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LETTER OF INTENT.

PRODUCTION OF POLARIZED RADIOACTIVE BEAMS WITH LASER ION SOURCES (FEASIBILITY TEST).

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Introduction.

Production of unstable nuclei with oriented nuclear spin (polarized nuclei) is of importance for different fields of modern physics. Anisotropy of β-radiation in the decay of polarized nuclei can be utilized in measurements of nuclear electromagnetic moments, in studies of the fundamental properties of the nuclear interaction as well as in condensed matter research. During the last few decades an impressive number of various methods to polarize radioactive nuclei have been developed. The variety of these experimental techniques reflects the importance as well as the difficulties and the challenges of the subject. Each of these techniques has certain merits and drawbacks and can be applied only for specific regions of the nuclear chart. ***Therefore any other possibility to produce intense and pure radioactive beams with a considerable degree of nuclear polarization should be investigated.***

We propose here to test such a possibility by using the ISOLDE resonance ionization laser ion source (RILIS) [Mis93]. The high chemical selectivity of a two or three steps resonance ionization process as well as a high ionization efficiency makes the RILIS a very powerful tool with many attractive applications. During the recent years the RILIS has been used very intensively at ISOLDE in many studies of the spectroscopic properties of exotic nuclei, in astrophysics experiments and solid state physics research. Moreover it has been demonstrated recently that the RILIS can be used successfully for isomer separation as well as for in-source atomic spectroscopy of exotic atoms [Kös00]. The production of polarized beams can enlarge further the scope of the RILIS applications.

Nuclear polarization in the RILIS can take place when circularly polarized laser beams are applied for the resonance ionization process. The resonance multiphoton ionization by circularly polarized lasers has been the subject of numerous investigations since these processes have been proposed as efficient sources of polarized photoelectrons [Lam73]. It was pointed out in ref. [Gra76] that the photoelectron polarization is expected to drop considerably when the time that atoms spend in excited state before the next excitation photon is comparable than the nuclear I.J precession period (I nuclear spin, J electron spin). Indeed, after absorbing the circularly polarized light, an atom finds itself in an excited state with polarized electron spin. If the hyperfine interactions are effective enough during the atomic lifetime of the excited state the electron polarization can be transferred to the nuclear spin. This effect is undesirable for the production of polarized photoelectrons but can be effectively utilized in RILIS for the production of nuclear polarization [Fed78]. Indeed, typical atomic lifetimes of excited states in RILIS (time between laser pulses) is of order of 10 ns. It means that any atom with a hyperfine splitting (hfs) of an excited state larger than 100 MHz will have polarized nuclear spins after the resonance excitation process. This polarization mechanism is different from the conventional optical pumping technique since the polarization is produced only once during excitation lifetime in between of the laser ionization steps.

The degree of the nuclear polarization depends on the particular excitation scheme, on the timing of the lasers pulses and the laser power. The line width of the RILIS is rather large mainly due to Doppler broadening (an inhomogeneous line broadening, typically few GHz) and due to power broadening (a homogeneous line broadening, less than 1 GHz). Therefore for many atoms the hyperfine multiplets of the ground and excited states are not resolved. However, in [Ney97] it has been shown that even if several hyperfine levels are excited by an inhomogeneously broadened laser pulse, it is quite possible to obtain a significant amount of nuclear polarization (~ 20 %). What has not been investigated so far theoretically is the case when the homogeneous line width (due to the higher power broadening of the laser beam) is larger than the hyperfine splitting. Then interference effects have to be taken into account when calculating the final state nuclear polarization. Even two-photon absorption process can take place in the case of high laser power. One should avoid therefore high laser power which causes the homogeneous broadening and interference effects.

It is of great interest to test:

1. whether the nuclear polarization is indeed produced in the RILIS
2. if it is possible to transport the polarized nuclei to experimental stations without significant depolarization .

We will discuss below the general idea of such tests as well as a list of possible problems that can arise and ways to overcome them.

Feasibility test.

For the feasibility test we propose a slight modification of the RILIS optical setup by introducing $\lambda/4$ plates to transfer the linear polarization of the dye laser beam to a circular one. The direction of the produced polarization of the ions will be along the beam axis. After mass separation the nuclei are implanted into a standard beta-NMR setup with a horizontal holding magnetic field and two detectors at up/down positions with respect to the holding field direction. This beta-NMR setup is available at the COLLAPS collaboration beam line [Arn87,Kei00]. The produced nuclear polarization is observed by monitoring the asymmetry of beta-radiation. By rotating the $\lambda/4$ plates and hence, changing the light polarization direction by 180°, one reverses the direction of the produced nuclear polarization. The comparison of the beta-asymmetries for the reverse polarization directions will allow to correct for systematic errors.

The choice of an appropriate test isotope is determined by many considerations, which we will try to present below:

1. Depolarization by hyperfine interactions and release from the target:

The candidate atom should preferable have and electronic spin coupled to zero after the laser ionization. If not, fast precession of electronic spins in random external fields (like switch magnet stray fields) could depolarize the nuclear polarization via the hyperfine interaction. In case of a non-zero electron spin a fast passage through the low field regions is crucial.

Moreover the element should be released easily from the typical ISOLDE target.

These two argument immediately limits the number of the candidates to the following elements: Al, Cu, Ga, Ag, In, Lu, Y, Sb, Bi. We have not considered alkali elements since most of them are polarized readily by optical pumping in a collinear spectroscopy setup [Arn87,Kei00]. In addition high efficiency of surface ionization in the ionizer tube reduces laser selectivity of the laser ionization of alkali elements [Mis93].

From other considerations discussed below (convenient laser excitation scheme, nuclear and atomic properties and safe implantation in the stopper etc) it seems that Al is a good candidate. The two-step laser ionization into continuum has been tested for Al recently. The obtained laser selectivity was found to be of order of factor 70 (probably this can still be improved). The estimated yield for ^{25}Al ($T_{1/2}$=7.2 s) from a Ti foil target is about 10^6 atoms per second. This relatively high yield may be sufficient to measure even small asymmetry effects and to optimize the asymmetry value as a function of many parameters. The hf splitting of the $4S_{1/2}$ excited state of Al, 420 MHz, is strong enough for fast nuclear polarization. Moreover the production of polarized neutron-deficient Al isotopes around N=Z line is of great interest. For example, the polarized beam of ^{24g,m}Al would allow to measure the magnetic moments of these nuclei, which is the T_z=1 member of the T=1 isospin multiplet; the corresponding magnetic moments of the T_z= -1 members, ^{24g,m}Na , are already measured. The measurement of magnetic moments of isospin multiplet members provides unique information regarding iso-scalar and iso-vector parts of the magnetic moment operator [Bro88].

It is particularly interesting to polarize even more neutron-deficient isotopes. In this case one can try to observe beta-delayed proton emission from polarized nuclei. The anisotropy of the beta-radiation will modify the line shape of the beta-delayed proton emitted by the recoiling daughter nucleus [Fyn00]. These studies could be complimentary to another ISOLDE experiment proposed for heavier proton emitters [Rik00].

2. Depolarization in the RILIS ionizer.

Another concern is the precession of atomic spins during the transport of ions along the RILIS ionizer tube. The atoms are ionized by the lasers along the whole length of the tube (3 cm) and are exposed to the magnetic field generated by the currents that heat the target. Therefore the ions produced at different positions along the ionizer tube will spend different times in the magnetic field region and will have different precession angles of their atomic spin leading to an overall depolarization. To fight against the problem one can: 1. apply a coil around the ionizer to create a holding field along the polarization axis; 2. cut the extracted ion beam with a beam chopper to obtain only particles ionized in a specific part of the ionizer.

3. Rotation of nuclear spin in the magnetic field of the mass-separator.

The next problem is the transport of the polarized nuclei through the mass-separator. As we select ions with electron spin J=0, only interaction of the nuclear spin with surrounding magnetic fields needs to be considered. 60 keV Al ions spend around 5 μs in the magnet which is enough for the nuclear spin to rotate several times around the separator magnetic field direction. The ratio of this precession angle to the magnet bending angle is an **f**-factor f=gA/2 [Stef81], where g is the nuclear g-factor and A is the atomic mass of the nucleus. If individual trajectories and, hence, the bending angles of various ions are slightly different, their nuclear spins will precess slightly differently causing a small diffusion of the average polarization. This overall depolarization is small in case of a small spread in the ion trajectories and is proportional to $\mathbf{f}^2$.

The collective precession of the nuclear spins ensemble creates an experimental problem since the direction of the holding field of the beta-NMR setup will not necessarily be parallel to the polarization direction. Ideally one has to build a Wien filter to adjust the polarization direction to the direction of the holding field. Fortunately the f-factor for ^{25}Al is equal to 18.2 corresponding to 3.54 full turns for the 70 degree GPS bending magnet. Thus for this specific test isotope the orientation of the nuclear polarization will be almost perfectly parallel to the holding field.

4. Beta-NMR properties.

From the known log-ft and Q-value data one can estimate a beta-asymmetry factor for ^{25}Al decay of -0.65. The beta-decay proceeds mostly via a dominant branch to the ground state of ^{25}Mg. Thus, the polarized nuclei will exhibit a quite strong anisotropy of the beta radiation.

The implantation of Al ions in various hosts should be reasonably safe with respect to the creation of lattice defects. The stable ^{25}Mg daughter nucleus does not create any problem with radioactive background build-up during the experiment.

The experimental information regarding the relaxation times of Al ions implanted in various hosts is rather scarce. A long relaxation time 4(1) s was reported in ref [Min76] when polarized ^{25}Al nuclei were produced and stopped in a thick Si crystal at room temperature. In [Lad72,Min81] ^{28}Al ($T_{1/2}$=2.3 min) nuclei were implanted correspondingly into Al_2O_3 and Li at liquid helium temperature. In ref. [Min81] authors quote a relaxation time of 1.4 s for Al implanted into Li metal at a host temperature of 1.5-4.2 K. The beta-asymmetry was observed for ^{28}Al implanted into an Al_2O_3 crystal at 77 K host temperature [Sto78].

During the feasibility test we will prepare several implantation hosts (metals as well as ionic crystals) to try different implantation conditions. We will also have the opportunity to cool the implantation hosts down to 30 K temperature.

Conclusion.

We have described in this letter of intent the idea to polarize nuclei using polarized laser light in the RILIS and discussed how to test the feasibility of this idea. To perform some tests we will require 3-4 shifts with $^{25,24}Al$ beams obtained with RILIS. Some additional Ti foil target development is probably also needed to improve Al yields. The beta-NMR setup of the COLLAPS collaboration will be used for the test.

In the case of positive results of such tests a more elaborated proposal for experiments with $^{24,23}Al$ nuclei will be prepared.

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