PolarEx, A FUTURE FACILITY FOR ON-LINE NUCLEAR ORIENTATION AT ALTO MULTIPOLARITY MIXING RATIO DATA ANALYSIS*

R. Thoër, C. Gaulard, S. Roccia

CSNSM, Université Paris Sud, CNRS/IN2P3, Université Paris Saclay
Orsay, France

F. Ibrahim, F. Le Blanc, D. Verney

IPN Orsay, Université Paris Sud, CNRS/IN2P3, Université Paris Saclay
Orsay, France

(Received December 12, 2018)

Low Temperature Nuclear Orientation (LTNO) experiments can probe magnetic properties of nuclei. The presence of PolarEx at the ALTO facility allows to perform these kind of on-line experiments with neutron rich beams. This paper presents the formalism of the LTNO technique and the set-up of PolarEx. It focuses on the analysis process for multipolarity mixing ratio extraction.

DOI:10.5506/APhysPolB.50.591

1. Introduction

In a nucleus, the multipole mixing ratio δ for a given gamma-ray transition is proportional to the ratio of two multipolarity matrix elements for this transition (*e.g.* E2/M1). Therefore, it gives a direct access to information about both the electric and magnetic properties, and about reduced transition probabilities B[E(M)L]. In this way, the δ value broadens our knowledge about nuclear level structure and transition properties [1].

Experimentally, the mixing ratio can be derived from angular distribution measurements using the Low Temperature Nuclear Orientation (LTNO) technique. One can measure such a distribution from an oriented nucleus, strongly improving the sensitivity. When it is coupled to On-Line implantation of radioactive beam, it becomes a powerful tool for such studies. At

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

Orsay, the PolarEx (Polarization of Exotic nuclei) set-up is being installed at the ALTO facility [2] and it will give access to On-Line Nuclear Orientation of neutron rich nuclei. Thus, with its versatility, PolarEx is perfectly adapted to study the nuclear interaction and, moreover, it gives direct access to nuclear magnetic moments and hyperfine magnetic fields.

In this paper, we focus on the analysis methods to extract δ values from data obtained with LTNO experiments, and we discuss the complementarity of the two methods.

2. Low Temperature Nuclear Orientation

When a nucleus has a non-zero spin $\vec{I}$, it has a magnetic moment $\vec{\mu}$ which interacts with a magnetic field, $\vec{B}$, through the Hamiltonian

$$\mathcal{H} = -\vec{B} \cdot \vec{\mu} = -\mu_{\mathrm{N}} g \vec{B} \cdot \vec{I}, \tag{1}$$

where μ_{N} is the nuclear magneton and g the gyromagnetic factor. The eigenvalues of the Hamiltonian are the energy levels $E_m = -gBm\mu_{\mathrm{N}}$, where m is the eigenvalue of the spin projection. One can see in Fig. 1 that the interaction with a magnetic field produces a Zeeman splitting which lifts the nuclear spin degeneracy. These sub-levels are populated with respect to the Boltzmann distribution

$$p(m) = \frac{e^{\frac{-E_m}{kT}}}{\sum\limits_m e^{\frac{-E_m}{kT}}}, \tag{2}$$

where $p(m)$ is the population of the sub-level m, k the Boltzmann constant and T the temperature. Under normal conditions, the thermal energy is much higher than the energy difference between sub-levels ($E_m \ll kT$). As a result, the sub-levels are nearly equally populated and the nucleus is non-oriented (Fig. 1, left). By decreasing the temperature to a value close to the energy difference between sub-levels ($E_m \simeq kT$), the populations become different for each sub-level. The nucleus is thus oriented (Fig. 1, right).

In LTNO experiments, the anisotropic decay products of the oriented nucleus of interest is observed and described by the angular function $W(\theta)$.

Considering a gamma emission detected at angle θ with respect to the polarisation direction, the anisotropy is described by the ratio between the number of gamma detected when the nucleus is oriented (N_{cold}) and when it is non-oriented (N_{warm}). Experimentally, the angular distribution is given by $W(\theta) = \frac{N_{\mathrm{cold}}(\theta)}{N_{\mathrm{warm}}(\theta)}$.

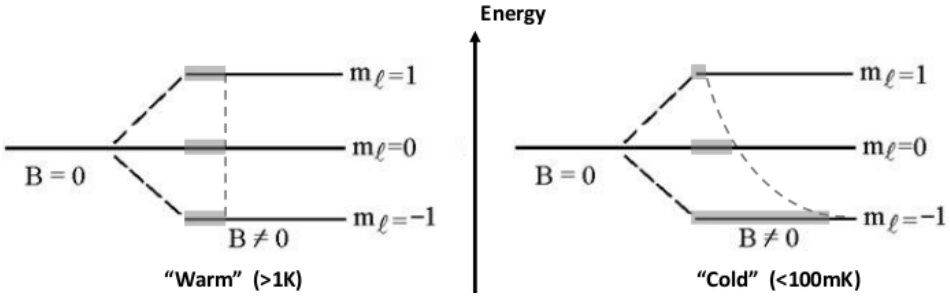
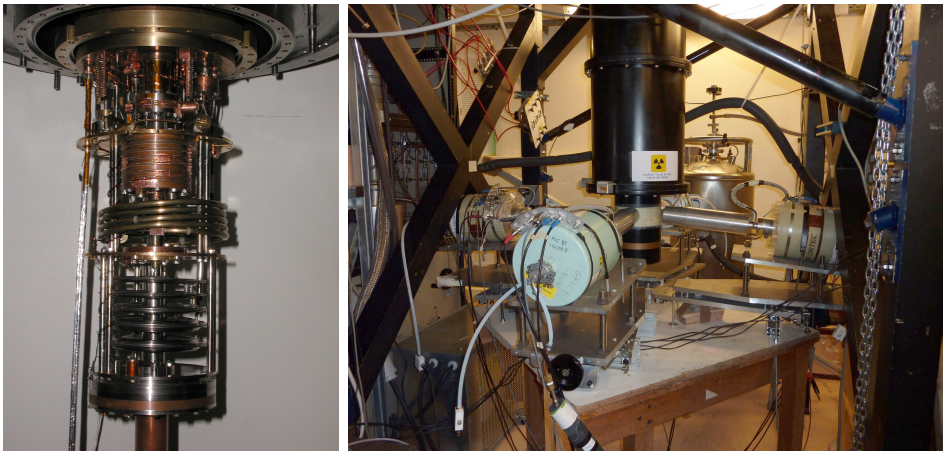


Fig. 1. Population evolution following a Boltzmann distribution for the case $I = 1$. On the left-hand side, the nucleus is non-oriented (warm), and on the right-hand side, the nucleus is oriented (cold).

3. PolarEx set-up

The very low temperatures needed to measure the angular distribution $W(\theta)$ of a sample, are achieved with a ^{3}He–^{4}He dilution refrigerator (Fig. 2 (a)). Its power ranges from 20 μW at 25 mK to 2 μW at 10 mK. It can lower the thermal energy to 7 mK to orient the nuclei, and it cools a magnet to reach its superconducting phase.



(a) The dilution unit (b) The cryostat and detection system

Fig. 2. The PolarEx experiment.

The nuclei are implanted into a ferromagnetic material fixed on a "cold finger" located at the center of the magnet. This magnet is made of multifilamentary niobium–titanium wires. It is designed in a symmetrical holed cube shape to reduce possible systematic effects. The applied magnetic field (0.5–1 T) magnetizes the ferromagnetic foil. The alignment of all the fer-

romagnetic hosts creates a very high hyperfine magnetic field (10–100 T). The effective magnetic field felt by the nuclei is the sum of the applied field and the hyperfine induced one.

The cold sample is surrounded by four HPGe detectors disposed at right angle on a horizontal plane in order to detect the gamma emission (Fig. 2 (b)). This number of HPGe detectors could be increased up to eight. It is also possible to add particle detectors inside the cryostat, providing the great versatility of PolarEx.

The PolarEx set-up is located at the ALTO facility and is currently operating off-line (sample top loaded into the cryostat). Meanwhile, the beam line connecting PolarEx to ALTO is under construction and will be ready by the end of 2019 to perform On-Line experiments (the nuclei are directly implanted into the cryostat from the bottom up). The coupling of PolarEx with ALTO will open a wide range of studies of neutron rich nuclei.

In the next section, we will describe how the angular distribution $W(\theta)$ measured with PolarEx can be used to extract the multipole mixing ratio δ.

4. Data analysis methods for multipole mixing ratio computation

The angular distribution shown in Section 2 can also be formally expressed as

$$W(\theta) = 1 + \sum_{\lambda} f B_{\lambda}(I_0) U_{\lambda} Q_{\lambda} A_{\lambda} P_{\lambda}(\cos\theta)\,, \tag{3}$$

where $P_{\lambda}(\cos\theta)$ is the Legendre polynomial, I_0 the nuclear spin of the parent nucleus, Q_{λ} the correction factor for the solid angle of the detector (close to unity) and f the fraction of nuclei that experience the hyperfine field.

The orientation parameters B_{λ} describe the orientation of the parent nuclear state, and they are proportional to the density matrix elements $\langle I_0 m|\,\rho\,|I_0 m'\rangle = p(m)\delta_{mm'}$. They are temperature-dependent since $p(m)$ is the population given by equation (2).

U_{λ} are the deorientation coefficients, taking into account the deorientation due to unobserved transitions. The state of interest of the daughter nucleus is usually less oriented than the parent because the nuclear transitions populate in a similar way all the daughter nucleus sub-levels. For each unobserved transition occurring between the initial state I_0 of the parent nucleus and the one of interest, there are corresponding coefficients U_{λ} that take this deorientation effect into account. They depend on the multipolarity of the transition and of the spins of the intermediate states involved. Thus, the calculation of the U_{λ} coefficients requires the knowledge of all spins, multipolarity mixing ratios and branching ratios of the feeding transitions. We will describe how these limitations can be overcome later.

The angular distribution coefficients A_λ describe the radiation asymmetry of the observed transition. They only depend on the spins of the initial and final states involved (I_i and I_f) and on the multipolarity of the studied transition. In the case of a pure transition of multipole order L, these coefficients simply reduce to

$$A_\lambda = F_\lambda(L, L, I_\mathrm{f}, I_\mathrm{i})\,, \tag{4}$$

elseways, if there is a mixing of multipolarity with a ratio δ, the A_λ coefficients become

$$A_\lambda = \frac{F_\lambda(L, L, I_\mathrm{f}, I_\mathrm{i}) + 2\delta F_\lambda(L, L', I_\mathrm{f}, I_\mathrm{i}) + \delta^2 F_\lambda(L', L', I_\mathrm{f}, I_\mathrm{i})}{1+\delta^2}\,, \tag{5}$$

where the F coefficients are known from the appendix of [3]. The mixing ratio δ is defined as the ratio of the reduced matrix elements $\delta = \frac{\langle I_\mathrm{f}|O(\sigma' L')|I_\mathrm{i}\rangle}{\langle I_\mathrm{f}|O(\sigma L)|I_\mathrm{i}\rangle}$ with $L' = L+1$, and σ stands for electric or magnetic transition. Therefore, in order to extract the δ value of a particular transition, one needs to determine the angular distribution parameters A_λ that can be obtained by two methods (temperature-dependent and independent) as described in the following.

The first method (temperature-dependent) is straightforward. To extract A_λ, one needs to measure the angular distribution $W(\theta)$ and to compute all the parameters of equation (3). However, there are two drawbacks: the precision on δ will depend on the measurement of the temperature, and all the U_λ need to be calculated, which implies that the spin and the multipolarities of each state involved need to be known. To overcome these issues, we can use the same method as Fox *et al.* [4], which is temperature-independent, as described in the following.

By expanding equation (3) for two angles (0 and $\pi/2$) and assuming that B_λ, A_λ , U_λ and Q_λ are independent of the angle, it leads to

$$A_2 \;=\; \frac{\frac{3}{8}[1-W(0)] + [W(\pi/2)-1]}{-\frac{7}{8}B_2 U_2 Q_2}\,. \tag{6}$$

If we consider a second transition (with its own A'_2 and A'_4) emitted by the same level, then the B'_2, U'_2 and Q'_2 are the same as B_2, U_2 and Q_2. We thus obtain a simplified ratio of the A_2s

$$\frac{A_2}{A'_2} \;=\; \frac{\frac{3}{8}[1-W(0)] + [W(\pi/2)-1]}{\frac{3}{8}[1-W'(0)] + [W'(\pi/2)-1]}\,. \tag{7}$$

Similar expressions for A_4 and A'_4 can be obtained. Thus, it is possible to determine A_λ ratios as a function of measured quantities only. Then,

if one of the two transitions has a pure multipolarity, its A_λ only reduce to $F_\lambda(L, L, I_\mathrm{f}, I_\mathrm{i})$ (Eq. (4)) and the unknown A'_λ can be easily computed (Eq. (7)). Consequently, the δ value can be obtained thanks to equation (5). This approach leads to a measurement of A_λ and to a determination of δ independently of the temperature, without a complete knowledge of the level scheme. This is true for two gammas of similar energy. However, if the energies are different, the two geometrical factors Q_λ and Q'_λ are also different, and they will be included in the previous expression (Eq. (7)) as shown in [5].

5. Ongoing analysis

These analysis methods have been first tested on ^{57}Fe: its 122 keV γ transition has a very well known mixing ratio value [4]. The two techniques previously explained to extract δ are in good agreement and they both reproduce very well the existing data. This leads us to define the sensitivity of PolarEx and to get confidence in these analysis processes.

These analysis methods were also used to study ^{56}Fe for which mixing ratios are well-known, badly known or still unknown [6]. With our analysis, we have reproduced existing mixing ratios, have improved the precision of some of them, and have measured new δ values. This analysis is still ongoing, and the results will be published soon.

6. Conclusion

In the present paper, we have shown that the LTNO technique combined with PolarEx is well-suited for precise measurements of multipolarity mixing ratio. Two methods of analysis have been tested on ^{56,57}Fe.

With the radioactive beams of ALTO, we will be able to study neutron-rich nuclei, and we plan to focus on these nuclei around $N = 50$ and $N = 82$ regions, where there are missing important information. The characterization of the $N = 50$ shell gap and its evolution with large neutron excess is a major challenge for the nuclear structure community.

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