NUCLEAR MAGNETIC AND QUADRUPOLE MOMENTS OF EXOTIC ISOMERIC STATES*

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An overview of some recent results on nuclear moment measurements on isomers is being given. Neutron rich isomers have been produced in a fragmentation reaction at GANIL. Using the spin-orientation of the fragment beam, isomeric g-factors around ^{68}Ni have been measured by detecting the Larmor precession via the isomeric γ-decay (TDPAD-method). Isomers in the mass $A \sim 180$ region were produced in a fusion-evaporation reaction at Louvain-la-Neuve. The quadrupole moment of a 5 quasi-particle isomer in the deformed nucleus ^{179}W was measured using the Level Mixing Spectroscopy (LEMS) method. Both results show how details on the nuclear structure can be investigated via nuclear moment measurements.

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1. Introduction

The development of radioactive beam production and selection techniques has initiated many experiments to study the properties of exotic nuclei, in order to investigate the behavior of nuclear matter when approaching the drip lines. As soon as neutron-rich nuclei could be studied, it became clear that the structure of these nuclei with large isospin could not be predicted with the existing nuclear models. New phenomena, such as halo structures, new and disappearing shell closures, new regions of deformed nuclei were discovered. Several properties of nuclei need to be studied to obtain a full picture of the nuclear structure. Via the magnetic dipole moment and the electric quadrupole moment one can get insight into the single

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particle structure as well as the collective nature of the nucleus. Since several years we have been developing new methods [1–3] and adapting existing methods [4], to study static nuclear moments of isomers and ground states. The techniques can be applied to exotic nuclei produced via projectile fragmentation reactions or to isomers produced in a fusion-evaporation reaction. In this contribution we give an example of both cases.

2. Spin-orientation by nuclear reaction

Measuring nuclear moments of short lived nuclear states (half lives of less than a second) requires fast spin-orientation methods combined with on-beam detection of the radiative (β- or γ-) decay of nuclei submitted to several hyperfine interactions (magnetic dipole, electric quadrupole , ...).

For isomers produced in a fusion-evaporation reaction, it is well-known that the isomeric spins are being aligned, with the spins preferably perpendicular to the beam direction (large oblate alignment) [5]. High alignments, up to 60–80 %, can be obtained. If the isomers are being stopped in the target, or recoil-implanted in a host crystal mounted on top of the target, the alignment is maintained. If the isomers are recoiling out of the target, and travelling some distance before being implanted into a host, most of the spin-orientation is being lost due to the interaction of the nuclear spin with the randomly oriented electron spin. Then a moment measurement using perturbation methods becomes impossible. It has been shown that if the isomers can be selected in a noble-gas like electron configuration, some of the orientation can be maintained after recoil separation [6]. We have also shown that in a LEMS experiment, the recoil-distance method can be used [7]. The development of this formalism has led to a new technique that could be used to study g-factors of short lived isomers (0.5–100 ns) [8].

The discovery of the presence of spin-polarization [9] and spin-alignment [10] in a selected ensemble of secondary projectile fragments was a major breakthrough in the study of nuclear moments of very exotic nuclei far from stability. Using the spin-orientation obtained during the fragmentation process, nuclear moments of very short-lived states (down to the time of flight in the mass separator, typically 200 ns) can be studied. Although the spin-orientation process is not yet fully understood, several groups have started to use this orientation to measure changes in the β-decay asymmetry of exotic nuclei [11–13] from which information on the nuclear g-factor and spectroscopic quadrupole moment can then be extracted. While most groups have focused on using spin-polarized beams, our group has developed some techniques that allow taking advantage of the full yield of forward emitted fragments which are purely spin-aligned [2, 3, 14].

3. g-factors of isomers studied by TDPAD + ion-γ correlation

During the past 5 years, it has been shown in several experiments that in fragmentation reactions also high-spin isomers can be populated in significant amounts [15, 16]. By selecting fully stripped fragments, the spin-orientation of this isomeric ensemble can be maintained during the flight through the mass spectrometer. This opens up several possibilities to study the structure of neutron-rich isomers, which is not possible by other methods. With a spin-aligned isomeric fragment beam one can use for example the Time Differential Perturbed Angular Distribution method [17] to study the g-factor of the isomers. Or one could apply the γ-LMR [18] or LEMS [1] methods to study their quadrupole moments. Spin-aligned isomers also allow to extract from the measured angular distribution information on the character of the gamma-transition (electric or magnetic) by using the Clover detectors as Compton polarimeters [19].

To obtain fully stripped fragment nuclei, the primary beam energy needs to be sufficiently large. Light nuclei are all produced fully stripped after an intermediate energy fragmentation reaction (50–100 MeV/a). The heavier the nuclei of interest, the higher the required primary beam energy in order to obtain fully stripped atoms as the most intense fragment beam. An experiment on a known isomer in ^{43}Sc produced in the fragmentation of a 500 MeV/u ^{46}Ti beam revealed the presence of significant alignment in the selected isomeric beam [20]. We have conducted a pioneering experiment

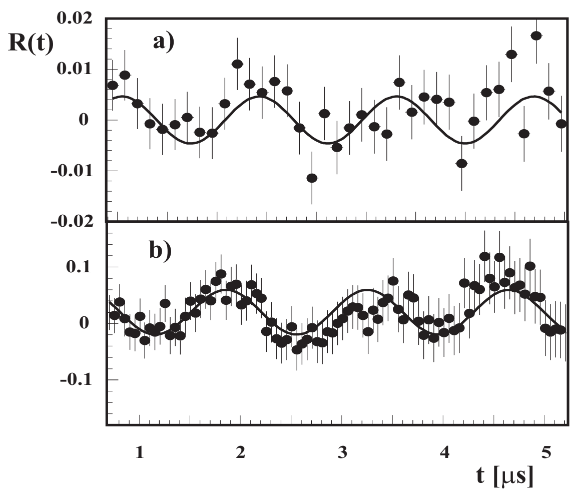

Fig. 1. (a) Measured γ-anisotropy $R(t) = \frac{N(0)-\varepsilon N(90)}{N(0)+\varepsilon N(90)}$ for the $E_\gamma = 313$ keV $9/2^+$ decay in ^{67}Ni. (b) Same data, on which an autocorrelation function was applied [21, 22].

to use the spin-alignment for the study of the g-factors of several isomers around ^{68}Ni, all selected in a single setting of the LISE spectrometer at GANIL. By requiring an event-by-event ion — delayed gamma correlation in a time window of 20 μs, clean gamma-spectra for each of the isomers could be obtained. The selected ion rate was limited to 8000 ions/s by closing the slits of the spectrometer, in order to avoid too many random coincidence's (in fact the number of random coincidence's turned out to be still very high, as one of the isomers was very short-lived). Preliminary results of this experiment as well as experimental details and details on the data analysis have been presented in previous conference contributions [4] and [21] for the $13/2^+$ ($T_{1/2} = 355(2)$ ns) isomer in ^{69}Cu. We have also been able to measure the g-factors of the $I^\pi = 9/2^+$ isomer in ^{67}Ni ($T_{1/2} = 13.3$ ms) (Fig. 1), as well as for an isomer in ^{66}Co ($E_\gamma = 175$ keV, $T_{1/2} = 823(5)$ ns). A paper in which the result for ^{67}Ni is being discussed and compared to shell model calculations has been submitted [22]. We have shown that the g-factor of this $9/2^+$ isomer is extremely sensitive to small admixtures of a $\pi\mathrm{p}-\mathrm{h}\ 1^+$ excitation of the $Z = 28$ core, and that about 2 % of the wave function contains admixtures of this type (Fig. 2).

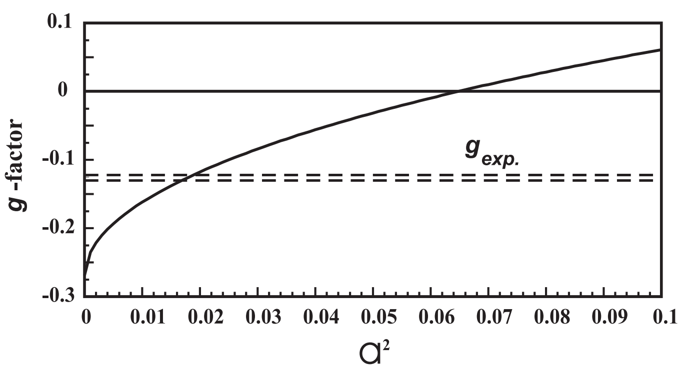

Fig. 2. Experimental g-factor for the ^{67}Ni (9/2+) isomer compared to a calculated g-factor as a function of the mixing probability between a pure $\nu g_{9/2}$ configuration and a $\nu g_{9/2} \otimes (\pi f_{7/2}^{-1} f_{5/2})_{1^+}$ configuration.

4. Quadrupole moment of a 5 quasi-particle isomer in ^{179}W

In well deformed nuclei, isomers known as "K-traps" occur because their decay requires a change of the nuclear spin orientation relative to an axis of symmetry. K is a quantum number that represents the projection of the total nuclear spin along the symmetry axis of the deformed nucleus. A number of such states have been established in the Hf-W-Os nuclei in the mass $A \approx 180$ region.

The $Z = 74$ W nuclei are known to exhibit substantial prolate deformations ($\beta_2 \approx 0.25$) in their ground states [23]. These were deduced from Coulomb excitation experiments, in which the reduced transition probabilities (the transition quadrupole moments) of the first excited 2^+ states in even–even $^{180-186}$W isotopes were measured. The experiments we performed, provide for the first time a direct measurement of a static quadrupole moment in the $_{74}$W nuclei. This measurement allows to find out if there is a difference between the deformation of the nuclei in their ground state and in their high-seniority multi-quasiparticle excitations.

The experiments were performed at the CYCLONE cyclotron at Louvain-la-Neuve, using the LEMS technique [1]. The experimental set-up consists of a split-coil 4.4 T superconducting magnet with the magnetic field directed along the beam axis, a target holder allowing precise temperature control at the target position in the interval 4–600 K, and 4 Ge detectors, which monitor the target through the holes of the magnet. They are positioned at 0° and 90° with respect to the beam-axis [1].

The choice of a suitable host material is crucial for the LEMS experiments, since the measured quadrupole frequency depends on both the nuclear quadrupole moment and the EFG of the material as $\nu_Q = \frac{e}{h} Q_s V_{zz}$. For the LEMS experiments on the W-isomer a $_{81}$Tl host was chosen. Tl has a hexagonal structure (hcp) for temperatures below 503 K, and a cubic (bcc) lattice for temperatures above it. The lattice of $_{81}$Tl is close to the ideal crystal and the EFGs of different atoms sitting at substitutional sites are known to be small [24]. It is also well known that in the hcp phase, the EFG of Tl is strongly temperature dependent and decreases with temperature [25]. The host was heated in order to reduce the EFG of W$\underline{\text{Tl}}$, and to anneal defects in the Tl host, possibly created during the in-beam implantation. To determine the EFG for W(Tl) we performed theoretical band-structure calculations made with the WIEN97 package [26]. This resulted in a value of $V_{zz}(\text{W}\underline{\text{Tl}}) = 2.54 \times 10^{21}$ V/m^2 at 0 K. A dedicated experiment to measure the temperature dependence was performed [27], from which we derived the EFG at 473 K: $V_{zz}(\text{W}\underline{\text{Tl}}) = 0.55(^{+0.12}_{-0.08}) \times 10^{21}$ V/m^2 assuming the $\text{T}^{3/2}$ temperature dependence.

From the measured LEMS curve (Fig. 3) we derived a quadrupole frequency $\nu_Q = 53(8)$ MHz [28]. Using the deduced field gradient, this results in a spectroscopic quadrupole moment of $Q_s = 4.00(^{+0.83}_{-1.06})$ eb. Accepting that K is a good quantum number, the measured quadrupole moment is related to the intrinsic quadrupole moment, Q_0 through the relation:

$$Q_s = Q_0 \frac{3K^2 - I(I+1)}{(2I+3)(I+1)} \,. \tag{1}$$

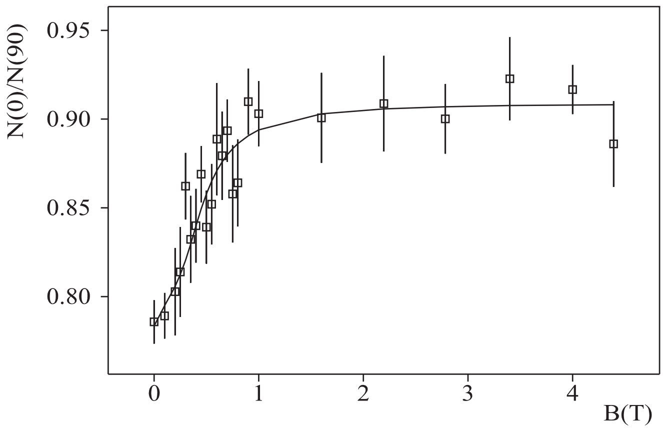

Fig. 3. Sample LEMS curve for the $I = K = \frac{35}{2}$, $E_i = 3349$ keV isomer in ^{179}W, implanted in a Tl polycrystaline foil at a temperature of 473 K.

This yields a value $Q_0 = 4.73(^{+0.98}_{-1.25})$ eb, which corresponds to a quadrupole deformation $\beta_2 = 0.185(^{+0.038}_{-0.049})$, taking into account that $Q_0 = \frac{3}{\sqrt{5\pi}} ZR^2\beta_2$, $R = r_0 A^{1/3}$ and $r_0 = 1.2$ fm. In the upper portion of Fig. 4, the intrinsic quadrupole moment of the $K = \frac{35}{2}$ isomeric state is compared to the ground-state quadrupole moments of the $_{74}$W nuclei, which have been

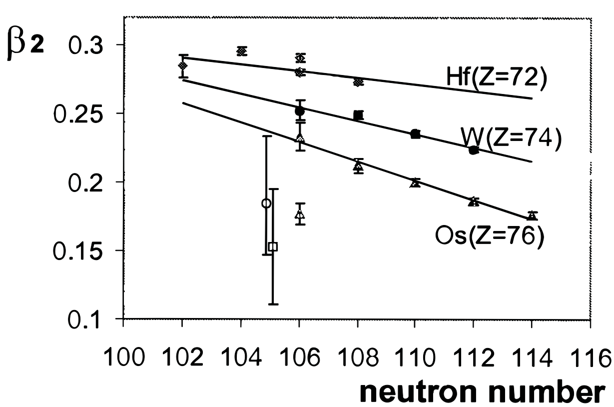

Fig. 4. Systematics of the ground-state charge deformation for the $_{72}$Hf (filled diamonds), $_{74}$W (filled circles), and $_{76}$Os (filled triangles) nuclei, as derived from measured B(E2,$0^+ \rightarrow 2^+$) transition probabilities [23], compared to the deformation derived from the static quadrupole moments of the high-K isomers in ^{179}W (open square for this work and open circle for Ref. [30]), ^{178}Hf (open diamond) [34] and ^{182}Os (open triangle) [33].

extracted from the reduced transition probabilities [23]. Also the Q_0 values, derived from the measured moments of the $K = 25$ isomer in ^{182}Os and the $K = 16$ isomer in ^{178}Hf, are added to the figure, as well as the ground-state moments for the $_{72}$Hf and $_{76}$Os nuclei. Note that in the case of ^{178}Hf (as well as for ^{177}Lu [29]) the measured ground state and the isomer quadrupole moments take similar values, while in the case of ^{179}W and ^{182}Os they differ considerably. In addition, an independent value can be obtained for ^{179m}W by using the existing spectroscopic data for the rotational band which is built on the top of the $K = \frac{35}{2}$ isomer. From the measured branching ratio of the cascade-to-crossover transitions in this band, $\lambda = 0.26(9)$, a value for $\mid (g_K - g_R)/Q_0 \mid = 0.045(11)$ eb^{-1} was derived [30]. Assuming that $g_R = 0.30(5)$, consistent with the systematics of the region [31], and taking into consideration the measured magnetic moment of $\mu = 8.31(8)\mu_N$ for this state [32], a value $Q_0 = 3.9(1.5)$ eb was found. These results demonstrate that the measured values for the quadrupole moments of the high-K isomers in ^{179}W and ^{182}Os, do not fit to the systematic trends, which were observed for the ground-state moments in the region [23].

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