β-level mixing resonance: A method to study the spin alignment and spin polarization of projectile fragments

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In this paper we present the β-level mixing resonance (β-LMR) method as a tool to measure the initial spin-orientation of exotic nuclear beams produced and oriented in a fragmentation reaction. Understanding this spin-orientation process is the key to allow studies of nuclear moments of nuclear states far from stability. The β-LMR method is a unique tool, sensitive to both the spin-polarization and the spin-alignment component in the selected ensemble of fragment spins. In the paper we describe the formalism to extract this information from the experimental data and report on a first test experiment.

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I. INTRODUCTION

As with most of the techniques to measure nuclear moments, the prerequisite for the β-level mixing resonance (β-LMR) techniques [1,2] is to start from an initially oriented ensemble of nuclear spins. It has been shown that nuclei produced in a projectile fragmentation reaction are spin oriented [3–6]. While spin-alignment (A) is obtained simply by selecting recoiling nuclei in the forward direction, spin-polarization (P) requires selection at an angle with respect to the primary beam.

A major advantage of the β-LMR method is its applicability in either case of spin orientation (polarization, alignment, or a combination of both) while β-NMR [7] and multiple-rf β-NQR [8] are limited to an initially polarized secondary beam. Several β-NMR measurements were performed to study polarized beams of fragments selected at an angle with respect to the primary beam axes [4,9–13]. It should be noted, however, that the mechanism leading to spin-oriented fragments is not yet completely understood. In previous studies, only the spin-polarization component was measured, although an alignment component was present as well. On the other hand, in the case of forward selected fragments there is a complete lack of information on the behavior of spin orientation as a function of the reaction parameters (primary and secondary beam energy, fragment mass, etc.). We demonstrate in this paper the possibility to deduce both the initial spin-alignment and spin-polarization component from the amplitude of the level mixing resonance by switching the direction of the magnetic field. We plan to use this technique in the future to make an elaborate study of the spin orientation created in a projectile fragmentation reaction. This can be done by performing β-LMR on fragments of which the nuclear moments, β decay, and solid state properties are known, such that the only unknown parameter is the initial spin orientation. Here we develop the model and provide the basic equations to study the spin orientation of secondary exotic nuclear beams. We report on a first test experiment to show the feasibility of this technique.

II. DESCRIPTION OF AN ORIENTED ENSEMBLE OF FRAGMENT NUCLEI

An ensemble of nuclei with spin I, having $(2I+1)$ quantum-states denoted as $|m\rangle$ states is called spin aligned if the probability $[p(m)]$ to populate the $|+m\rangle$ and $|-m\rangle$ states is equal and $p(m=0$ or $\pm 1/2)$ is different from $p(m=I)$ (m being the projection of I on a quantization axis with axial symmetry). If the ensemble is not inversion symmetric, e.g., for a certain m number the probability $p(m) \neq p(-m)$, the ensemble is called spin polarized.

The initial orientation [(A) or (P)] is axially symmetric with respect to a reference frame of which the z axis is defined by this symmetry axis. The symmetry axis of the initial alignment does not necessarily correspond to the symmetry axis of the initial polarization. Both orientations will be described in their own orientation frames (denoted as ''$or_{(A)}$'' for alignment and ''$or_{(P)}$'' for polarization) and in the final LMR formalism they will be transferred to the laboratory frame (lab) (Fig. 1).

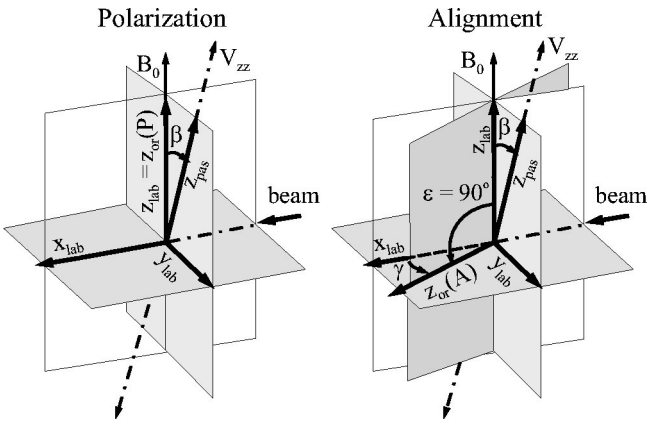

FIG. 1. Frame definition in the case of β-LMR. There is a separate orientation frame for the alignment $[z_{or}(A)]$ and for the polarization $[z_{or}(P)]$. The tilt angle β between the $z_{\rm lab}$ axis and the $z_{\rm PAS}$ axis is important.

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A general description of the orientation of an ensemble of spins is given by the orientation tensors $B_k^n(I,t)$ as defined in Refs. [14,15]. Spin polarization is described by the odd tensor components $[B^0_{1,3,\ldots}(I,t=0)_{or_{(P)}}]$ and spin alignment by the even tensor components $[B^0_{2,4,\ldots}(I,t=0)_{or_{(A)}}]$. The higher order tensors have negligible contributions for nuclei with $I<4\hbar$ [16], so here we only consider $B_1^0(I,t=0)_{or_{(P)}}$ and $B_2^0(I,t=0)_{or_{(A)}}$ which are related to $P(t=0)$ and $A(t=0)$ as follows [15,16]:

$$B_1^0(t=0)_{or_{(P)}}=-\sqrt{\frac{3I}{I+1}}P(t=0), \tag{1}$$

$$B_2^0(t=0)_{or_{(A)}}=\frac{\sqrt{5}|\alpha_2(\max)|}{\sqrt{(I(I+1)(2I+3)(2I-1)}}A(t=0), \tag{2}$$

with $\alpha_2(m)=I(I+1)-3m^2$ defined such that $-1\leqslant A\leqslant 1$. For maximal oblate alignment ($A<0$), all nuclei are produced in the lowest $|m\rangle$ state ($m=0$ or $\pm 1/2$) and for maximal prolate alignment ($A>0$) all nuclei are produced in the highest state ($m=I$).

The orientation of the beam is observed in the laboratory frame. By transforming the initial orientation tensors to the laboratory frame, the tensors (B_k^n) with $n\neq 0$ also become nonzero:

$$B_k^n(I,t=0)_{\rm lab}=\sqrt{\frac{4\pi}{2k+1}}e^{+in\gamma}Y_k^n(\epsilon,0)B_k^0(I,t=0)_{or} \tag{3}$$

with the Euler angles [17] ϵ and γ defined as in Fig. 1.

The orientation frame of the polarization has its z axis perpendicular to the reaction plane. In the case where projectile fragments are selected in the horizontal plane at an angle relative to the primary beam axis, the $z_{or_{(P)}}$ axis is in the vertical direction. Consequently, in the case of a β-LMR setup, it coincides (parallel or antiparallel) with the laboratory frame (Fig. 1) so the angle $\epsilon=0°$ or 180°:

$$B_1^0(I,t=0)_{\rm lab}=(+/-)B_1^0(I,t=0)_{or_{(P)}}, \tag{4}$$

$$B_1^{\pm 1}(I,t=0)_{\rm lab}=0. \tag{5}$$

Due to symmetry considerations, the z axis of the orientation frame of an aligned ensemble $[z_{or_{(A)}}]$ of nuclei is oriented parallel to the beam axis. Because the z axis in the laboratory frame is perpendicular to the beam axis, the Euler angles take values $\epsilon=90°$ and $\gamma=0°$. In the particular case where a secondary beam is purified by a mass separator, the angle γ is nonzero, due to the difference between the Larmor frequency and the cyclotron frequency in the dipole magnets [1]. The transformation of the alignment tensor components can be written as follows:

$$B_2^0(I,t=0)_{\rm lab}=\sqrt{\frac{4\pi}{5}}Y_2^0(90°,0°)B_2^0(I,t=0)_{or_{(A)}}, \tag{6}$$

$$B_2^{\pm 1}(I,t=0)_{\rm lab}=0, \tag{7}$$

$$B_2^{\pm 2}(I,t=0)_{\rm lab}=\sqrt{\frac{4\pi}{5}}e^{\pm i2\gamma}Y_2^{\pm 2}(90°,0°)B_2^0(I,t=0)_{or_{(A)}}. \tag{8}$$

III. PERTURBING THE INITIAL ORIENTATION BY β-LEVEL MIXING

A. The Hamiltonian

The level mixing formalism is based on the combination of two static interactions: an electric quadrupole [interaction of the nuclear quadrupole moment with the electric field gradient (EFG) of the host] and a magnetic dipole interaction (interaction of the nuclear magnetic moment with the magnetic field at the position of the nucleus). The Hamiltonian of an ensemble of nuclei with spin I, submitted to an axially symmetric EFG (V_{zz}) and a static magnetic field B_0, can be written in the principal axis system [(PAS), Fig. 1] of the EFG as

$$\mathcal{H}_{\rm LMR}=\mathcal{H}_Q+\mathcal{H}_B \tag{9}$$

$$=\frac{\omega_Q}{\hbar}(3I_z^2-I^2)-\omega_B I_z\cos\beta+\omega_B I_x\sin\beta, \tag{10}$$

where $\omega_B=g\mu_N B_0/\hbar$ is the magnetic interaction frequency, $\omega_Q=eQV_{zz}/\hbar 4I(2I-1)$ is the quadrupole interaction frequency, Q is the spectroscopic quadrupole moment, and β is the tilt angle between V_{zz} and B_0 (Fig. 1). When $\beta=0°$, i.e., when the orientation of the EFG coincides with the magnetic field, the Hamiltonian is axially symmetric ($\omega_B I_x\sin\beta=0$) in the PAS frame and the eigenstates ($|m>$) are fully determined by the magnetic quantum number m (the projection of $\vec{I}$ on the $z_{\rm PAS}$ axis).

For a small tilt angle β, the last term in the Hamiltonian ($\omega_B I_x\sin\beta$) can be considered as a perturbation. This causes a breaking of the axial symmetry, giving rise to a two-level-mixing interaction in the first order perturbation theory [18]. It induces mixing of the level populations of the crossing states $|m\rangle$ and $|m'\rangle$ at the crossing field, which occurs if $\omega_B=3(m+m')\omega_Q\cos\beta$ [19,20]. The level mixing is seen as a repelling of the two respective hyperfine m-quantum states. The mixing of the level populations results in a resonant change of the β-asymmetry around the mixing field values. The position of the resonances is dependent on the ratio of the nuclear moments of the nucleus and the amplitude is dependent on the initial orientation. Analytic expressions for the mixed eigenstates, calculated in a two level-mixing approximation using the quasidegenerate perturbation theory [18], are given in Refs. [1,2,19].

B. The angular distribution in β-LMR

The resonant change of the initial spin orientation can be measured by the radioactive decay distribution. The time integrated angular distribution of the decay of the perturbed nuclear system can be calculated explicitly [14,15]:

$$W(\theta,\phi,\tau)=\sqrt{4\pi}\sum_{k,n}A_kB_k^n(I,\tau)_{\rm lab}Y_k^n(\theta,\phi). \tag{11}$$

The angular distribution contains information on the type of detected radiation ($\beta,\gamma,\ldots$) via the radiation parameters A_k, on the position of the detectors with respect to the laboratory frame via the spherical tensors $Y_k^n(\theta,\phi)$, and on the perturbed spin orientation via the orientation tensors $B_k^n(I,\tau)$.

The measured quantity in a β-LMR experiment is the asymmetry of the β decay as a function of the externally applied magnetic field B using $As(B)=[1-R(B)]/[1+R(B)]$ with $R(B)=W(0°,\tau)/W(180°,\tau)$. $W(0°,\tau)$ and $W(180°,\tau)$ are, respectively, the time integrated β-intensity emitted parallel and antiparallel with respect to the magnetic field orientation. The measured asymmetry reduces to

$$As(B)=-A_1B_1^0(I,\tau)_{\rm lab}. \tag{12}$$

The orientation tensor $B_1^0(I,\tau)_{\rm lab}$ can be written as a function of the initial orientation $B_k^n(I,t=0)_{\rm lab}$ and the perturbation factors $G_{kk'}^{nn'}(I,\mathcal{H}_{\rm LMR},\tau)_{\rm lab}$:

$$B_k^n(I,\tau)_{\rm lab}=\sum_{k',n'} G_{kk'}^{nn'}(I,\mathcal{H}_{\rm LMR},\tau)_{\rm lab}B_{k'}^{n'}(I,t=0)_{\rm lab}. \tag{13}$$

The perturbation factors contain all interaction parameters, such as quadrupole frequency, magnetic moment, spin, lifetime, etc., and are extensively described in Ref. [19].

In a β-LMR experiment only $B_1^0(I,t=0)_{\rm lab}$, $B_2^0(I,t=0)_{\rm lab}$, and $B_2^{\pm 2}(I,t=0)_{\rm lab}$ are nonzero, including the transformation of the orientation tensors from the orientation to the laboratory frame, and we can explicitly write Eq. (12) as

$$\begin{aligned} As(B)=&-A_1B_1^0(I,t=0)_{or_{(P)}}G_{11}^{00}(I,\mathcal{H}_{\rm LMR},\tau)\\ &-A_1B_2^0(I,t=0)_{or_{(A)}}\left[-\frac{1}{2}G_{12}^{00}(I,\mathcal{H}_{\rm LMR},\tau)\right.\\ &\left.+\sqrt{\frac{3}{8}}G_{12}^{0\pm 2}(I,\mathcal{H}_{\rm LMR},\tau)e^{\pm i2\gamma}\right]. \end{aligned} \tag{14}$$

The first term of Eq. (14) contains the perturbation factor G_{11}^{00} which causes the breakdown of initial polarization: $As_{(P)}(B)$, and the second term contains the perturbation factors G_{12}^{00} and $G_{12}^{0\pm 2}$ which causes the transfer of initial alignment into polarization $As_{(A)}(B)$

$$As(B)=As_{(P)}(B)+As_{(A)}(B). \tag{15}$$

Each of the terms consists of three factors determining the amplitude of the resonance: the radiation factor (A_1), the orientation factor ($B^0_{1\text{ or }2}$), and the hyperfine interaction factor (or perturbation factor).

The perturbation factors are a function of the magnetic to the quadrupole interaction frequency ratio, the nuclear spin, lifetime, and the tilt angle β [19]. For the noncollinear case ($\beta\neq 0$), and if the energy difference between the mixing states is larger than their natural linewidth, the perturbation factors reduce to pure Lorentz absorption or Lorentz dispersion resonances [1,19]

$$G_{11}^{00}(I,\mathcal{H}_{\rm LMR},\tau)=1+\frac{1}{2}\sum_i g_{11}^i(L)\mathbf{L}_i, \tag{16}$$

$$G_{12}^{00}(I,\mathcal{H}_{\rm LMR},\tau)=\frac{1}{2}\sum_i g_{12}^i(L)\mathbf{L}_i, \tag{17}$$

$$G_{12}^{02}(I,\mathcal{H}_{\rm LMR},\tau)=\frac{1}{2}\sum_{i(\Delta m=2)} g_{21}^{i(\Delta m=2)}(D)\mathbf{D}_i. \tag{18}$$

The geometrical factors $g_{kk'}$ determine the amplitude of the resonance and are sums over Wigner $3J$ symbols. The amplitude of the resonances is fully determined by the geometrical factors $g_{kk'}$ (sums over Wigner $3J$ symbols [19]), the nuclear spin and the order of the perturbation, but independent on the nuclear moments.

As the $\mathbf{L}_i$ and $\mathbf{D}_i$ resonances are approaching zero, the β asymmetry at nonresonant fields is sensitive to the initial polarization ($G_{11}^{00}=1$) but not to the initial alignment ($G_{12}^{00}=G_{12}^{0\pm 2}=0$). At resonant fields, an amount of the initial polarization will be destroyed and from the initial alignment, an amount of secondary polarization will be created.

Particularly interesting is the influence of inverting the magnetic field on the amplitude of the resonance. Due to the inverted field the sign of the mixing levels changes. This exerts no influence on the Lorentz absorption resonance $\mathbf{L}_i$ but it changes its amplitude $g_{kk'}(L)$ by a factor $(-)^{(k+k')}$. For a Lorentz dispersion resonance, changing the sign of the mixing levels changes $\mathbf{D}_i$ by a factor $(-)^{(\Delta m-1)}$ and $g_{kk'}(D)$ by a factor $(-)^{(k+k')+(\Delta m-1)}$ [17,19]. Consequently Lorentz absorption and dispersion resonances will only change sign by inverting the field if $(k+k')$ is an odd number. Therefore a resonance originating from the initial polarization ($k=k'=1$) will not change sign by inverting the field and a resonance originating from the initial alignment ($k=1$, $k'=2$) will change sign by inverting the field

$$As_{(P)}(B)=As_{(P)}(-B), \tag{19}$$

$$As_{(A)}(B)=-As_{(A)}(-B). \tag{20}$$

Having a mixed initial orientation, dependent on the sign of the field, the resonant effect from the initial polarization and the initial alignment will add up or cancel out. This characteristic feature of β-LMR makes it possible to deduce both the initial alignment and the initial polarization by measuring the resonances at positive and negative field

$$\begin{aligned} \frac{As(B)+As(-B)}{2}=As_{(P)}(B)=&-A_1B_1^0(I,t=0)_{or_{(P)}}\\ &\times G_{11}^{00}(I,\mathcal{H}_{\rm LMR},\tau) \end{aligned} \tag{21}$$

$$\frac{As(B)-As(-B)}{2}=As_{(A)}(B)=-A_1B_2^0(I,t=0)_{or_{(A)}}\times\left[-\frac{1}{2}G_{12}^{00}(I,\mathcal{H}_{\mathrm{LMR}},\tau)+\sqrt{\frac{3}{8}}G_{12}^{0\pm2}(I,\mathcal{H}_{\mathrm{LMR}},\tau)e^{\pm i2\gamma}\right]. \tag{22}$$

From the sum of the resonances measured, the resonance originating from the initial polarization ($B_{1_{or}}^0$) is obtained, while the subtraction of these resonances gives a resonance due to the initial alignment ($B_{2_{or}}^0$). In the ideal case where the asymmetry parameter A_1 is known or can be calculated, the initial orientation can be deduced from the amplitudes of Eqs. (21) and (22).

Unfortunately several effects can give rise to a reduction of the measured polarization: the geometrical limitations of the setup, scattering of β particles in the crystal, implantation behavior of the nuclei in the crystal, relaxation of the orientation in the host material, and background radiation coming from β decay of contaminating and/or daughter nuclei. Thus the measured values will always provide a lower limit to the real orientation produced in the reaction. To some extent it is possible to take these effects into account.

The reduction due to the detection solid angle can be calculated and is called the Q_k factor which is added to the angular distribution [21]. The loss due to scattering can be simulated, knowing the energy of the β decay, the properties of the crystal and the experimental setup, using the GEANT code [22]. The GEANT calculation also includes the geometrical reduction.

As the quadrupole frequency is a product of the quadrupole moment and the electric field gradient, it is important to implant the nuclei in a correct site in the crystal where the nuclei experience this EFG. If this is not the case, the electric field gradient changes and gives rise to a resonance at a different position or no resonance at all. The β radiation coming from the fraction of nuclei implanted in a wrong site is the most difficult to account for. To avoid this, the choice of the crystal will be dependent on what is known of the implantation behavior of the impurity-host combination in solid state literature.

Several processes can be the cause of losses via relaxation [23–25]. The spin-lattice relaxation time is dependent on the impurity-host combination. For impurities implanted in metals, the relaxation is mainly of the Korringa-type and the time constant is measured for many impurity-host combinations [7,26,27]. In this case the reduction often can be taken into account. The best case is to implant the nuclei in an insulator: without free electrons the relaxation time is long and relaxation effects can be neglected [27].

Another possible cause of reduced measured polarization is the presence of other β-decaying nuclei in the selected secondary beam, either contaminants or daughter nuclei. If the Q_β of the contaminating β decay is significantly smaller than the Q_β of the nuclei of interest, this influence can be reduced with an energy selection in the β spectrum. If not, the β's will overlap in the spectra and form a constant background. If the amount of contamination is known, which is usually the case, it can also be taken into account.

In the case of the projectile-fragmentation reaction, a variety of isotopes with a mass equal or below the mass of the primary beam are produced. Performing a β-LMR, aiming to measure the orientation, fragments will be selected with characteristics to reduce the possible losses as much as possible (known asymmetry parameter, short lifetime, higher Q_β, no daughter decay, etc.), and it is important to incorporate all possible losses in the final result.

IV. SIMULATIONS AND DISCUSSION

Several simulations were made, computing the perturbation factors by expressing the interaction Hamiltonian in the laboratory frame and diagonalizing it numerically [28]. The effect on the amplitude of the resonance due to a combination of an initially spin-aligned and spin-polarized ensemble of nuclei is shown. We consider an ensemble of nuclei with spin $I=2$, $B_1^0(I,t=0)_{or_{(P)}}=0.2$ ($P=-14\%$), and $B_2^0(I,t=0)_{or_{(A)}}=0.2$ ($A=17\%$) and simulate the change of the asymmetry $[As(B)]$ of the ensemble of nuclei due to the level mixing interactions as a function of the applied magnetic field. In Figs. 2(a)–2(c), we present the change in asymmetry induced by the initial alignment $[As_{(A)}(B)]$, by the initial polarization $[As_{(P)}(B)]$, and the combined result $[As(B)]$ for ^{14}B: [$I^\pi=2^-$, $t_{1/2}=12.8$ ms, $Q_\beta=20.62$ MeV, $\mu=1.184\mu_N$ [5], $\nu_Q(\mathrm{Mg})=106$ kHz [29]]. A radiation parameter $A_1=-0.7$ was assumed. For these simulations an angle $\beta=6°$ is chosen. In Fig. 2(a) we demonstrate that by inverting the sign of the magnetic field, the transfer of alignment into polarization is such that the created polarization changes sign but the amplitude stays constant. In Fig. 2(b) the breakdown of polarization is shown and inverting the field has no influence on the resonances. In Fig. 2(c) an ensemble of nuclei with an initial amount of polarization and alignment is presented. Due to the combination of spin orientations one observes that, for one direction of the field, the breakdown of polarization and the created polarization reinforce each other, while for the other field direction, they cancel each other out. When performing a β-LMR experiment on an ensemble of nuclei with both spin-alignment and spin-polarization components it is very important to measure the asymmetry for both positive and negative fields, as it is possible to miss the resonance in one of the field directions.

To study the spin orientation it is necessary to measure the resonant change of the asymmetry in both directions of the field. Subtracting or adding the resonances will give respectively the change in β asymmetry due to the initial spin alignment and initial spin polarization.

V. TEST EXPERIMENT ON ^{12}B

The feasibility to measure spin orientation using the LMR method is demonstrated using ^{12}B nuclei implanted in a Mg single crystal. The experiment was conducted at the Van de Graaf accelerator at the Laboratoire d' Analyze par Réac-

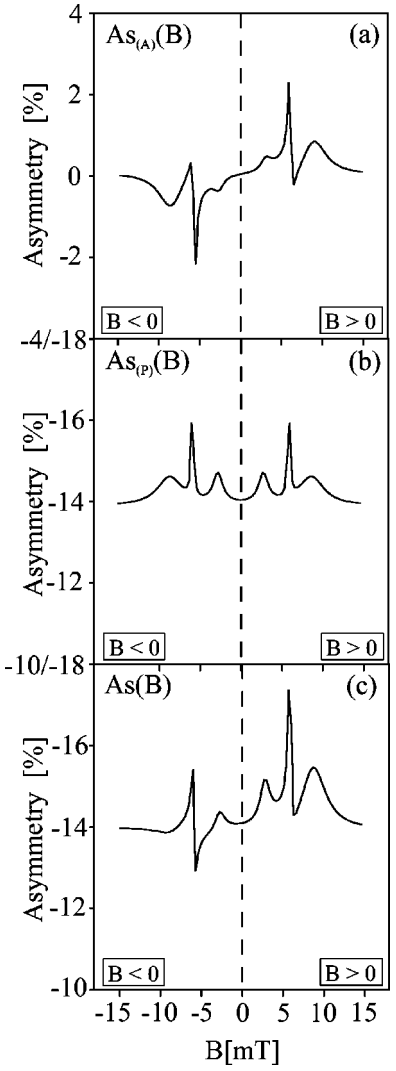

FIG. 2. Simulations for a β-LMR of ^{14}B(Mg): (a) the asymmetry due to the transfer of initial alignment into polarization $[B_1^0(I,t=0)]_{or}=0.0$, $B_2^0(I,t=0)_{or}=0.2$, (b) the asymmetry as a function of the applied field due to the breakdown of initial polarization $[B_1^0(I,t=0)]_{or}=0.2$, $B_2^0(I,t=0)_{or}=0.0$, (c) the combined asymmetry $[B_1^0(I,t=0)_{or}=0.2$, $B_2^0(I,t=0)_{or}=0.2]$. All simulations are made for positive and negative fields.

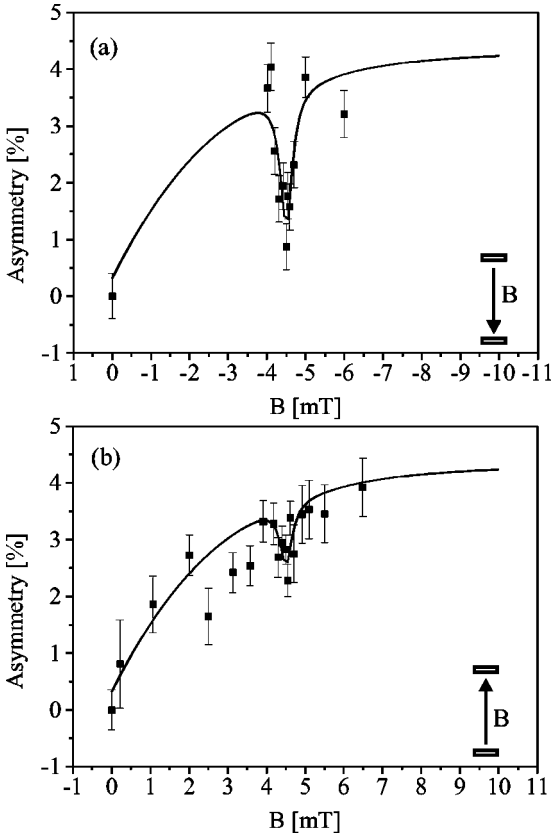

FIG. 3. A β-LMR measurement on ^{12}B(Mg) for two opposite field directions (the tilt angle β is put at 1.5°): (a) the β asymmetry of the ^{12}B nuclei implanted in a Mg single crystal is shown as a function of negative magnetic fields and (b) for positive fields. Both curves are fitted with a decoupling curve and a Lorentz absorption resonance. The difference in amplitude between the resonance at negative field and the resonance at positive field is related to the spin alignment of the nuclear ensemble.

tions Nucléaires (LARN) of the University of Namur. The experimental details are published in Ref. [2] and only relevant information concerning the extraction of the spin-aligned and spin-polarized component will be given here.

The ^{12}B nucleus has been used as a test case for many experiments involving β decay, because its nuclear ground-state properties are well known [$I^{\pi}=1^+$, $T_{1/2}=20.20$ ms, $Q_{\beta}=13.4$ MeV, $\mu=1.00306\mu_N$, ν_Q(Mg) $=46.5$ kHz] [30,31]. The β decay is a pure Gamow-Teller transition ($1^+\rightarrow 0^+$) so it has a maximum asymmetry parameter $A_1=+0.816$, meaning that the β decay from a polarized ensemble of ^{12}B nuclei will be highly asymmetric with respect to an applied holding field. The nuclei were produced by directing a deuteron beam of 1.5 MeV onto a ^{11}B target (90 mg/cm^2 on a gold backing of 25 μm [32]). The nuclei, which were ejected from the target at an angle of 45° with respect to the beam direction were selected. This selection results in a maximum polarization [33], accompanied by some amount of alignment [34].

After the production and selection, the ^{12}B nuclei were recoil implanted into a Mg single crystal. The implantation behavior of ^{12}B(Mg) is well known [31,35] and the spin-lattice relaxation is of the order of 0.1 s [36]. None of these will induce a significant reduction of the measured polarization. The Mg single crystal has a hexagonal closed packed (hcp) structure. The principal axis of the crystal was oriented at an angle $\beta=1.5(5)°$ with respect to a static magnetic field axis. All measurements were performed at room temperature. Two sets of β telescopes, one at 0° and the other at 180° with respect to the magnetic field axis, were mounted inside the vacuum chamber. The change in β asymmetry was monitored using the upper to lower detector counting ratio. Experimental asymmetries were normalized to the ratio at zero field ($B_0=0$), where no spin orientation is present due to small perturbing electric fields which will be decoupled at larger magnetic field values.

A LMR measurement in both directions of the field has been performed. The β asymmetry [Eq. (15)] of the ^{12}B

nuclei implanted in Mg is shown as function of negative magnetic fields in Fig. 3(a) and as function of positive fields in Fig. 3(b). In both cases we see the asymmetry growing with increasing external field until saturation is reached. We see clearly a resonance occurring on top of the decoupling curve at 4.5 mT, with a larger amplitude for negative fields than for positive fields. As described above, it is possible to derive the spin polarization and the spin alignment from the two resonances. We found a measured polarization $P_{\mathrm{meas}}=-4.6(1.2)\%$ and a measured alignment $A_{\mathrm{meas}}=-2.8(1.3)\%$. For this experiment, the decrease in the measured orientation comes from the scattering of the β particles in the crystal and the geometrical limitations which is calculated with the GEANT code [a reduction of 14(1)%]. Taking this into account we find a deduced polarization $P_{\mathrm{ded}}=-5.2(1.6)\%$ and a deduced alignment $A_{\mathrm{ded}}=-3.6(1.8)\%$. This experiment provides a clear indication for the feasibility to measure the spin orientation by means of the β-LMR method.

VI. CONCLUSIONS

We have developed the β-LMR formalism to be able to deduce the spin-alignment and the spin-polarization component of the orientation of a nuclear ensemble. We have shown with simulations and a test experiment that by inverting the magnetic field in a β-LMR measurement, it is possible to deduce the initial spin alignment as well as the initial spin polarization of an ensemble of nuclei.

The next step of these studies will be to perform a series of β-LMR experiments on nuclei produced in a projectile fragmentation reaction, for which the nuclear moments and solid state properties are known, which will provide us the possibility to study systematically the spin orientation created in the reaction. Such a study is needed in order to be able to understand and predict the expected amplitude and sign of the resonance in a β-LMR experiment which would make the measurement of unknown nuclear moments of exotic nuclei more feasible.

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