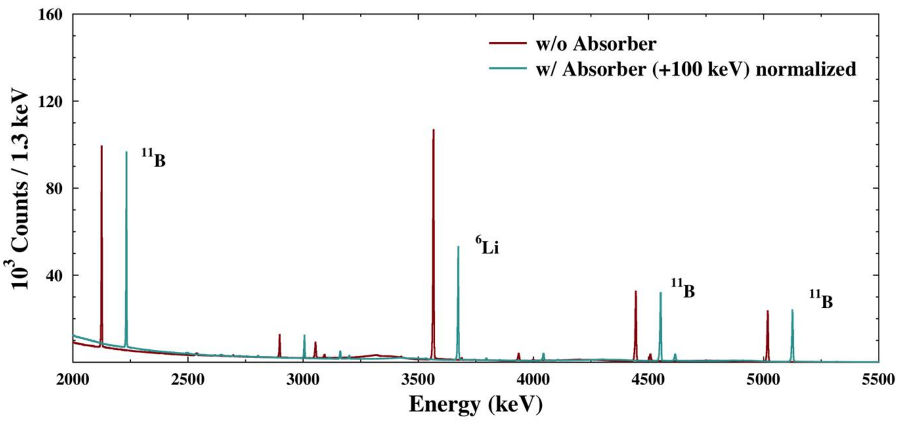

Figure 6. Nuclear resonance fluorescence off ^{6}Li in a nuclear self-absorption experiment at the Darmstadt bremsstrahlung site at the S-DALINAC. The 3563-keV γ-ray line from the $J^\pi_T = 0^+_1 \to 1^+_0$ isovector $M1$ decay transition in ^{6}Li is very pronounced. The lithium target was surrounded by ^{11}B for normalization purposes. The figure shows two γ-ray spectra from one and the same target, one of them taken with a bremsstrahlung beam modified by an upstream lithium absorber (and shifted by +100 keV for better visibility). The absorption of 3563-keV photons by the absorber is proportional to the natural line-width of this state and leads to a precisely measurable reduction of NRF intensity relative to a normalization standard.

modern nuclear theory. It has recently been shown that chiral currents can contribute up to 10% to $B(M1)$ values [13]. A precision measurement of the $M1$ decay strength in ^{6}Li to better then 1% accuracy is desirable. We have recently demonstrated that this goal can be achieved in nuclear self-absorption [14] experiments. Figure 6 shows the γ-ray spectra that were obtained. The self absorption of the $M1$ excitation of ^{6}Li has been determined to sub-% level.

5. Summary

In our contribution we have discussed our recent progress on the experimental investigation of magnetic dipole phenomena in nuclei. While our data are currently under analysis it is obvious that new instruments or the advances of traditional experimental techniques have the potential for new approaches to and deeper insight into nuclear $M1$ phenomena.

Acknowledgments

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