Magnetic Moment of the Fragmentation-Aligned ^{61}Fe $(9/2^+)$ Isomer

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We report on the g factor measurement of an isomer in the neutron-rich $^{61}_{26}$Fe ($E^* = 861$ keV and $T_{1/2} = 239(5)$ ns). The isomer was produced and spin aligned via a projectile-fragmentation reaction at intermediate energy, the time dependent perturbed angular distribution method being used for the measurement of the g factor. For the first time, due to significant improvements of the experimental technique, an appreciable residual alignment of the nuclear spin ensemble has been observed, allowing a precise determination of its g factor, including the sign: $g = -0.229(2)$. In this way we open the possibility to study moments of very neutron-rich short-lived isomers, not accessible via other production and spin-orientation methods.

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The measurement of electromagnetic (EM) moments has traditionally played a central role in the critical evaluation of nuclear structure models since they elucidate the single-particle nature (magnetic moments) and the shape (quadrupole moments) of the nuclear state under investigation. Their particular behavior around nuclear shell closures, approaching Schmidt values for magnetic moments and small values for quadrupole moments, makes them good tools to investigate shell closure near and far from β stability.

One of the main restrictions in the study of EM moments is the necessity to obtain spin-oriented nuclear ensembles. In particular, for the study of neutron-rich nuclei that are mostly produced via fragmentation reactions at high or intermediary energies, the mechanism to produce oriented states is not yet well understood. The first observation of spin alignment of ensembles of isomeric states in a projectile-fragmentation reaction at an energy of 500 MeV/u was reported by Schmidt-Ott *et al.* [1]. At projectile energies below 100 MeV/u, so-called intermediate energies, nuclear spin alignment was reported recently by Georgiev *et al.* [2] in a study of isomeric states in the vicinity of ^{68}Ni. However, only a very small residual alignment observed in the decay of the ^{67}Ni and the ^{69}Cu isomers was reported. The main difficulty encountered in this experiment [2] was to maintain the produced alignment from the target to the implantation point.

In this Letter, we report an important experimental achievement in the study of EM moments of neutron-rich isomers. For the first time, high quality data could be obtained for an isomer in the neutron-rich ^{61}Fe nucleus.

We focused here on the role played by the $\nu g_{9/2}$ orbital in the low-energy level structure of nuclei near $N = 40$ in the particular case where this orbital manifests itself as an isomeric state. The ^{61m}Fe, with 35 neutrons, is one of the lightest nuclei exhibiting such an isomeric state ($T_{1/2} = 239(5)$ ns) at a rather low excitation energy ($E^* = 861$ keV) decaying via a ($M2$) transition of 654 keV in cascade with a ($M1$) transition of 207 keV to the ground state (see Fig. 3). The $(9/2^+)$ tentatively assigned spin and parity is based on systematics, β-decay study of ^{61}Fe [3], the isomer's lifetime, and the observed transitions depopulating the isomer [4]. A measurement of the g factor of the isomeric state in ^{61}Fe can provide information about its structure and can also confirm the suggested spin/parity.

The nuclei of interest were produced following the fragmentation of a 54.7 MeV/u ^{64}Ni beam accelerated at the GANIL facility, with a mean intensity of 7×10^{11} pps, impinging on a 97.6 mg/cm^2 thick ^{9}Be target placed at the entrance of the LISE spectrometer [5]. In order to minimize the in-flight decay of the isomer, the detection setup (Fig. 1) was positioned at the first focal plane of the LISE spectrometer (time of flight $\approx$200 ns). A 300 μm thick removable silicon detector, placed downstream of the setup, was used to optimize the selection of ^{61}Fe fragments by means of energy-loss vs time-of-flight identification. Once the selection was performed, the silicon detector was removed and a 50 μm thick plastic scintillator, placed in front of the catcher foil, was used to provide the $t = 0$ signal for the subsequent time dependent perturbed angular distribution (TDPAD) measurement. The choice of a thin plastic scintillator instead

of a silicon detector for providing the start signal was made for two reasons. First, as the fragments are selected fully stripped with the LISE spectrometer and in order to preserve the initial alignment until the eventual stop in a catcher foil, it is important to avoid as much as possible the capture of electrons that can completely destroy the orientation of the nuclear ensemble. The electron pickup upon passing through the scintillator is estimated to be below 2% [6], much lower than that in a 300 μm thick silicon detector (60%–70%) [2]. Second, the intensity of the secondary beam (between 17 and 80 kHz for the present experiment) can be 1 order of magnitude higher than the intensities acceptable for a silicon detector (below 10 kHz). As a catcher for the reaction products, we used an annealed high-purity 500 μm thick Cu foil. Iron ions have the same electronegativity and similar atomic radius as Cu atoms and hence Cu, with its cubic lattice structure, is expected to provide a perturbation-free environment for implanted Fe fragments [7]. The Cu foil was placed between the poles of an electromagnet that provided a constant magnetic field $\vec{B}$ in the vertical direction.

The Larmor precession of the initially aligned ensemble of isomeric states in the applied field of about 0.7 T was monitored with four coaxial Ge detectors placed in the horizontal plane around the Cu foil as shown in Fig. 1. Time spectra were collected, having as start the signal due to the ion passage through the plastic scintillator and as stop the signal given by the detection of a prompt or delayed γ ray. To extract the precession pattern out of the time spectra, data from detectors positioned at 90 ° with respect to each other were combined to generate the $R(t)$ function for each γ transition:

$$R(t) = \frac{I_{12}(\theta, t) - \epsilon I_{34}(\theta + \frac{\pi}{2}, t)}{I_{12}(\theta, t) + \epsilon I_{34}(\theta + \frac{\pi}{2}, t)} \sim A_2 B_2^0 (t = 0) \cos[2(\omega_L t + \alpha - \theta)], \quad (1)$$

with $\vec{\omega}_L = -\frac{g\mu_N \vec{B}}{\hbar}$ and $\alpha = -\frac{\pi}{2}(1 - \frac{gA}{2Z})$ both depending on the g factor. α is the rotation angle of the aligned ensemble symmetry axis with respect to the beam axis induced when passing through the two dipole magnets of the LISE spectrometer [2]. I_{12} and I_{34} are the summed isomeric events in detectors placed at 180 degrees, e.g.,

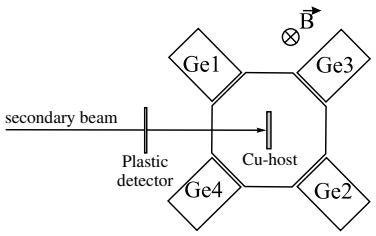

FIG. 1. Schematic drawing of the TDPAD experimental setup. The beam passes through a 50 μm plastic scintillator before being stopped in a 500 μm Cu foil.

$I_{12} = N_\gamma(\text{Ge1}) + N_\gamma(\text{Ge2})$ (see Fig. 1); A_2 is the angular distribution parameter of the observed γ-ray transition; B_2^0 is the second component of the orientation tensor describing the initial orientation of the selected ensemble of spin-aligned isomeric states; θ equals $\pi/4$. ϵ is the relative efficiency for detecting γ intensities I_{12} and I_{34} and it was determined by the ratio between I_{12} and I_{34} for a given γ transition. The data acquisition was validated on an event by event basis by the coincidence between a heavy ion signal from the plastic scintillator and a γ ray registered by one of the germanium detectors within a time window of 3 μs. In order to diminish the number of accidental coincidences in this time window, we have used a package suppressor (PS) that brought on target one beam pulse (package) every 952 ns instead of every 95 ns. The time resolution of these packages is about 2 ns. Comparison of $R(t)$ functions with and without use of the PS resulted in an increase of the detected alignment by a factor of $\sim$3 for the case with PS. This increase can be partly explained by the decrease of the number of implanted isomers during or outside the time window of 3 μs that have a shifted $t = 0$ for the $R(t)$ functions. Comparison with GEANT simulations [8] that are taking into account the beam structure indicates that only 11% of the increase in the amplitude could be due to these types of accidental coincidences. More detailed information about these simulations and possible sources for the increase of the observed alignment can be found in [9]. Nevertheless, a full explanation of the observed increase of the $R(t)$ amplitude is still subject to further investigations and a systematic measurement of $R(t)$ as a function of beam structure is in view.

Certain physical effects need also to be taken into account when deducing a precise value for the g factor from the observed Larmor frequency. The distribution of the magnetic field over the beam spot, the paramagnetic amplification of the applied magnetic field, the Knight shift, and other effects that can locally modify the magnetic field felt by the oriented ensemble, e.g., Ref. [10], can induce minor modifications of the Larmor frequency. In order to avoid systematic errors due to these corrections and to validate the experimental setup and method, we have measured the Larmor precession under identical conditions for an isomer with a similar lifetime in another iron isotope: the $I^\pi = 10^+$, $E^* = 6527$ keV, and $T_{1/2} = 364(7)$ ns isomer in ^{54}Fe having a known g factor, $g(10^+) = +0.7281(10)$ [11].

The measured lifetime of the ^{54m}Fe isomer $T_{1/2} = 370(9)$ ns is in good agreement with previous measurements [12]. The $R(t)$ function of the ^{54m}Fe was constructed by summing up all of the γ transitions in the stretched $E2$ cascade depopulating the isomer because it is known that in such cascades the angular distribution is the same for each γ transition: $U_2(\gamma_1)U_2(\gamma_2)\ldots U_2(\gamma_n) \times A_2(\gamma_{n+1}) = A_2(\gamma_1) = -0.369$ [13], where $U_2(\gamma_i)$ are the deorientation coefficients. The effective value of the mag-

netic field extracted from it [Eq. (1) and Fig. 2, top right] is 0.680(4) T.

^{54m}Fe served also as a probe to measure the residual alignment of the ensemble of isomeric states as a function of its angular momentum distribution [14]. For the selection of the fragments in the wing of the momentum distribution ($p_{\text{fragment}} < p_{\text{projectile}}$), the amplitude of the $R(t)$ function, 3.3(2)% (Fig. 2, top right), yields a large negative alignment, $-12.5(9)$%, the sign being in agreement with the predictions of a kinematical fragmentation model [15,16]. The comparison between the calculated and the experimental alignment is presented in Fig. 2 (bottom).

The half-life of the ^{61}Fe isomer was deduced independently from the 207 keV and the 654 keV γ rays deexciting the isomer, being 240(5) ns and 238(5) ns, respectively, in agreement with the earlier reported value [4] and resulting in a final value $T_{1/2} = 239(5)$ ns. The $R(t)$ functions of the two γ rays exhibit an opposite phase. This is due to the different multipolarities for the two transitions. The ratio between the amplitudes of the two $R(t)$ functions is $-1.43(16)$ (Fig. 3, right). Using GEANT simulations of the experimental setup [8] and assuming that the 654 keV and 207 keV transitions have pure $M2$ and $M1$ multipolarities, respectively, and the level sequence is from Fig. 3, we estimated this ratio to be $-1.30(6)$. The size of the beam spot at the implantation point has also been taken into account in order to determine the geometrical factor of the detection setup. The good agreement between the two ratios (experimental and simulated) indicates that the multipolarities and sequence of the γ transitions used for the determination of the experimental alignment are correct. This is a first indication that the suggested level sequence in ^{61}Fe is indeed $3/2^-$ (g.s.), $5/2^-$, $9/2^+$.

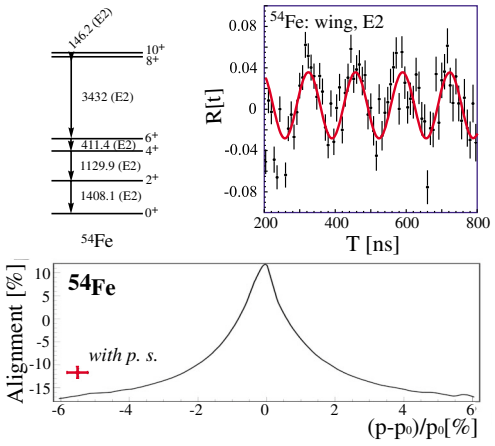

FIG. 2 (color online). Top: the decay scheme of the 370(9) ns isomer in ^{54}Fe and the $R(t)$ function of the summed γ transitions. Bottom: comparison between the measured (with package suppressor) and the calculated alignment. The theoretical curve is divided by a factor of 1.8.

For ^{61m}Fe, we have studied the alignment for two selections, respectively, in the center and in the outer wing of the longitudinal momentum distribution. The alignment of the ensemble of isomeric states, deduced from the amplitude of the $R(t)$ function of the 654 keV decay is $+6.2(7)$% for the central selection (the value of the amplitude being $-2.7(3)$% and $-15.9(8)$% for the wing selection (for an amplitude of $+4.49(14)$%)) (Fig. 3, left bottom), assuming a pure $M2$ transition.

For the determination of the gyromagnetic factor, we used the $R(t)$ function of the 654 keV direct decay of the isomeric state for the central and wing selection of the fragments momentum (Fig. 3, top). We made this choice in order to avoid any influence of the deduced g factor on the intermediary 207 keV state. A value of $-0.229(2)$ was extracted by a χ^2 fit, using expression (1) with both frequency and initial phase, α, depending explicitly on g; the value of the effective magnetic field, B, is taken from the ^{54}Fe data as described above. The error on the fitted g factor includes the error on the effective field.

In Fig. 4 we present the measured g factors of $9/2^+$ isomeric states around $N = 40$, including also the g factor of ^{61m}Fe. The data are taken from [2,12,17]. The comparison with the other g factors of known $9/2^+$ isomeric states in the region strongly supports the $9/2^+$ spin and parity assignment for the ^{61m}Fe isomer.

One can observe the symmetry with respect to $Z = 28$ (proton magic number) of the g factors for the $N = 35$ chain, suggesting that two particle or two hole proton configurations affect the g factor in a similar way. The increase of g factor values when going away from $Z = 28$ indicates an increase of core polarization effects due to

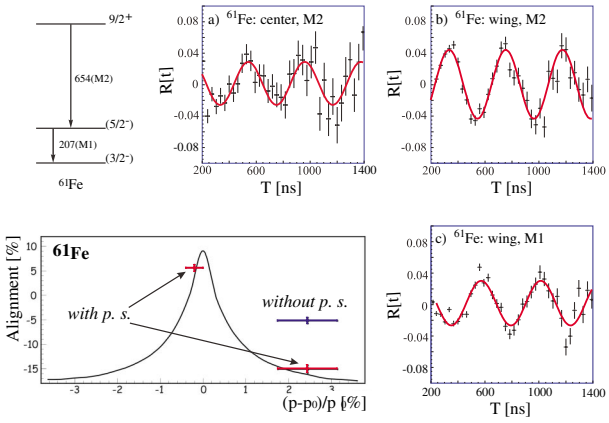

FIG. 3 (color online). Top and right bottom: the decay scheme of the 239(5) ns isomer in ^{61}Fe and the $R(t)$ functions for (a) ^{61}Fe (center, 654 keV); (b) ^{61}Fe (wing, 654 keV); (c) ^{61}Fe (wing, 207 keV). The $R(t)$ function for 207 keV is consistent with that for the 654 keV but with opposite phase, as expected from the assumed multipolarities of the corresponding γ transitions. Left bottom: comparison between the measured (with and without package suppressor) and the calculated alignment. The theoretical curve is divided by a factor of 1.8.

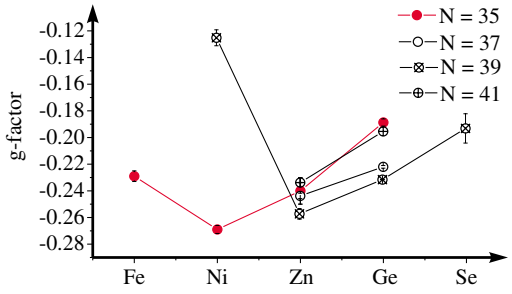

FIG. 4 (color online). g factor systematics around $N = 40$ for known $9/2^+$ isomeric states. This measurement is the first one below $Z = 28$, and supports a symmetric behavior with respect to the $Z = 28$ shell closure. The unusual value for the g factor of ^{67}Ni could be explained by 2% proton excitations across $Z = 28$ [2], but a remeasurement is highly recommended.

the opened proton $\pi f_{7/2}$ shell ($Z < 28$) or to the additional protons into the $\pi p_{3/2} f_{5/2} p_{1/2}$ shell ($Z > 28$).

Because of the sensitivity of the g factor towards single-particle properties of the wave function of the studied state, we have compared the measured value with the one predicted by large scale shell model (LSSM) calculations [18]. We considered an inert core of ^{48}Ca, and the valence space is composed by $\nu p_{3/2} f_{5/2} p_{1/2} g_{9/2}$ and $\pi f_{7/2} p_{3/2} f_{5/2} p_{1/2}$. We allowed up to $6p - 6h$ excitations, meaning that the total number of particles excited from $\nu p_{3/2} f_{5/2} p_{1/2} g_{9/2}$ to $\nu g_{9/2}$ for neutrons, and from $\pi f_{7/2}$ to $\pi p_{3/2} f_{5/2} p_{1/2}$ for protons, was less than or equal to 6. The interaction used, called fpg, is described in [19] and in the references therein. The first $9/2^+$ state is calculated to be at 720 keV and its wave function is a mixture of a large number of configurations, the mean occupation of the $\nu g_{9/2}$ orbital being ≈ 1. The very mixed structure of the wave function might be an indication of a rather deformed potential for the $9/2^+$ state. This is supported by the spectroscopic quadrupole moment, $Q = -57.9e$ fm^2, which corresponds to a deformation $\beta_2 = -0.24$ assuming that ^{61m}Fe is an axial deformed rotor with $K = I = 9/2$.

The calculated free g factor is $g(9/2^+) = -0.277$. The effective value is $g(9/2^+) = -0.1627$ if a quenching factor of 0.7 is used for the nucleon spin g factor. The value of the quenching factor is quite arbitrary because at present, there is no systematical comparison between experimental data and shell model calculations into the considered fpg valence space. The experimental result that lies in between the free and the effective calculations may provide an important input into this issue [20].

In conclusion, the measured g factor is in very good agreement with the assigned $9/2^+$ spin and parity, both from systematics and shell model calculation points of view. From the comparison with LSSM calculations, there are indications that this state is characterized by a deformed potential. A measurement of the quadrupole moment, Q, of this state is therefore important. Based on the large observed residual alignment, such a measurement is currently being planned. It is important to note that for the determination of the sign of the deformation, one has to obtain a spin-polarized ensemble of isomeric states [21,22].

The appreciably large residual alignment measured for the ^{61m}Fe and ^{54m}Fe fragments indicates that fragmentation reactions at intermediate energies can provide a powerful tool to align ensembles of nuclear states. As this type of reaction is up to now the only way to produce (very) neutron-rich short-lived ($\sim$50 ns–μs) isomeric states, one can now use it for the investigation of the nuclear structure away from stability via EM moments measurements.

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