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Shape mixing in $0\nu\beta\beta$ candidates

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Abstract. Weak processes are typically observed through nuclear effects, as they mediate between different eigenstates of either one nucleus, or a pair of nuclei. Since the derivation of important parameters of the weak interaction and weakly-interacting particles, such as their masses, spin dependencies, and alike, heavily relies on nuclear theory, it must be assured that theory properly describes the relevant wave functions. A special challenge for neutrinoless double-beta decay, for example, is the location of many candidate isotopes in regions of the nuclear chart, where nuclei may exist simultaneously in different shapes, hence, different wave function components belonging to different nuclear deformations mixing into the nuclear eigenstates. In addition, isovector parameters of nuclear models are not often well constrained, posing an additional challenge. Through the measurement of properties of the nuclear scissors mode, a magnetic isovector excitation at low energies, using photon-scattering techniques, we obtain data that is relevant to constrain the structure of the nuclei and their eigenstates in question. Furthermore, our recent research program comprises the investigation of isotopes relevant for the detection of hypothetical massive weakly-interacting particles.

1. Introduction

The broad topics of weak-interaction physics and nuclear physics strongly overlap, although not always obvious. Nuclei play a major role either as laboratories for the investigation of weak-interaction processes, or as witnesses for weakly interacting particles in sophisticated detectors. Although nuclei are bound and governed by the strong interaction, they also interact weakly, best known through the occurrence of β decay. Topics addressed include the determination of the fundamental nature of neutrinos and their masses through the search for neutrino-less double-beta ($0\nu\beta\beta$) decay. Another popular aspect is the search for new weakly-interacting particles, such as the hypothesized WIMPs, connecting nuclear and weak-interaction physics to dark matter searches. In order to be suited for such studies, though, the physics of the involved nuclei needs to be sufficiently well understood, which includes their electromagnetic response and overall structure, governed by the strong force, the classical nuclear physics. Often, information on the nuclear physics input into weak processes cannot be obtained experimentally, directly, but relies on nuclear theory. Therefore, it is of utmost importance that theory is constrained

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by experiment. That means especially to constrain the wave functions of relevant eigenstates of the nucleus as much as possible, through the measurement of level and decay energies and the electromagnetic matrix elements among them, which carry fingerprints of their structure. In the following, especially the relation to nuclear matrix elements for the description of $2\nu\beta\beta$ and $0\nu\beta\beta$ decay, for which we obtained new experimental data, will be discussed. In the end, other implications of nuclear structure for weak processes, i.e., the scattering of weakly interacting particles off nuclei, will briefly be addressed.

2. Nuclear structure for $0\nu\beta\beta$ decay

Various experiments are underway or planned for, to search for the $\beta\beta$-decay process without the emission of neutrinos. The observation of such decay would, firstly, determine the fundamental nature of the neutrino as a Dirac- or Majorana-like particle, and if the latter, would open a possibility to determine its mass. Typically, in experiments such as GERDA [1] and MAJORANA [2] (Ge based), CUORE [3] (Te based), CUPID [4] (Te/Se based), or EXO [5] (Xe based), the decaying material is simultaneously the main component of the active detector. The signal searched for is a peak structure at the Q value of the double-beta decay, which would indicate that no energy has been transmitted to any neutrinos in the decay process. Should such a signal be separated from background, which, in some cases may stem from γ-rays from the detection isotopes themselves, the nuclear matrix elements for the $0\nu\beta\beta$ process would be needed in order to extract a neutrino mass. Those matrix elements, however, are not directly accessible experimentally, but require nuclear theory. Hence, theory needs to pinpoint the wave functions of initial and final states precisely enough to give a reliable value for the nuclear matrix element. An interesting possibility has been risen recently [6], which is the occurrence of a $0\nu\beta\beta$ transition to the excited 0^+ state in the daughter nucleus, in particular in the case of the ^{150}Nd$\rightarrow$^{150}Sm transition. We will introduce the experimental approach to address this phenomenon, based on measurements of the decay behavior of the nuclear scissors mode, in the following.

2.1. The scissors mode

The scissors mode [7, 8, 9] is an orbital M1 valence-shell excitation, which is typically observed at about 3 MeV excitation energy [10, 11]. The geometrical interpretation in well-deformed nuclei is a scissors-like counter-oscillation of the deformed proton versus the deformed neutron bodies. In other classes of nuclei the mode is also observed and can be described as a two-phonon excitation comprised of a proton-neutron symmetric quadrupole phonon and its mixed-symmetric counterpart [12]. In well-deformed nuclei, the scissors mode is the lowest-lying mixed-symmetry state. Its location in energy is sensitive to isovector model parameters, such as the Majorana parameters within the interacting boson model (IBM-2) [8]. Hence, locating the scissors mode is important to constrain the proton-neutron degree of freedom in nuclear structure models, and its M1 excitation strength depends strongly on the underlying structure and on effective g factors.

2.2. Decay behavior, shape mixing, and $0\nu\beta\beta$ rates

Like its excitation strength, also the decay behavior of the scissors mode depends on the underlying structure of the nucleus. In a deformed nucleus, the dominant decay paths are to the ground state and the first excited 2^+ states. In more spherical systems, however, the transition to the ground state should be suppressed, since it would afford the annihilation of two phonons. In this case, a strong decay to the first excited 0^+ state would be expected.

Considering the locations of nuclei which can $\beta\beta$ decay in the nuclear chart, one finds that a large number of them are located in regions which are known for fast shape changes and shape coexistence. For example, Ge and Se isotopes have long been discussed in terms of shape coexistence (e.g., recently in Ref. [13]), and in ^{76}Se significant shape mixing between the ground and first-excited 0^+ states is evident through the strong E0 strength among those states. Another example is the $\beta\beta$-decay partners ^{150}Nd and ^{150}Sm at neutron numbers $N = 90$ and $N = 88$, respectively. This is exactly in the region well-known [14] for a shape-phase transition [15] from spherical to deformed shapes, with strong mixing between both shapes at the transitional point near $N = 90$.

In a situation of configuration mixing between the lowest 0^+ states, the scissors mode may decay to both states, 0^+_1 and 0^+_2, because both share the same structure. That means the configurations that the scissors mode has been excited from, are found in both 0^+ states. Therefore, a signature of configuration mixing would be a similarly strong decay of the scissors mode into the ground and the first excited 0^+ states (compare figure 1).

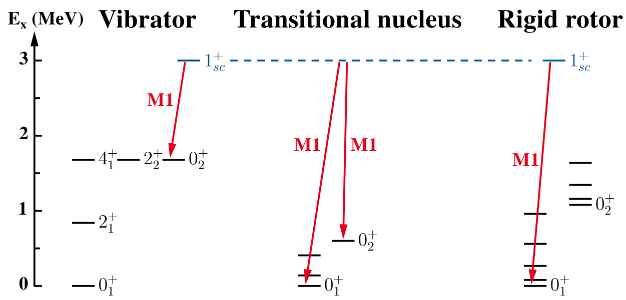

Figure 1. Decay schemes of the scissors mode in vibrator, rotor, and transitional nuclei.

For a 0ν or $2\nu\beta\beta$ decay between nuclei in such a structural region, it may occur that the ground-state wave function of the decay mother has a significant, eventually even stronger overlap with the excited-state wave function of the daughter state. Since $\beta\beta$ transition rates are enhanced if the structures of the mother and daughter states are similar, this situation can subsequently lead to an enhancement of the $\beta\beta$-decay matrix element to the excited 0^+ state in the daughter nucleus. A first hint to this mechanism, as well as to the sensitivity of the scissors mode to such cases, has firstly been found in the study of ^{154}Gd [6], where the decay of the scissors mode into both, the 0^+_1 and 0^+_2 states has been observed in a combination of photon-scattering and β-delayed γ-spectroscopy studies. The fixing of isovector model parameters and the structural location of ^{154}Gd in the IBM-2 model space led to about an order of magnitude enhancement of the $0\nu\beta\beta$-decay matrix element predicted by the model.

In the same work [6], the decay of ^{150}Nd into ^{150}Sm was identified as a case where the $0\nu\beta\beta$ matrix element to the excited state could even become larger than that to the ground state, due to a stronger wave function overlap of the ground state of ^{150}Nd with the excited state of ^{150}Sm. This fact would result from the location of these isotopes at the $N = 90$ shape phase transition, where the spherical and deformed configurations mix differently into the respective states of both isotopes. Motivated by this prediction, we performed a first photon-scattering experiment on ^{150}Sm, in order to search for a fingerprint of shape coexistence, namely, the decay of the scissors mode into both 0^+ states, as outlined below.

2.3. Experiment at HIGS

The experiment has been performed at the High-Intensity γ-Ray Source (HIγS) [16] at the Free-Electron Laser Laboratory at TUNL, on the campus of Duke University. The facility is capable of delivering γ-ray beams over a broad range of energies, with an energy spread of about 3 % (hence, near-monoenergetic), and with near 100 % polarization. The γ-rays are produced through Compton backscattering in an electron storage ring. Electron bunches in the ring produce visible laser light in the free-electron laser section, which is mirrored back and forth on the long axis of the ring, and can then interact with another electron bunch at a well-defined interaction point. The Compton-backscattered photons are then collimated and led to the experiment, located far downstream. Typical photon rates at our energy of interest around 3 MeV are 10^8 per second.

These γ-rays impinge on the probe, typically consisting of several grams of isotopically enriched material (in order to compensate for the rather small photo-absorption cross section). Target nuclei can then get resonantly excited into excited states, which due to the angular momentum carried by the incident photon mostly have angular momentum $J = 1$. Because of the high degree of polarization of the incident beam, the parities of excited states can be determined by a simple polarimeter setup with γ-ray detectors within and perpendicular to the plane spanned by the beam axis and the polarization vector. 1^+ states will radiate only within that polarization plane upon deexcitation to the ground state, whereas γ rays from the deexcitation of 1^- states to 0^+ are only emitted perpendicular to the plane.

Apart from the polarization, another advantage of γ-ray beams from Compton backscattering is the small energy spread of the beam. Compared to the traditional use of γ-ray beams from bremsstrahlung, which cover all energies from zero up to the energy from the incident electrons for beam production, a much lower background at low energies can be achieved using Compton backscattering. Therefore, the sensitivity to observe decays from resonantly-excited states into states other than the ground state is greatly enhanced as compared to bremsstrahlung experiments.

For our experiment the γ^3 setup [17] at HIγS has been employed, which consists of a combination of high-purity germanium (HPGe) and lanthanum-bromide ($LaBr_3$) detectors. Due to the very compact geometry of the setup, in principle measurements of $\gamma\gamma$ coincidences after photo-excitation are possible. In our case of investigating the scissors mode of ^{150}Sm, the photo-excitation cross section was not sufficient to allow for a coincidence measurement, however, the high-resolution detectors placed at 90° relative to the beam axis were sufficient to observe the decays of interest. It was possible to assign the observed γ-rays uniquely to the decays of specific excited states, since the level density around 3 MeV is still rather low.

The method of nuclear resonance fluorescence (NRF) can be reviewed in [18]

2.4. ^{150}Sm

^{150}Sm had previously been measured using bremsstrahlung beams [19], therefore, absolute cross sections which are necessary to extract absolute reduced transition strengths were already known. In Ref. [19] parities have not been measured directly, but rather inferred from the branching transitions of dipole-excited states to the ground and 2^+_1 states, following the Alaga rules [20]. The Alaga rules, however, require a good K quantum number, which is not ascertained in a weakly-deformed soft nucleus like ^{150}Sm. In fact, we find deviations from the previous parity assignments. Figure 2 shows the spectra taken with HPGe detectors within and perpendicular to the polarization plane. Clearly, ground-state transitions from dipole-excited states are only visible in one of the two spectra, depending on their parity. The strongest M1-excited 1^+ state in literature is the state at 3081 keV. The present data show with no doubt that this state is actually a 1^- state, hence, not belonging to the scissors mode. Nevertheless, we measure positive parity for the state at 3113 keV, identifying it as the strongest fragment of the scissors mode of ^{150}Sm.

In the γ-ray spectra of the in-plane HPGe detectors we were able to identify a peak at an energy of 2373 keV. This transition is not present in the spectra in the out-of-plane detectors, and its energy matches the transition energy of the 3113-keV state to the 0^+_2 state, which we therefore identify it with. This allows to extract the branching ratio of the scissors mode to the ground and 0^+_2 states, and, along with the known absolute excitation cross section and taking into account

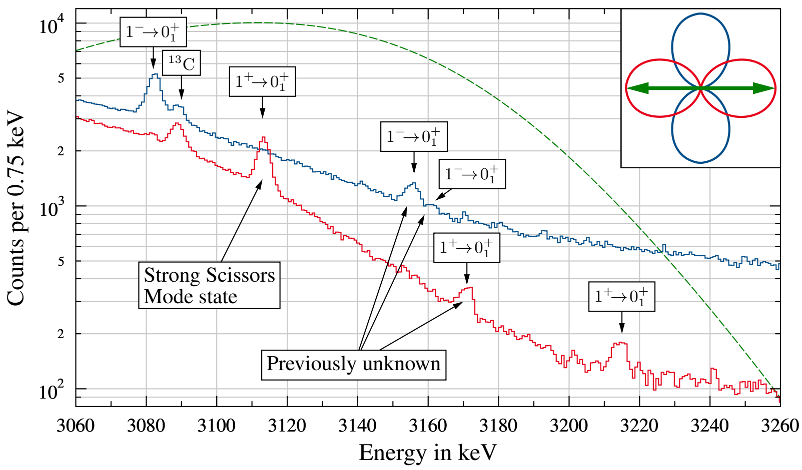

Figure 2. Spectra from the HPGe detectors within (red, bottom) and perpendicular to (blue, top) the polarization plane. Transitions from dipole-excited states are marked, including the parities of the states. The insert shows the radiation patterns from M1 (red) and E1 (blue) excited states, relative to the polarization vector indicated by the green arrow.

other observed decays of the 3113-keV state to the 2_1^+ ad 2_2^+ states, yields the absolute ground-state and 0_2^+-state B(M1) transition strengths. We obtain B(M1;$1_{sc}^+ \to 0_1^+$)= $0.071(10)\mu_N^2$ and B(M1;$1_{sc}^+ \to 0_2^+$)= $0.030(9)\mu_N^2$. Both transitions are of the same order of magnitude, and even agree within a factor of two. This is the behavior expected for the case of shape coexistence, where the scissors mode can decay with similar strengths to either 0^+ state. Also, this finding agrees with the prediction [6] that shape mixing occurs for the ^{150}Nd/^{150}Sm pair of isotopes, which would lead to a dominant $0\nu\beta\beta$ matrix element to the excited 0^+ state in ^{150}Sm. A similar study on ^{150}Nd has recently been performed, and both measurements will give input to new model calculations to properly describe the structure of both isotopes, and to give more reliable predictions for the $0\nu\beta\beta$ matrix elements between the ground state of ^{150}Nd and the ground and excited 0^+ states of ^{150}Sm.

3. Upcoming and ongoing studies

Further studies into nuclear structure relevant for weak-interaction physics, performed at TU Darmstadt, are briefly addressed in the following.

3.1. $0\nu\beta\beta$ decay

Photon-scattering experiments analog to that described above have and will be performed on other pairs of nuclei which are discussed in the context of detectors to observe $0\nu\beta\beta$ decays, e.g. ^{82}Se/^{82}Kr (SuperNEMO) or ^{76}Ge/^{76}Se (GERDA/MAJORANA). In both cases, we observe transitions from the scissors mode into the excited 0^+ states. In addition, the spectra yield information on γ-rays from the nuclei of interest, which may be close to the endpoint energy of the $\beta\beta$-decay spectrum, where the signal from $0\nu\beta\beta$ decay is expected. Such γ rays would have to be taken into account in background considerations for the respective detectors, since $J = 1$ states could be excited by background radiation penetrating their shielding, e.g., neutrinos.

3.2. ν scattering

From data taken at HIγS at higher energies (up to the particle thresholds of the investigated isotopes), we expect to obtain valuable information on the nuclear M1 response, in particular the spin-flip resonance. The latter is composed of states excited by exciting a single proton or neutron from a $l \pm 1/2$ to a $l \mp 1/2$ orbital. Little detail about the location and the overall shape of this resonance is known to date, with only few examples addressed by experiment (e.g., ^{136}Xe [21]). This is of interest for investigations into (ν, ν') neutrino-scattering of nuclei, which can excited quite selectively such 1^+ states from the ground state, as shown in QRPA calculations [22].

3.3. WIMP search

First measurements at the S-DALINAC facility of TU Darmstadt have just recently started, to investigate the electron-scattering form factors to the first excited states of the odd-A ^{129,131}Xe isotopes. This is of interest due to the use of natural Xe in the Xenon1T [23] WIMP detector, where the odd-A Xe isotopes make a considerable fraction of the overall detector mass. Recent works [24, 25] addressed the question of how WIMP-nucleus cross sections might be altered should WIMP-neutrino scattering be spin dependent. In this case, scattering to the first excited state could dominate the detector response. The electron-nucleus scattering experiments will test the nuclear wave functions used in the respective calculations.

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