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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

(Following HIE-ISOLDE Letter of Intent I-124)

Nuclear-moment studies in the odd-mass In isotopes up to N=82 using the Tilted Foils technique

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Abstract

We propose to study the magnetic moments of the neutron-rich odd-even In isotopes up to N=82 using the Tilted Foils technique and the recently installed beta-NMR setup at REX-ISOLDE. With only one proton hole in Z=50 and a neutron number approaching N=82, the indium isotopes should be a very good test ground for the extreme single-particle approximation and could provide essential data for tuning the nuclear interaction in the vicinity of the doubly-magic ^{132}Sn. Moments of single-particle states adjacent to closed shells are also crucial to determine the corrections to the M1 operator from core polarization and meson exchange effects. In addition to the $9/2^+$, presumed to be of pure single proton hole configuration, the $1/2^-$ isomeric states should shed light on a recent hypothesis of low-energy vibration/collectivity in the region. The detailed study of the Tilted Foils technique at higher masses is of crucial importance for its application for further g-factor studies and for the production of post-accelerated radioactive beams in light of the HIE-ISOLDE letter of Intent I-124.

Requested shifts: 22
Beamline: 2nd beamline

1. Physics motivation

The electromagnetic moments of the neutron-rich indium isotopes, directly below the doubly magic ^{132}Sn, have never been studied. With only one hole in the Z=50 shell and a neutron number approaching N=82, the indium isotopes should be less susceptible to collective effects. Consequently, they are expected to reveal details of the nuclear structure in the scope of the spherical shell model. Indeed the odd isotopes in the range $^{105-127}$In all have $9/2^+$ ground states. The magnetic moments of the isotopes in the range $^{111-127}$In are nearly constant around 5.5 μ_N [Ebe87] (see Fig. 1). These are in close proximity of the Schmidt value for a proton hole in the $g_{9/2}$ orbital at 6.8 μ_N, which probably reflects the fact that at Z=49 the proton distribution is already settled and therefore rigid against core polarization effects as a function of the increasing neutron number. A slight increase of the magnetic moments , going closer to the Schmidt limit, is observed for the ground states of $^{105-109}$In when approaching the N=50 shell closure. A similar effect, if observed for ^{129}In and ^{131}In, could be a direct indication about the robustness of the N=82 closure.

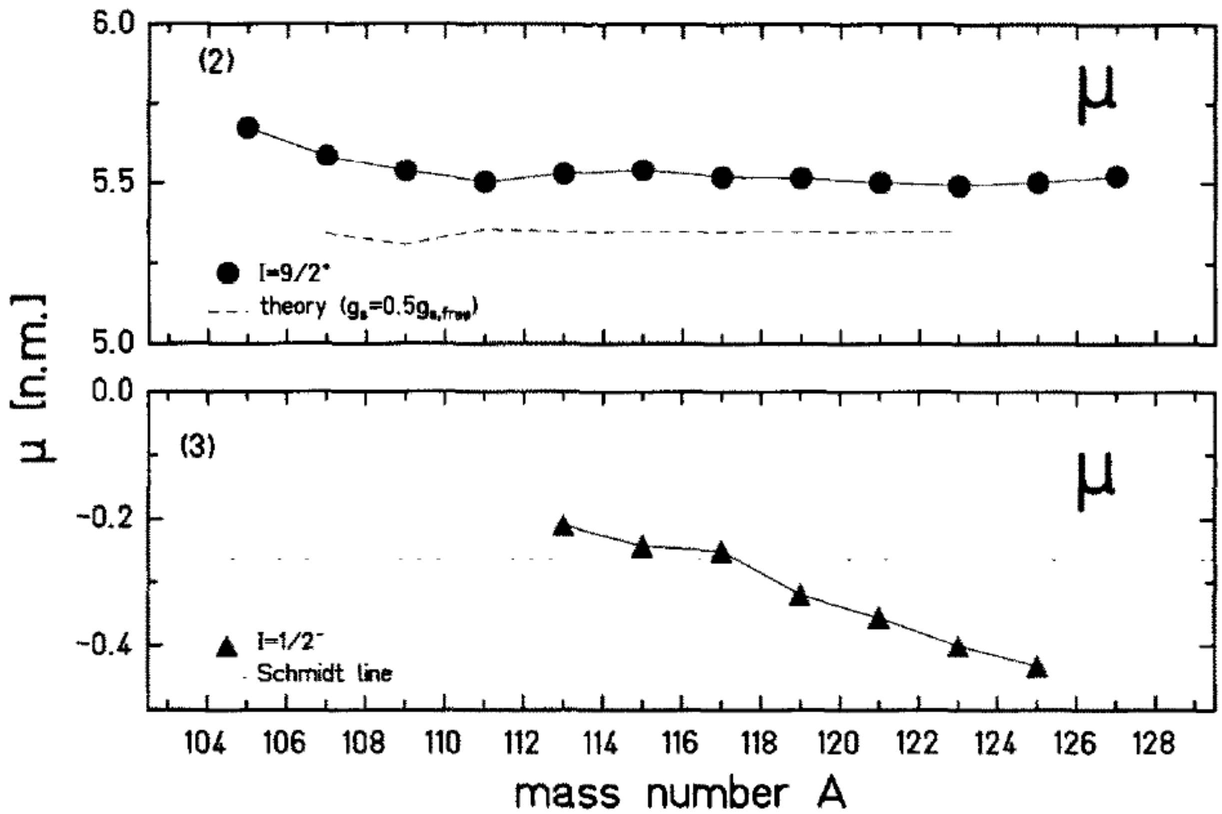

Fig. 1. Nuclear moments of the $9/2^+$ ground state (upper part) and the $1/2^-$ (isomeric state) of the odd-mass In isotopes. Figure from [Ebe87]

A prominent feature of the odd indium isotopes is the presence of $1/2^-$ states at about 300 keV excitation energy. As there is a parity change and a large difference in angular momentum with respect to the ground state, these are long-lived isomers, which, in the very neutron-rich cases, are purely beta decaying. As such they are suitable for study directly by the NMR method on polarized beams. These isomers have been populated in the fission reactions of uranium, induced by the 600 MeV protons from the SC driver on a uranium-carbide target, as well as in thermal-neutron induced fission on ^{235}U targets. The yield of these $1/2^-$ isomers is about 1/10 of the intensity of the ground states. They are expected to be populated also in the current ISOLDE configuration using 1.4GeV proton beam from the PSB with a similar ground-state vs. isomeric-state ratio. The structure of the $1/2^-$ isomers is quite intriguing as their magnetic moments, in contrast to the ground states, show a prominent and surprising variation [Ebe87].

They cross the $\pi(p_{1/2})$ Schmidt limit -0.26 μ_N at ^{117}In and continue to decrease down to -0.43 μ_N in ^{125}In (the last isotopes in which $\mu(1/2^-)$ is known), therefore reaching 1.7 times the single-particle value. Various possible explanations have been considered at the time. An admixture of $[p_{3/2} \times 2^+]_{I=1/2}$ would indeed contribute to a more negative magnetic moment. However, such core excitations, if present for the ground states, would result in substantial modifications of their magnetic moments, which is not observed experimentally. The question rises whether clearly spherical ground states coexist within few-hundreds keV with states with considerably collective contributions in their wave functions. An intriguing point is whether the collective admixtures in the $1/2^-$ states would decrease when approaching N=82 that could be observed with a return of their magnetic moments towards the Schmidt limit as below ^{117}In.

At HIE-ISOLDE we propose to study the odd-even isotopes ^{127}In, ^{129}In and ^{131}In applying the beta-NMR method on beams, polarized by the Tilted Foils technique. The known ground state magnetic moment of ^{127}In will be used as a reference. The ground states of ^{129}In and ^{131}In will be measured in order to determine the purity of the single-proton $g_{9/2}$ configuration at the N=82 neutron shell closure, and evaluate the effects of core-polarization and meson exchange. If produced in sufficient quantities the $1/2^-$ isomers will be measured as well. The higher-spin isomers, respectively $21/2^-$ in ^{127}In, $23/2^-$ in ^{129}In [Gau04] and $21/2^+$ in ^{131}In [Fog84] would be out of our scope of studies at this first attempt.

Finally, the proposed work may shed some light on a recent hypothesis, based on data from the region, questioning the existence of of low-energy vibrations in nuclei [Gar10].

2. Experimental method and feasibility

The beta-NMR method will be used for the nuclear moment measurements in the present study. This technique requires an ensemble of spin-polarized nuclei that will be obtained using the Tilted Foils (TF) method. When ions have traversed a foil at an oblique angle an atomic spin polarization is obtained via the interaction between the ions and surface of the foils [Tol81]. The atomic polarization could be further transferred into a nuclear polarization through the interaction of the electronic spin, J, with the nuclear spin, I, during the flight of the ions in the vacuum [Gol81]. The obtained overall nuclear polarization can be substantially enhanced, compared to the atomic one, by letting the ions pass through a multi-stack of foils [Gol85]. Depending on the ratio between the atomic and nuclear spin more- or less-effective transfer of the polarization can be obtained as a function of the number of the foils in the stack. For atomic spin that is about 3 times smaller than the nuclear spin (J ~1/3*I) a saturation of the nuclear polarization level can be obtained using about 10 to 15 foils. If the nuclear spin is smaller than the electron spin ($I < J$) the polarization transfer is less favored, the level of the maximum nuclear polarization transferred is lower than the level of atomic polarization and saturation is reached with fewer foils (see Fig. 2 for comparison). As a general rule it can be claimed that the higher the nuclear spin, the higher the level of nuclear polarization that can be achieved. The possibility of measuring, under the same conditions, the nuclear polarization both for a low-spin state ($1/2^-$ in this case) and a higher-spin one ($9/2^+$) can provide a crucial test of our understanding of the TF polarization-transfer mechanism.

Another important point to consider in the application of the TF technique is the energy of the ions that are traversing the foils. Taking a critical read of the results presented in Ref. [Deu83] as well as Ref. [Has84, Daf85] it can be inferred that the cases of highest level of nuclear polarization observed are for ions exiting the stack of foils with energies in the range of 20 to 200 keV/u. A detailed study of the nuclear polarization, as a function of beam energy and charge states, is presented in Ref. [Hir12]. Practically all of the cases where polarization of nuclear ground states have been observed are for masses lower than 20. The only exception is reported in Ref. [Hir11], where an asymmetry of 0.75% has been observed for ^{123}In. This value can be considered as a lower limit of the nuclear polarization in this case. All other experiments in which higher-mass nuclei have been studied concern higher-spin microsecond isomeric states. What we propose here is to make a detailed study of the nuclear polarization starting from a known case of ^{127}In, similar to the one performed for ^{8}Li. Such an investigation is crucial for the understanding of the mechanism of atomic polarization (its dependence on the energy and charge state of the beam) and its transfer into a nuclear polarization.

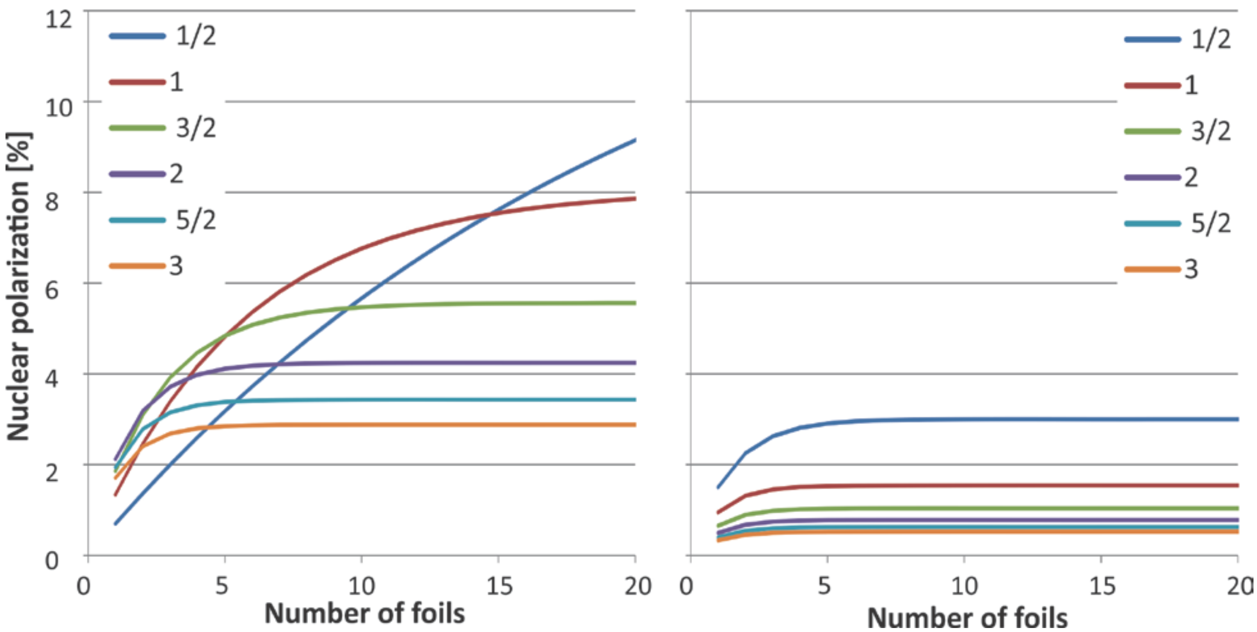

Fig. 2. Nuclear polarization as a function of the number of foils and electron spin for (left) the case of ^{8}Li as of Ref. [Hir12] and (right) for a nucleus with spin 1/2 (all other parameters as of [Hir12]).

The TF technique has been applied at ISOLDE on the High-Voltage platform [Lin00, Bab04]. In these experiments a moderate level of polarization has been observed. In July 2012 we performed a test using the newly installed beta-NMR setup at the second beamline after REX. We started with the case of ^{8}Li as in Ref. [Hir12] and obtained results very similar to those reported (see Fig. 3). For example, using a Mylar degrader the initial beam energy was lowered from 300 keV/u down to 190 keV/u before going through a stack of 10 carbon foils of 4 μg/cm^2 each. The tilting angle between the foils and the beam was 75°. Two broad scans were performed at two different directions of the foils as presented in Fig. 3. As expected, they give opposite direction of the polarization with comparable amplitude of the observed asymmetry. In order to confirm the observed effect we have performed as well a narrow frequency scan (green dots on Fig. 3) from which the fine structure of the NMR resonance can be observed. As a result, we obtained an asymmetry ~2%, from which the level of nuclear polarization can be derived as ~6%. This is in a very good agreement with the observations from [Hir12].

The intensity of the **^{8}Li** beam, at the entrance of the TF apparatus, was estimated to be about **4x10^5 pps**. *With this intensity an error-bar of 0.2% was obtained for the asymmetry for 5-points scans within ~2 hours of data taking.*

The results we obtained in the July 2012 test run give us the confidence that the beta-NMR setup, in combination with the TF apparatus, is fully operational and the TF method by itself well under control by our collaboration.

A common concern in the proposed region is the production of isobaric contamination from surface-ionized spallation products among which caesium is the most abundant. An UCx target, irradiated by low and intermediate energy neutrons from a "neutron converter", however, will generate contamination with about a factor of 100 less, while the yields of indium will be reduced only by a factor of 3.

Furthermore, resonant laser ionization increases the yields of indium at least 7 fold [Dil02]. Combining the known yield of ^{132}In [Dil02] with calculated in-target isotope production [Got12], and correcting for the half-lives, it is possible to estimate the yields of $^{127, 129, 131}$In and their contamination. The results are presented in Table 1.

Table 1: Estimated yields of Indium from laser ionization next to estimated isobaric contamination from caesium with "converter target" (see the text for details).

A	In (ions/μC)	Cs (ions/μC)
127	9.6×10^6	5×10^5
129	2.3×10^6	9×10^5
131	1.5×10^5	1×10^6

For the cesium ions we quote 10% of the in-target production [Got12], as its surface ionization is considerably reduced when niobium ionizing cavity is used instead of tungsten. These levels of contamination can be handled by the β-NMR technique as the cesium isotopes decay almost entirely by electron capture; their half-lives are much longer than the measurement times; and their E_β^{max} values are considerably smaller than those of the corresponding In isotope. Potentially Barium could be a source of some β^+ activity. However, it is not as well produced and ionized as cesium, and therefore will be a small fraction of the beam. If necessary one can use degrader plates to shield the scintillation detectors from the low-energy beta-decay activity. Furthermore, making energy cuts in the β spectra makes it possible to select the β^- activity of the indium isotopes. This is also the approach we are planning of using for the reduction of the low-energy beta-activity built up from the daughter products of the In isotopes. For each of the listed cases, the E_β^{max} values for the cesium isotopes are much lower compared to the Sn or the other decay activities.

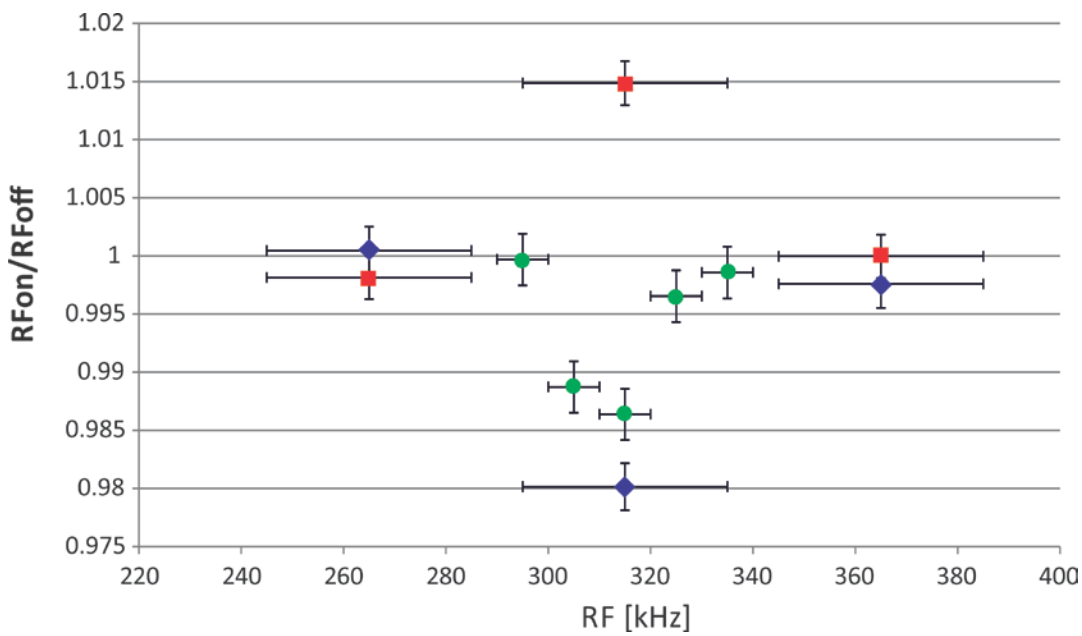

Fig. 3. Online results from the TF test in July 2012. Blue diamonds and red squares represent opposite direction of the foils and broad frequency scan. The fine scan was done just for one direction of the foils (green dots).

In order to estimate the beam-time request we used the numbers from Table. 1. Assuming 4% TRAP+EBIS+REX efficiency [Wen12], from the values in Table 1 the following conservative intensities of post-accelerated beams could be obtained: ^{127}In(g.s.) – 4 x 10^5; ^{129}In – 9 x 10^4 and ^{131}In – 6 x 10^3.

Therefore we would need **4 shifts** for testing the **TF technique** at high mass as a function of the beam energy. **6 shifts** would be necessary for the measurement of the magnetic moment of the ground state of ^{129}**In**, provided that 0.75% asymmetry would be the maximum attainable value for the heavy masses. Within these 6 shifts we would be able to perform at least two scans (broad- and narrow RF frequency modulations). Within **9 shifts** at least a single high precision scan would be done for the ground state of ^{131}**In**. **Three** more **shifts** are requested for a narrow **laser scan on the 9/2$^+$ states** in order to optimize their yields with respect to the 1/2- isomers and to make an initial estimate of the g factors.

Summary of requested shifts:

- 4 shifts for an investigation of the energy dependence of the TF polarization as a function of the beam energy at high mass;
- 6 shifts for a precise measurement of the ground state magnetic moment of ^{129}In;
- 9 shifts for determining the ground state magnetic moment of the N=82 nucleus ^{131}In;
- 3 shifts for a narrow laser scan with RILIS of the 9/2+ states in ^{127,129,131}In.

This sums up to a **total of 22 shifts** requested, using a UCx target, a neutron converter, and RILIS.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(Tilted Foils experiment at REX)*

Part of the	Availability	Design and manufacturing
Tilted Foils experimental setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazards:

Hazards	
Electrical and electromagnetic	
Magnetic field	~0.1 T
Non-ionizing radiation	
Radiofrequency (1-300MHz)	~1 MHz (inside vacuum chamber = Faraday cage)
High Voltage	
	2.2 kV for the 4 Photo-Multiplier tubes