EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Determination of the Magnetic Moment of ^{140}Pr

January 5, 2011

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CERN-INTC-2011-013 / INTC-P-297
05/01/2011

Abstract: We propose to measure the nuclear magnetic moment of the neutron-deficient isotope ^{140}Pr using collinear laser spectroscopy at the COLLAPS experiment. This nuclide is one of two nuclear systems for which a modulated electron capture decay has been observed in hydrogen-like ions in a storage ring. The firm explanation of the observed phenomenon is still missing but some hypotheses suggest an interaction of the unpaired electron with the surrounding magnetic fields of the ring. In order to verify or discard these hypotheses the magnetic moment of ^{140}Pr is required since this determines the energy of the 1*s* hyperfine splitting.

Requested shifts: 9 shifts in 1 run

1 Physics Motivation

Orbital electron capture (EC) decay of hydrogen-like (H-like) $^{140}\mathrm{Pr}^{58+}$ and $^{142}\mathrm{Pm}^{60+}$ ions has been investigated in the experimental storage ring ESR at GSI [1]. These two nuclear systems have been selected because they provide:

- the most simple and well-defined quantum state of the parent ion which is an atomic nucleus in the ground state ($I^\pi = 1^+$) and one bound electron (in the K-shell), both coupled to the total angular momentum $F = 1/2$ in the ground state, provided that the magnetic moment of the nucleus is positive;

- a *strict two-body* final state consisting of a monochromatic neutrino with orbital angular momentum $l_{\nu_e} = 0$ and a bare daughter nucleus in the ground state ($I^\pi = 0^+$), both coupled to $F = 1/2$, and with no third particle (γ-, X-rays, bound electrons) involved.

Surprisingly, the obtained results indicate a periodic modulation on top of the expected exponential decrease. The modulation periods of 7.06(8) s and 7.10(22) s (laboratory frame) were extracted for ^{140}Pr and ^{142}Pm ions, respectively. The averaged value for the amplitude of the periodic modulation is $\langle a \rangle = 0.20(2)$. Though the experimental data suffer from limited statistics, the "zero hypothesis" of a pure exponential decay could be rejected on the 99% confidence level for both investigated nuclear systems [1].
A firm explanation of the observed effect is still missing and is broadly discussed in literature, see for example [2–27]. The finding of very similar oscillation periods of about 7 s in the two investigated systems suggests at first a technical artefact as their common origin. For example, they could be due to periodic instabilities in the storage ring or of the recording systems. Nevertheless, several hypotheses have been suggested and await their experimental verification or disproof. A few of them are discussed below:

1. It is likely that the H-like ions are produced in a coherent superposition of the two hyperfine states with total angular momenta $F_i = 1/2$ and $F_i = 3/2$ (i reflects the initial, parent state). This could lead to the well-known phenomenon of quantum beats with a beat period $T = h/\Delta E$, where ΔE is the hyperfine splitting. Magnetic moments of ^{140}Pr and ^{142}Pm have been estimated from the known magnetic moments of the neighboring odd-A nuclei to be about $+2.5\mu_\mathrm{N}$ [28, 29]. This corresponds to the ΔE values of the order of 1 eV [30], which yields beat periods more than twelve orders of magnitude shorter than the observed ones.

2. A hypothetical, yet unknown, mechanism transfers the parent ions within 7 s from the $F_i = 1/2$ state to the $F_i = 3/2$ state and back. This results in modulations, because an allowed EC decay ($l_{\nu_e} = 0$) from the upper $F_i = 3/2$ state is *forbidden* by the conservation of total angular momentum since the final state has a total angular momentum $F_f = 1/2$ (f indicates the final, daughter state). The main argument against this mechanism is that the total decay probability should be reduced, which is not in agreement with the corresponding decay measurements at the ESR [31, 32].

3. The electron neutrino is generated in the EC decay as a coherent superposition of at least two mass eigenstates (m_1 and m_2). This means that in the two-body kinematics

also the recoiling daughter nuclei appear as a coherent superposition of states that are entangled with the electron neutrino mass eigenstates by momentum- and energy conservation. Assuming asymptotic energy and momentum conservation, one can derive that the difference of neutrino energies ΔE is

$$\Delta E = E_2 - E_1 = \frac{\Delta m^2}{2M_P}, \tag{1}$$

where $\Delta m^2 = m_2^2 - m_1^2$. If the modulations are caused by the energy splitting ΔE, then one expects almost the same modulation periods for ^{140}Pr and ^{142}Pm ions which have almost the same nuclear masses M_P. We emphasize here that this hypothesis is strongly disputed in literature (see, e.g., [2–8, 10–12]).

4. The modulation arises from the coupling of the orbital rotation in the ESR to the spin of the electron and the nucleus (Thomas precession) [8].

5. A mechanism was suggested in [9] which involves resonant multi-photon transitions induced by the periodic magnetic field of the ESR between the magnetic substates of the ground state with the total angular momentum $F_i = 1/2$.

It is clear that the observed modulated EC decays must be corroborated by studies with high statistical significance of other two-body decays. Experiments on helium-like ions aiming to test the hypotheses related to the interactions of the single bound electron have been recently conducted at GSI. However, the analysis of the data is not completed yet. Furthermore, it has to be investigated how the oscillation period – if persisting at all – depends on the nuclear mass M_P. The EC decay of H-like $^{122}I^{52+}$ ions has been recently studied in the ESR. The analysis is still ongoing. However, very preliminary results can be found in [24–26]. It should be noted, that experiments with implanted ^{142}Pm [33] and ^{180}Re [34] (neutral) atoms do not show modulations. A clean two-body decay kinematics is, however, missing in these measurements [35, 36].
The hypotheses 1, 2, 4 and 5 are sensitive to the size of the magnetic moment of ^{140}Pr and partially to its sign. Both of them are experimentally unknown. The theoretical prediction of these odd-Z, odd-N nuclei covers a broad range of possible values and is thus not reliable. Therefore, we propose to measure the magnetic moment of one of these two systems, namely the ^{140}Pr nucleus. An accurate value of the magnetic moment of ^{140}Pr will provide decisive information about the validity of several suggested explanations of the observed modulated two-body beta decays and will also allow further laser spectroscopic investigations of the hydrogen-like ion at the storage ring ESR. Here, it will be possible to directly excite the ground state hyperfine transition in $^{140}Pr^{58+}$ with a pulsed laser and therefore manipulate the lifetime of the nucleus. To locate the transition, the magnetic moment must be determined to high accuracy.

2 Experimental Method

The nuclear spin $I = 1$ [37] of the praseodymium isotope ^{140}Pr results in a hyperfine splitting of atomic energy levels from which the nuclear magnetic moment can be derived

[38]. Therefore, we intend to measure the hyperfine structure of this radioactive isotope with high-resolution collinear laser spectroscopy at the COLLAPS setup. There is no information on the yield of ^{140}Pr in the ISOLDE yield tables. However, the (SC-)yield of ^{133}Pr is listed as $1.5 \cdot 10^7$ (Ta target) and for ^{142}Pr (UC_x target) a yield of $1 \cdot 10^7$ is reported using a W surface ion source. Hence, the expectation of a similarly large yield for ^{140}Pr is certainly justified, which is more than sufficient for collinear laser spectroscopy with COLLAPS. Assuming these yields, which can be subject to beam development studies, the application of ISCOOL is not needed. For optical spectroscopy of praseodymium no modifications of the existing COLLAPS experiment are required.
It is planned to use the strong transition $4f^3\ 6s\ ^5\mathrm{I}_4 \longrightarrow 4f^3\ 6p\ ^4\mathrm{H}_3$ in Pr^+ with a corresponding wavelength of 390.844 nm [39]. This is a transition starting from the ground state of the praseodymium ion. The hyperfine splitting and thus the magnetic dipole hyperfine constants A of the $4f^3\ 6p\ ^4\mathrm{H}_3$ state and $4f^3\ 6s\ ^5\mathrm{I}_4$ state in stable ionic praseodymium ^{141}Pr are well known [40, 41]. Also the magnetic moment of this nucleus is $\mu_I(^{141}\mathrm{Pr})$=4.2754(5)μ_N [42], which makes it a suitable reference for determining the magnetic moment of ^{140}Pr. The required wavelength will be produced with a Ti:Sa laser followed by a commercial frequency doubler. Both systems are readily available at COLLAPS.
A simulation of the expected hyperfine spectra based on a magnetic moment of $\mu_I(^{140}\mathrm{Pr})$=+2.5μ_N estimated from the moments of neighboring nuclei using momentum coupling rule at an acceleration voltage of 50 kV is shown in Fig.1. Collinear laser spectroscopy of the stable isotope $^{141}\mathrm{Pr}^+$ is currently under preparation at the TRIGA-LASER beamline [43] at the Institut für Kernchemie at the University Mainz in order to further investigate the chosen transition.
Typical detection efficiencies at the COLLAPS beamline for systems like Pr^+ are of the order of 1 photon per $10^4 - 10^5$ ions and scattering backgrounds of 1000 photons/s per mW laser power. A laser power of 1-5 mW should be sufficient to slightly saturate the transition if the laser beam is expanded to the typical ion beam size of 3-5 mm. Hence, a background of the order of 5000 counts/s is expected while the signal rate is of the order of 100-1000/s. Taking the worse case of 100 signal photons per second, we should obtain a signal to noise ratio of 4 within 8 s per channel for the strong peaks. Considerably more time is required to observe the two weaker transitions. The weakest transition ($F = 3 \rightarrow F' = 4$) might not be observed since it has a strength of only 0.1% of the stronger peaks. However, this does not hamper the determination of the magnetic moment, since the required three values (A_{lower},B_{lower} and the center of gravity (c.g.) of the hyperfine structure) are overdetermined if five peaks are recorded and the ratio of the hyperfine parameters A and B are assumed to be constant for all isotopes. A possible small contribution of hyperfine anomaly can be neglected for the required amount of accuracy. Within the requested shifts we are aiming for an accuracy of 10^{-3} to verify the above mentioned hypotheses and to further enable laser spectroscopic studies on hydrogen-like ^{140}Pr in the GSI storage ring.
The observed oscillations in the GSI experimental storage ring are a widely and controversially debated hot topic in a large number of recent publications from theory and experiment. The attempts to understand this phenomenon observed on ^{142}Pm and ^{140}Pr will benefit from the measurements of this proposal. In order that the outcome of our

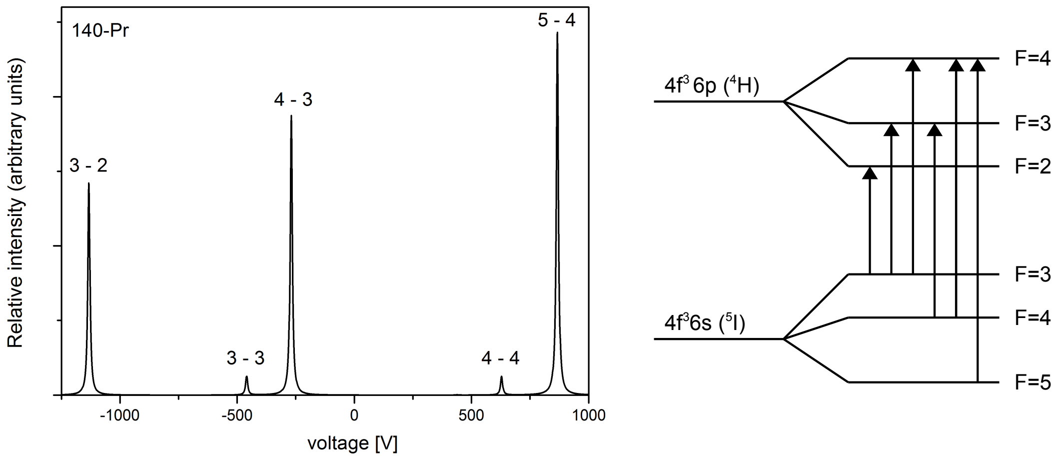

Figure 1: Expected hyperfine spectra of $^{140}\mathrm{Pr}^{+}$ based on the estimated magnetic moment of $\mu_I(^{140}\mathrm{Pr})$=+2.5μ_N (see text) at an acceleration voltage of 50 kV (F quantum numbers: lower state (F) - upper state (F')). The missing transition from $F = 3$ to $F' = 4$ at 435 V is too weak to be seen on the linear scale.

ISOLDE studies can be included in the ongoing research program at the ESR, it will be mandatory to schedule the single run requested here within the ISOLDE on-line period of 2011.

Summary of requested shifts: We ask for 9 shifts at the GPS using a tantalum target applying surface ionization for measuring the magnetic moment of the radioactive isotope ^{140}Pr including 3 shifts also for optimizing the conditions on stable ^{141}Pr.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: *COLLAPS*

Part of the	Availability	Design and manufacturing
COLLAPS	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT: Hazards named in the document relevant for the fixed COLLAPS installation.