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New laser polarization line at the ISOLDE facility

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Abstract. Following a growing interest in spin-polarized beams of radioactive ions, a new laser spin-polarization setup has been installed at the ISOLDE facility at CERN. The setup is located at the VITO beamline which aims to bring together several experimental techniques using polarized ions allowing for studies in nuclear physics, fundamental interactions, material and life sciences. Intensive design work which took place in 2016 allowed the installation of the first stage of the polarization line. With this experimental setup the ion beam can be neutralized, polarized and implanted into a solid sample inside an electromagnet which also hosts β-detectors, where the degree of nuclear spin polarization can be measured. In autumn 2016 the setup has been commissioned using short-lived ^{26}Na and ^{28}Na beams which have been polarized in the D2 line from their atomic ground state. The previously observed degree of β asymmetry were reproduced and thus the beamline is now ready for the first physics experiments with spin-polarized radioactive beams.

spin-polarized beam, optical pumping, radioactive-ion beam, β-decay asymmetry
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1. Introduction

Spin-polarized beams of radioactive nuclei can be of interest for studies in a range of fields, including nuclear structure, fundamental interactions, material science and life sciences. This is the motivation behind a recent initiative to build a permanent ISOLDE beamline, named VITO for Versatile Ion-polarized Techniques Online, as described in [R$^+$15]. Within this initiative, the first stage of the laser polarization line has been just completed. The experimental setup allows to polarize the radioactive ions and atoms of interest via optical pumping with lasers, to determine their β-decay asymmetry, and in addition to use these beams for β-detected Nuclear Magnetic Resonance (β-NMR). This experimental setup has been commissioned in autumn 2016 using short-lived ^{26}Na and ^{28}Na, which have previously shown large β-decay asymmetries as demonstrated at the COLLAPS setup at ISOLDE [KGK$^+$00].

In this contribution we will first briefly describe our technique to achieve nuclear spin polarization through optical pumping with laser light and the way to detect it. We will then present the recently designed VITO laser polarization setup, concentrating on the commissioning experiment, which took place in autumn 2016 using short-lived ^{26}Na and ^{28}Na beams. We will conclude this contribution by the short- and medium-term plans for the beamline and will mention some of the planned experiments.

2. Optical pumping and β-decay asymmetry

Detection of nuclear magnetic resonances via β-decay asymmetry requires an ensemble of short-lived nuclei which are polarized, i.e. the spins of a nuclear ensemble point in a preferential direction in space. The formula for spin polarization takes the form of $P = \langle m_I \rangle / I$, where I is the nuclear spin and m_I is the projection of the nuclear spin on the quantization axis (which can be defined e.g. by a magnetic field).

Spin polarization via optical pumping relies on multiple resonant excitations of the ion or atom by circularly polarized laser light, in order to polarize the atomic spins F ($\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$, J being the electron spin). During many ion/atom-laser interactions, the photon angular momentum is transferred to the atomic electrons, as shown in Fig. 1 on the example of the $|F = 3/2\rangle \rightarrow |F' = 5/2\rangle$ component of the D2 line in ^{28}Na. The light polarizes the total atomic angular momenta F by inducing transitions between the m_F magnetic sub-levels of the ground-state and excited-state hyperfine multiplets. As a result, the ion/atom is predominantly in the ground-state sub-level with maximum $m_F = +F$ if σ^+ light polarization is used **(i.e. the photon's spin orientation compared to the magnetic field direction is such that it triggers transitions with $\Delta m_F = +1$), or in the minimum $m_F = -F$ for σ^- polarization (the photon's spin orientation compared to the magnetic field direction is such that it triggers transitions with $\Delta m_F = -1$)**. The theoretical 100% polarization is lowered due to the so-called hyperfine pumping, in which the excited state decays to the other ground-state F-level, which cannot be excited by the same laser frequency.

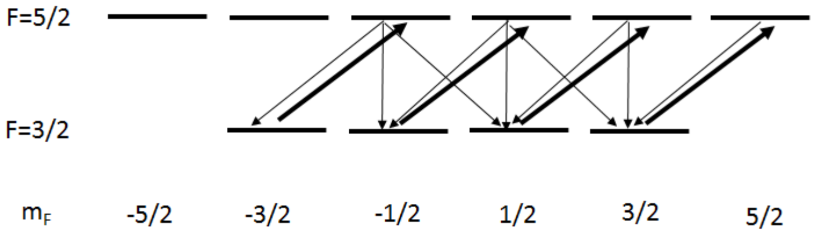

Figure 1. Atomic spin polarization via optical pumping with $\sigma+$ light on the example of $|F = 3/2\rangle \rightarrow |F' = 5/2\rangle$ component of the D2 line in ^{28}Na. $\sigma+$ circularly polarized light induces transitions with $\Delta m_F = +1$. Because the de-excitation can take place for $\Delta m_F = -1, 0, +1$, after several excitation-decay cycles the lower state with $m_F = +F$ will be mostly populated and the atomic spin will be polarized.

Due to the hyperfine interaction between the electron spin and the spin of the nucleus in free atoms (or ions), polarization of the atomic spins results also in the polarization of the nuclear spins, with the polarization axis along the laser beam axis [KY$^+$08]. The observed nuclear polarization is reached after the adiabatic decoupling of the spins in a gradually increasing static magnetic field. This strong field (typically between a few 100 and a few 1000 Gauss) is used to maintain the nuclear spin polarization after the ions/atoms are implanted into a host material, where their spin polarization can be observed via the asymmetry in their β decay.

Due to parity violation of the weak interaction, the emission of β particles from spin-polarised nuclei is anisotropic with respect to the polarization symmetry axis. The angular distribution for an allowed β decay is given by [NN06]:

$$W_\beta = 1 + a_\beta \, v/c \, P_I \, cos\theta. \tag{1}$$

Here a_β is the asymmetry parameter specific to the spin change in the decay of the probe nucleus, θ is the angle between the direction of β particle emission and nuclear spin (and the magnetic field as the polarization axis), and v is the velocity of the β particle. What is observed directly in the experiment, is the β-decay asymmetry A_{exp}, which is defined as the normalised difference in the number of beta particles detected parallel and antiparallel to the magnetic field direction, $A_{exp} = (N_0 - N_{180})/(N_0 + N_{180})$. Because the β detectors cover a certain solid angle, A_{exp} can be connected to the polarization via

$$A_{exp} = 1/2 \, a_\beta \, v/c \, P_I \, (1 + cos\theta). \tag{2}$$

Here, we neglected the polarization relaxation in the material in which the beam was implanted, since in NaF, which we used, it is much longer than the half-life of ^{26,28}Na. As can be seen from the above equations, even for 100% spin polarization, the observed β-decay asymmetry might be still very small, if the decay scheme is such that the a_β parameter is small.

3. Laser polarization setup at VITO

In the following, the experimental setup will be briefly described, while more details will be provided elsewhere [W. 16]. The first stage of the laser polarization setup was installed in the summer 2016. A CAD 3D drawing is shown in Fig. 2. The first element belonging to the VITO beamline, after the ion beam turns right from the ISOLDE central beamline, is a quadrupole doublet used to properly focus **the 30-60 keV beam** in front of the setup. The quadrupole is followed by an electrostatic deflector with a deflection angle of 5 degrees. It is equipped with a small window, where the laser light enters to interact the ions in the overlapping region downstream of the deflector. The 5-degree deflector was installed in 2014, before the first online run at VITO, which used unpolarized ^{68m}Cu for online Perturbed Angular Correlation Studies [AF16]. The beam-diagnostics box installed behind it hosts a variable aperture and a metal plate from which the ion current can be read out. The next element is the charge-exchange chamber (CEC) hosting a charge-exchange cell, in which the ion beam is neutralized by collisions with a Na or K vapour as it passes through. The cell is used only for species which are polarized more efficiently as neutral atoms (e.g. Li, Na, Ar and Cu isotopes). The chamber also hosts a set of acceleration-deceleration electrodes which can change the energy of the incoming ions by up to several keV, in order to Doppler-tune them into resonance with the laser light. At the end of the chamber an electrostatic deflector is used to separate the remaining un-neutralised ions from the fast atom beam. The CEC is followed by a chamber housing a photomultiplier tube positioned perpendicular to the beam axis, which can be used to detect fluorescece light emitted by the excited ions or atoms. This allows recording optical resonances of reference isotopes (usually stable isotopes produced as an intense beam). **It is followed directly by a 2-m optical-pumping section, where the spin polarization takes place, behind which the beam reaches the implantation chamber placed between the poles of NMR magnet. In the middle the chamber hosts a crystal or metal plate in which the atomic beam is stopped. On the sides thin Al-coated mylar foil is used as windows which let most β particles through, while maintaining high vacuum inside the chamber. Behind each window two 2-mm-thick plastic scintillator bars act as β detectors, which cover 10% solid angle, and whose light signal is transmitted via long plastic light-guides to photomultiplier tubes. Coincidence signals between the two detectors on each side of the chamber allow to lower the background counts. Behind the magnet a large beam-diagnostic box is placed to record the ion current and the beam profile during optimization of the beam transmission. The beamline ends with a viewport.**

To maintain the spin polarization along the beam axis and to avoid polarization losses due to stray magnetic fields and magnetic material in neighbouring setups which include superconduction magnets, a longitudinal magnetic field of 10-20 Gauss is created along the beamline. The field is provided by a series of large Helmholtz coils installed

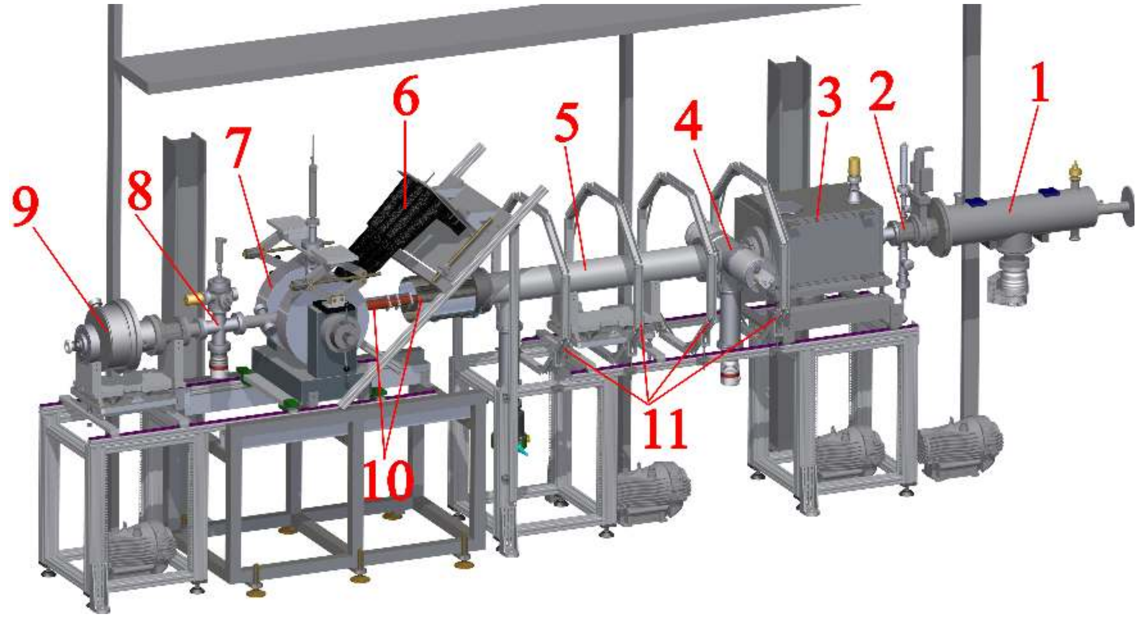

Figure 2. Laser polarization and β-NMR setups at the VITO beamline with the ion and laser beams entering from the right. (1) 5 degree bender, (2) beam-diagnostics box, (3) charge-exchange chamber, (4) optical-detection region, (5) optical-pumping tube, (6) β-detection system, (7) electromagnet providing strong magnetic field and implantation chamber with NaF crystal, (8) metal plate and aperture for beam diagnostics, (9) beam-diagnostics box, (10) solenoids, (11) Helmholtz coils.

between the charge-exchange chamber and the magnet. These coils are followed by a set of small solenoids, which generate an increasing longitudinal field (so called transitional field). Its overlap with the increasing transversal field of the NMR magnet leads to an adiabatic rotation of the atomic spin and decoupling of the electron and nuclear spins. Details will be given in the next section.

4. Online commissioning with ^{26,28}Na

4.1. Settings

The experimental setup has been commissioned with ^{26,28}Na during three short runs in autumn 2016, between which improvements to the setup were implemented. The runs covered test of the functioning of all elements of the beamline and the β-detection setup, as well as optimisation of the different settings (strength or guiding and NMR fields or degree of laser polarization and laser power). The aim was to obtain the degree of polarization reflected in the observed β-decay asymmetry comparable to the results already reported by the COLLAPS collaboration at ISOLDE [KGK$^+$00]. The isotopes ^{26,28}Na, whose properties relevant for the tests are presented in Table 1, were chosen for several reasons: (i) these isotopes can be well polarized as neutral atoms via the atomic D2 transition from the ground state, (ii) they are produced with high intensity at ISOLDE from various target materials (UC$_x$, Ta, Ti) using hot surface ionization

Table 1. Properties of ^{26}Na and ^{28}Na relevant for laser spin polarization

	^{26}Na	^{28}Na
spin	3	1
half-life	1.1 s	30 ms
beta asymmetry parameter	-0.93(2)	-0.75(1)
yield/s from UCx target [KGK+00]	3×10^7	6×10^5
nuclear polarization at COLLAPS [KGK+00]	39%	59%
nuclear polarization from this work	28%	59%

sources, (iii) a high degree of asymmetry is expected due to their large β-asymmetry factors, and (iv) our polarization can be compared to earlier measurements performed at the ISOLDE COLLAPS beamline [KGK+00]. The large difference in half-lives of the two isotopes allows also to compare the influence of the relaxation time (i.e. exponential decrease in polarization due to spin-lattice relaxation) on the observed asymmetry. The atomic transition selected for the polarization is the 3s $^2S_{1/2} \rightarrow$ 3p $^2P_{3/2}$ transition from the ground state of neutral Na (D2 line) at 589 nm, which gives quite narrow resonances with natural linewidth around 10 MHz.

The Na$^+$ ions are first neutralized when passing the charge-exchange cell filled with Na vapour. The non-neutralized ions were deflected from the beam axis while the neutralized atoms were overlapped with laser light set to the Doppler-shifted frequency of the atomic D2 line. The spin-polarized atomic beam was finally implanted into one of several crystals (NaF, NaCl, NaNO$_3$) placed in the middle of the NMR electro-magnet.

To determine the degree of nuclear-spin polarization, we recorded the changes in β-decay asymmetry when scanning across the hyperfine structure of the D2 transition for both directions of laser polarization (σ^+ and σ^-). The scans were performed by changing the velocity of the atomic beam by changing the voltage applied to the acceleration-deceleration electrode and the CEC (Doppler tune voltage).

The procedure to scan across the resonances and to record beta asymmetry was as follows. The data acquisition was triggered when the μs-long proton bunch from the CERN's Proton Synchrotron Booster impinged on the ISOLDE target (this took place every 1.2 s or its multiples). Immediately after the proton bunch hit the target the Doppler-tuning voltage was was incremented and the number of beta counts was recorded for a predefined time. The β decay asymmetry could be calculated from the number of β counts recorded as coincidence events in two thin detectors placed at 0 and 180 degrees with respect to the field direction. In this way the β-decay asymmetry was recorded as a function of the acceleration voltage, which can be easily translated into a Doppler-shifted laser frequency.

During the final tests in November 2016, the Na isotopes were produced in a UC$_x$ target with tungsten surface ionizer, accelerated to 30.2 keV and mass-selected in the

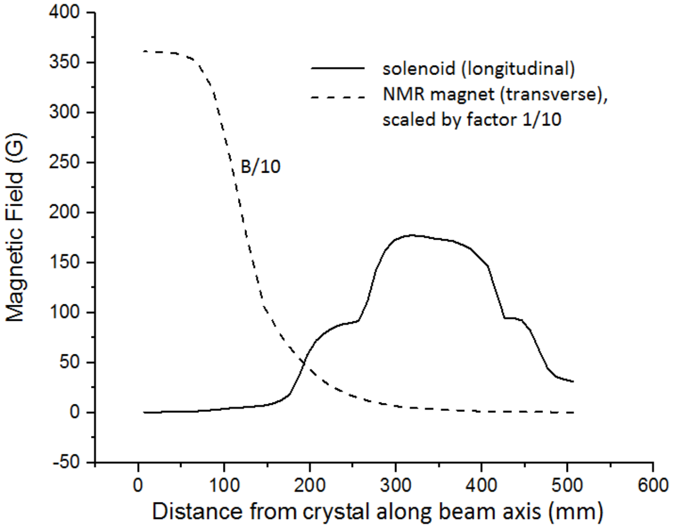

Figure 3. Measured longitudinal transitional field provided by two solenoids and transversal component of the electromagnet's field (scaled by factor 1/10, at the centre of the beamline. The atomic beam travels from the right to the left. The fields are used to adiabatically rotate and decouple the electron and nuclear spins.

high resolution separator, HRS. For ^{26}Na the time between consecutive proton bunches was 2.4 s or more while for ^{28}Na, due its very short half-life, a proton bunch was accepted every 1.2 s. The ISOLDE beamgate, which let the ions out into the setup, was set to 2.3 s for ^{26}Na and to 200 ms for ^{28}Na. The proton structure is important for nuclei with half-lives comparable or longer than the time between proton pulses (1.2 s or its multiples), because the atoms implanted after a given proton pulse continue decaying when the new atoms are implanted. This means that the asymmetry recorded for one acceleration voltage would be "contaminated" by polarization created at the previous voltages.

The field of the NMR dipole magnet was set to 0.35 Tesla and varied during the magnetic-field tests. The guiding field provided by large Helmholtz coils with a diameter of 80 cm starts behind the charge-exchange chamber (see [W. 16] for details). A field of 18 Gauss was induced along the beam axis and the transitional field induced in two solenoids placed in front of the NMR magnet peaked at 180 Gauss and 80 Gauss, optimised to match the field of the magnet. The strengths of this transitional field and of the magnet's field along the beam axis are plotted in Fig 3.

The estimated number of atoms being implanted in the crystal after each proton pulse was about 2.2×10^7 for ^{26}Na and 1.5×10^4 for ^{28}Na (based on the number of recorded β particles and the 10% solid angle covered by the β detectors). The crystal used was a NaF, as it is known to have a long relaxation time of 37 s for Na [KGK$^+$00]. This long relaxation time was confirmed by our September 2016 tests, since no decrease of asymmetry was observed during 4 s.

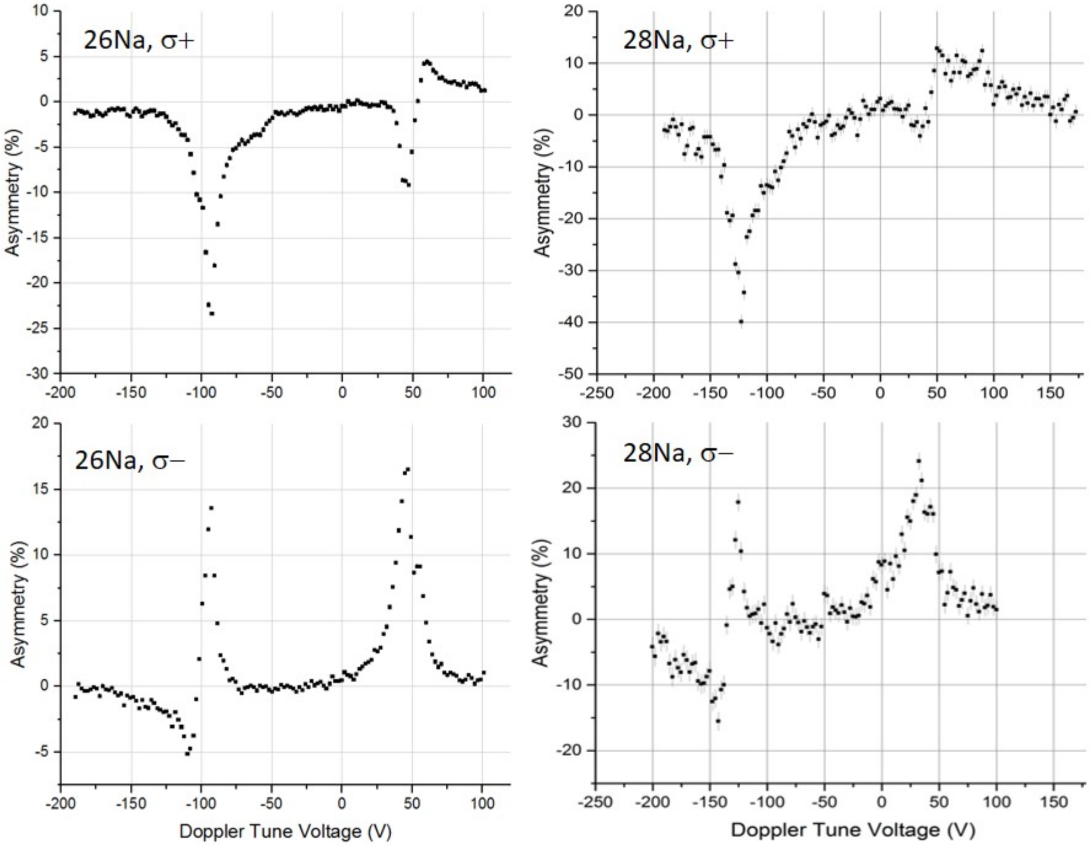

Figure 4. Hyperfine structure of the D2 line in atomic 26Na (left) and 28Na (right) as a function of the Doppler tune voltage observed in the β-decay asymmetry following excitation with $\sigma+$ (top) and $\sigma-$ (bottom) light. Each point corresponds to β counts recorded after only 1 proton pulse. Independent instrumental baseline was subtracted from all spectra. Statistical uncertainties in ^{26}Na spectra are smaller than the points.

The laser power in front of the circular polarizer was 100 mW with the laser beam diameter set between 10 and 15 mm, to ensure that all atoms in the beam could be excited with the laser. The degree of circular polarization of the light during experiment determined behind the exit window varied between 80 and 90%.

4.2. Results

The commissioning tests included changes in laser polarization and laser power, change of the crystal, and changes in the strength of the guiding fields and the NMR field. After various optimisations, the hyperfine structure of the D2 line for ^{26}Na and ^{28}Na with both σ^+ and σ^- laser polarization were recorded, as shown in Fig. 4.

The largest β-decay asymmetry for both nuclei was observed in the $|F = I+1/2\rangle \rightarrow |F' = I+3/2\rangle$ component for σ^+ light, seen at the Doppler tune voltage of around -100 V in Fig 4. The degree of asymmetry and the shape of the spectra are very similar to those reported by the COLLAPS collaboration [KGK$^+$00], [Kei96], where the achieved polarization was estimated to be between 40% and 60% (using the same transition and crystal, but with protons impinging on target every 4.8 s). Based on eqn. 2, the opening angle of our detectors (35 degrees), the β-asymmetry parameters given in Table 1, and the short observation time compared to the relaxation time in NaF, we obtain the degree of polarization in the strongest transition about 28% for ^{26}Na and 59% for ^{28}Na. These values are comparable to those reported in [KGK$^+$00] and [Kei96], as shown in Table 1. The lower polarization in ^{26}Na is mostly due to the higher spin of this nucleus, which leads to a lower degree of polarization. **The ratio of the nuclear spin polarization of ^{28}Na ($I = 1$) to polarization for ^{26}Na ($I = 3$) for the strongest component of the D2 transition is expected to be 1.6 [Kei96]. Our ratio of 2.1 is somewhat larger than this value.** The difference might come from lower asymmetry for ^{26}Na due to the "contamination" from nuclei implanted earlier and polarized with light at a different Doppler-shifted frequency, as described at the end of the previous section.

5. Outlook and summary

The degree of β asymmetry and spin polarization reported here, when compared to the established literature values, shows that the VITO laser polarization setup is ready to enter into the next stage of experimental campaigns.

The upgrades planned in the coming months concern an upgrade of the β-detection system, polarization of singly-charged ions, implantation of ions and atoms into liquid hosts, and the development of a set-up to measure angular correlations between emitted β particles, γ radiation, and eventually also neutrons from very short-lived nuclei. At a later stage we envisage to install a reionization cell and a 90 degree deflector, which would allow electrostatic bending of the ion beam (polarized either as ions or atoms). This will decouple the ions from the laser beam and will avoid polarization losses when turning the spins in the magnet's field.

The first planned physics experiments will concern fundamental interactions and NMR studies for chemistry and biology. Three proposals using the VITO laser polarization line have already been approved by the ISOLDE Scientific Committee. One of them [V$^+$14] concerns the high-precision measurement of the β-asymmetry parameter in the mirror decay of ^{35}Ar, which - with 0.5% precision - should contribute to the determination of the V_{ud} quark mixing matrix element, of prime importance for the tests of the unitarity of the CKM matrix. Two other proposals [M. 13b], [M. 13a] are devoted to NMR studies in liquid samples aiming to record the first biologically relevant chemical shifts obtained with the β-NMR method. The first of these proposals will use a ^{31}Mg beam while the second one aims at performing polarization tests of Cu isotopes. In addition, there is already interest to extend the beta-gamma studies to nuclear structure [Y$^+$10] and to add beta-neutron correlation studies [Mad]. β-NMR for nuclear structure and material science can be also envisaged.

In summary, we have reported here on the first spin-polarized radioactive beam using the new laser-polarization setup at the VITO beamline at ISOLDE. The degree of beta asymmetry and the underlying degree of spin-polarization were investigated with short-lived ^{26,28}Na beams. The results achieved earlier at the COLLAPS setup could be fully reproduced. The first stage of the experimental setup has thus been successfully commissioned and is now ready for physics experiments. Upgrades to the setup are already under way.

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