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Proposal to the INTC

Nuclear moments and charge radii of magnesium isotopes from N=8 up to (and beyond) N=20.

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Abstract.

We propose to measure the nuclear monopole, dipole and quadrupole moments of magnesium isotopes from the neutron deficient nuclei near the N=8 shell closure (^{21}Mg), up to the neutron rich Mg nuclei beyond N=20 (^{33}Mg). The physics issues that will be addressed in this project are related to

- * the properties of mirror nuclei (e.g. ^{21}Mg – ^{21}F being members of a T=3/2 multiplet)
- * the evolution of shell structure and deformation with isospin.
- * changes in the shell structure in the 'island of inversion' around ^{32}Mg and along the N=9 isotones.

Radioactive beams of Mg isotopes will be produced by the RILIS ion source. The Mg isotopes will be resonantly polarized at the COLLAPS set-up. With β-NMR techniques, precision measurements of g-factors and quadrupole moments of the radioactive ^{21,23}Mg and ^{29,31,33}Mg isotopes will be performed. Isotope shifts, thus changes in mean square charge radii, will be deduced from hyperfine spectra measured by collinear laser spectroscopy methods. This will provide complementary information on the Mg ground state deformations.

For the program in total 35 shifts of radioactive beam spread over several runs are requested for a period of two years starting from spring next year.

Physics motivations.

The magnesium isotopes, with 4 protons in the sd-shell, and neutrons gradually filling the sd-shell between N=8 and N=20, are an excellent laboratory to study the effects of changes in the proton-neutron interaction due to filling of the neutron sd-shell. At the two sides of the valley of stability, beyond the N=8 shell closure on the neutron deficient side and beyond the N=20 shell closure at the neutron rich side, short-lived magnesium isotopes occur (table 1). Such short-lived isotopes with non-zero spin (the odd Mg isotopes) are ideally suited for detailed investigations of their ground state nuclear moments (dipole and quadrupole) using β-NMR spectroscopy methods on polarized radioactive beams. At ISOLDE, highly polarized beams of radioactive Mg isotopes can now be produced using the collinear laser spectroscopy setup described below.

Table I : Properties of odd Mg isotopes. The calculations have been performed in an sd-shell model space with USD interaction, except for ^{31,33}Mg where calculations were performed in the sd-pf space with IOKIN.spdf [Smi03]. For ^{31}Mg, results labelled N are normal states and labelled I are intruder states. The result from a Mont Carlo Shell Model by Otsuka et al. [Ots03] is labelled M, because mixing between normal (0p-0h) and intruder (2p-2h) configurations are considered.

Isotope	N	I^{π}	$T_{1/2}$	g_{free}-g_{eff}	g_{exp}	$\mu_{exp}(\mu_N)$	Q_{eff}(mb)	Q_{exp}(mb)
21Mg	9	(3/2)+ (5/2)+	121.5 ms	/ -0.391			/ -127	
23Mg	11	3/2+	11.3 s	-0.344	-0.355	-0.5364(3)	+104	114(2)
25Mg	13	5/2+	Stable	-0.363	-0.34218	-0.85545(8)	+186	199(2)
27Mg	15	½+	9.48 min					
29Mg	17	3/2+	1.3 s	0.635			-95	
31Mg	19	(3/2+) N (3/2+) I (3/2+) M (7/2-)	230 ms	0.89 - 0.69 0.43 - 0.37 0.81 – 0.63 -0.32 - -0.20			+92 -146 +50 -204	
33Mg	21	(3/2+) (7/2-)	90 ms	0.76 - 0.58 -0.38 - -0.25			+129 -140	
N=normal; I=intruder; M=mixture								

There is a special physics interest in the neutron deficient, as well as the neutron rich region of Mg isotopes far from stability. Also the even-even isotopes, having a spin I=0 and thus not accessible for studies using precision measurements with nuclear hyperfine interaction methods, can reveal interesting information. By collinear laser spectroscopy using the same laser beam that has been developed for polarizing the odd Mg isotopes, we will be able to measure the atomic isotope shift and to deduce valuable information on the changes in nuclear charge radii between the magic numbers N=8 and N=20. Such measurements including the hyperfine structure, can also be performed on the abundantly produced longer-lived odd-A isotopes.

(1) Nuclear structure at the proton drip line.

The ground state spin of ^{21}Mg, a nucleus at the proton drip line, is not known. This nucleus has one neutron outside the closed *N* = 8 shell (assuming the normal shell model ordering of orbitals) and continues the sequence of isotones ^{15}C, ^{17}O, ^{19}Ne for which the ground state properties (including moments) are well known [Sto03]. A detailed investigation of the ^{21}Mg hyperfine spectrum using a polarized beam, and a precision measurement of its g-factor using β-NMR spectroscopy, will allow to determine the ground state spin of this isotope. Comparison of these properties with those of ^{15}C, ^{17}O and ^{19}Ne will allow investigating possible changes in the shell structure in the N=9 isotones from Z=6 up to Z=12.

^{21}Mg is also an interesting case for the study of properties of mirror nuclei. Only since the 90ies magnetic moments of T=3/2 mirror pairs have become accessible for investigation, through the projectile fragmentation induced spin-polarized beams. The Osaka-RIKEN-HIMAC-LBL collaboration has been able to measure the first complete quartet of T=3/2 mirror magnetic moments in the p-shell [Mat02]. The p-sd-shell mirror pair for A=17 has been completed at ISOLDE (IS 389) by a collinear laser spectroscopy measurement of the magnetic moment of ^{17}Ne [Gei02]. Assuming isospin symmetry, the spin expectation value can be deduced from the isoscalar (the sum) moment. A remarkable result is found in the ^{9}C-^{9}Li doublet, where the spin expectation value, deduced from the experimental mirror magnetic moments, is much larger than unity. In figure 1 this value is compared to the spin expectation values in T=1/2 mirror pairs. The other T=3/2 mirror pairs, for A=13 in the p-shell and for A=17 in the p-sd shell, are shown as well. In each of these cases the values are around or less than unity. The result for the A=9 mirror pair has not been understood theoretically until now.

The T=3/2 mirror pair ^{21}Mg-^{21}F is one of the few accessible T=3/2 cases in the sd-shell. The magnetic moment of ^{21}F has been measured [Mat99], so measuring the ^{21}Mg magnetic moment will allow to complete the result and will give for the first time information on T=3/2 mirror nuclei in the sd-shell (at least for Z even).

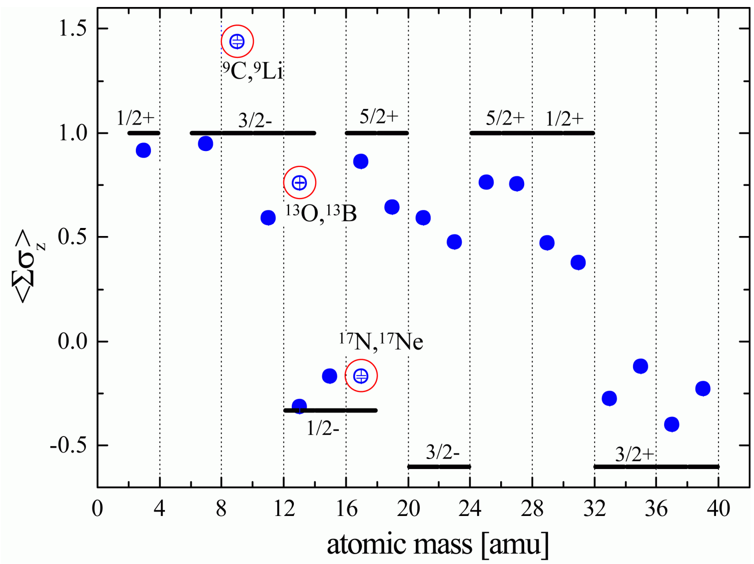


Figure 1: Spin expectation values for odd neutron states in the T=3/2 multiplet for A=9; 13 and 17 (open circles), compared to the values deduced in T=1/2 mirror pairs (filled circles). Error bars are all smaller than the dot.

A third motivation to study the properties of ^{21}Mg, and the trend in the ground state deformation of neutron deficient Mg isotopes, is related to the recent observation of increased reaction cross sections σ_R of ^{17}F, ^{23}Al and ^{27}P [Zha02]. The abnormally larger cross section than their neighboring nuclei suggests that there may exist a skin or halo structure in these isotopes with respectively N=8, N=10 and N=12 neutrons. Usually σ_R increases smoothly with A for an isotope series, because it is proportional to the mean square matter radius.

Compared to this, the mean square charge radius is much more sensitive to (proton) halo effects at the proton drip line. For ^{17}Ne it has been possible to measure the optical isotope shift yielding this quantity with respect to the less neutron deficient isotopes [Gei02]. The observed increase in the charge radius was found to be too small to support a pronounced halo structure.

(2) Nuclear Structure around N=20.

At the neutron rich side, the physics motivation is related to the study of properties of nuclei located near or inside the “island of inversion” around $N = 20$ and $Z = 12$. Several studies have revealed that the ground state of some of these nuclei, such as ^{32}Mg and ^{30,31}Na, are strongly deformed [Mot95,Pri02]. That has been interpreted in a shell model context, as a reduction of the neutron *sd-pf* shell gap along the N=20 isotones, as a function of Z. Due to the reduced shell gap, intruder configurations (*2p-2h* or *1p-1h* excitations of neutrons from the *sd*-shell into the *pf*-shell) appear at low excitation energy and even become the ground state in some cases. This has been confirmed e.g. by magnetic and quadrupole moment measurements on the neutron rich Na isotopes at ISOLDE [Kei00, Uts02]. Moment measurements are also carried out on the neutron rich Al isotopes (at GANIL), in order to investigate the ground state structure in these isotopes located between the suggested spherical ^{34}Si and deformed ^{32}Mg region [Bor02,Him03].

In the chain of Mg isotopes, ^{31}Mg and ^{33}Mg play an important role in understanding the changes in shell structure around N=20. With respectively one hole in the sd-shell (^{31}Mg), and one particle in the pf-shell (^{33}Mg), these nuclei will be governed by neutrons in the $d_{3/2}$ and $f_{7/2}$ orbitals. Within the *sd*-shell model, ^{31}Mg should have a $3/2^+$ ground state and ^{33}Mg a $7/2^-$ ground state. However, calculations performed for ^{31}Mg in a more extended model space, allowing *1p-1h* excitations and *2p-2h* excitations from the *sd* into the *pf*-shell, results in a deformed $7/2^-$ (*1p-1h* intruder) ground state. If mixing between the normal $3/2^+$ $(0\hbar\omega)$ and the *2p-2h* intruder $3/2^+(2\hbar\omega)$ is taken into account, the $7/2^-$ remains the ground state, but a deformed $3/2^+$ state occurs at very low excitation energy as well [Smi03, Ots03].

A beta-decay study of ^{31,32}Na, decaying to states in ^{31}Mg, performed some years ago at ISOLDE, suggested that the ground state spin/parity of ^{31}Mg is (3/2)+ [Klo93]. The lower part of the level scheme deduced from that work is presented in figure 3. The decay from the ^{31}Na positive parity ground state will mainly feed positive parity states in ^{31}Mg, including the lowest observed state, which is suggested to be the ground state. Negative parity states in ^{31}Mg might be fed via the beta-delayed neutron decay of ^{32}Na.

A recent ISOLDE fast-timing measurement [Mach03] on some excited levels in ^{31}Mg, populated again via the βn-decay of ^{32}Na, has revealed a short-lived isomeric state at 461 keV, $T_{1/2}$ = 10.5(8) ns. This isomeric state was interpreted as a possible intruder $7/2^-$ or $3/2^-$ state.

On the other hand, some years ago a long-lived isomer ($T_{1/2}$ at least 10 μs) with spin I=7/2 has been discovered at GANIL [Teu01,Ney01]. The isomer is identified using the β–Level Mixing Resonance (LMR) method on a *spin-aligned* projectile fragment beam [Ney94] at the LISE projectile fragment separator. In a LMR curve, the number of resonances that are detected in the β-decay asymmetry, as well as the distance between the resonances, allows a unique spin determination. This is demonstrated in figure 2, where the observed level mixing resonances in the β-decay of ^{31}Mg, have been fitted assuming a spin I=3/2, I=5/2 and I=7/2. The good agreement of the theoretical I=7/2 curve, and the fact that these resonances require a lifetime of at least 10 μs to be observable, is a strong indication that a long-lived $I^\pi=7/2^-$ intruder state is present in ^{31}Mg. The presence of a long-lived intruder $7/2^-$ isomer, next to a $3/2^+$ isomer in ^{31}Mg (it is at this moment probably not clear which is the ground state), is a clear signature for the possible coexistence of prolate, oblate and spherical states at low excitation energies.

To further identify the properties of the long-lived states in ^{31}Mg, spin-polarized fragment beams were developed at GANIL [Bor02]. A β-NMR experiment on a polarized ^{31}Mg beam has failed due to the very low intensity of the polarized fragment beam, being a factor 5 to 10 lower than the yield of an aligned beam.

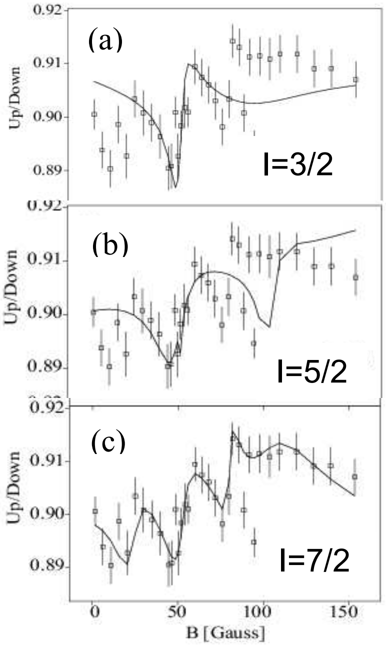


Figure 2: Fit of the LMR-data taken at GANIL, for ^{31}Mg implanted in a Mg single crystal at 4.1(1) K.

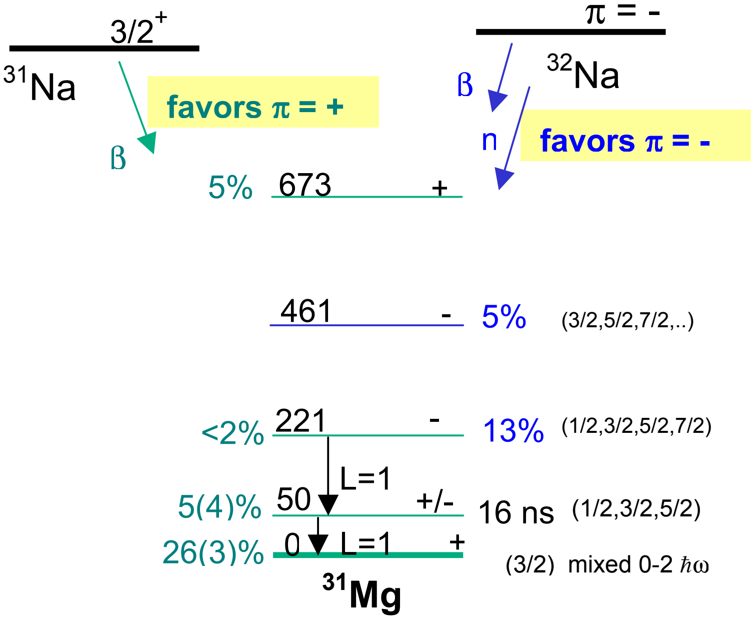


Figure 3: Excited states in ^{31}Mg, populated via the β-decay of ^{31}Na and ^{32}Na.

One of the goals of this proposal is therefore to measure the g-factors and quadrupole moments of both long-lived isomers in ^{31}Mg. Optically polarized beams at ISOLDE-CERN have the advantage that the polarization is induced via a 'resonant' atomic transition, which is sensitive to polarizing *either* the I=3/2 *or* the I=7/2 state. That means we are able to investigate the β-NMR (or β-LMR) spectra for both states independent from each other, while at a projectile fragmentation facility there is no possibility to distinguish the isomeric from the ground state beam. While a precision measurement on the g-factor, in combination with the hyperfine structure, will give direct information on the spin of the investigated states, its spectroscopic quadrupole moment will allow to deduce information on their deformation.

A measurement of the moments of the N=21 nucleus, ^{33}Mg, will allow to confirm the suggested ground state spin/parity assignment ($I^{\pi} = 3/2^{+}$) [NUM01]. This assignment is based on a study of the beta-decay from a ^{33}Na beam at ISOLDE, which suggests that the intruder state has become the ground state in ^{33}Mg.

(3) Deformation changes from N=8 to N=20.

Apart from a continuous increase with the nucleon number and pronounced shell effects, the mean square charge radii as a function of N reflect the development of deformation across the shell. In the sd-shell, this has been shown for Na, where laser spectroscopy measurements of isotope shifts have been performed already in the 70ies [Hub78]. More recently also isotope shifts for Ne-isotopes were performed, for which an extremely sensitive method of collinear laser spectroscopy has been developed at ISOLDE [Gei02]. For magnesium, it will be straightforward to perform optical isotope shift measurements in the region between ^{22}Mg and ^{30}Mg, where the yields are sufficient for a conventional fluorescence detection of optical resonances. These measurements, as well as accurate measurements of the hyperfine structure of odd-A isotopes, are anyway necessary to locate exactly the resonance positions of the short-lived isotopes to be investigated by β-NMR techniques.

Rather accurate isotope shift measurements are essential for resolving the small field shift effects that contain information on nuclear radii. This will be easily feasible only with the fluorescence detection for which the resonance shapes are not influenced by non-linear optical pumping effects and are thus independent of the hyperfine structure quantum numbers involved in the transitions.

An extension of isotope shift measurements towards both shell closures will depend on possible improvements in the sensitivity of fluorescence measurements on the one hand, and on the quantitative understanding and description of the β-asymmetry signals as a function of the laser frequency on the other hand.

Experimental setup.

A schematic view of the experimental setup in use for the experiments proposed here is shown in figure 4. Isotope-separated beams of the Mg isotopes are guided to the apparatus and merged with a beam of circularly polarized laser light in order to polarize the 60 keV ion beam by optical pumping. For magnesium, the most suitable optical pumping scheme is found in the excitation from the $3s\ ^2S_{1/2}$ ground state to one of the first excited *p*-states, $3p\ ^2P_{1/2}$ or $3p\ ^2P_{3/2}$, of the singly charged ion Mg+ [Dru80]. The transition lies in the ultraviolet (UV) spectral range at $\lambda = 280$ nm, which requires a frequency doubling of CW dye laser radiation. By a major investment of both funds and manpower we have installed an external ring cavity for efficient frequency doubling of the available dye laser radiation at 560 nm. Compared to the previously used [Gei99] intra-cavity frequency doubling, this gives a gain by a factor of 10 in the UV power available for the optical pumping process.

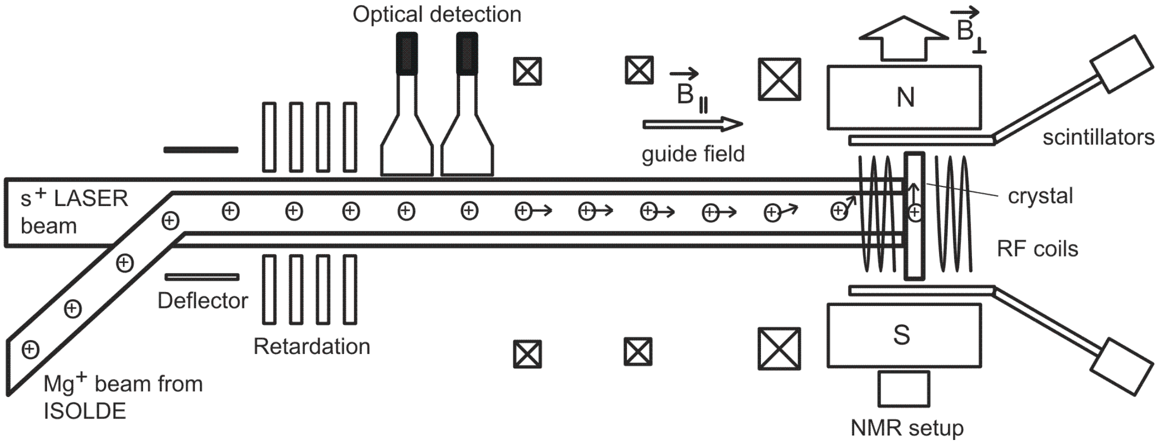
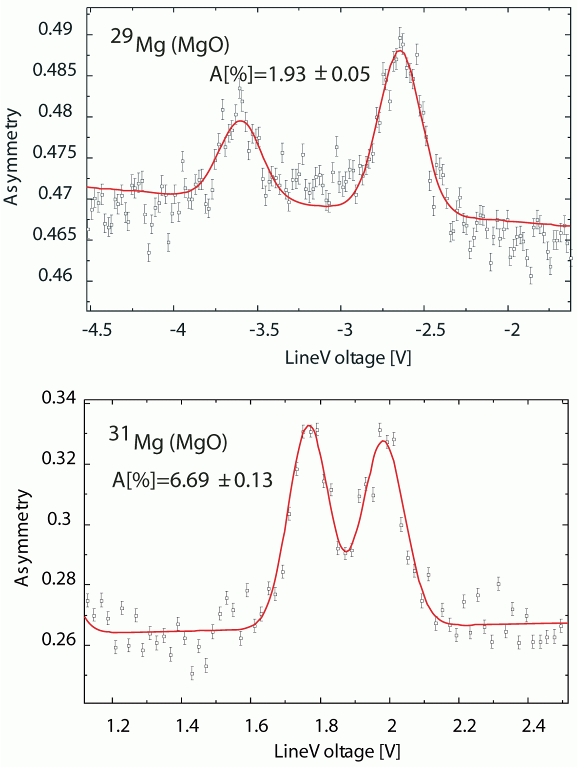


Figure 4: Schematic view of the experimental setup used for in-beam optical polarization, optical detection, and β-NMR experiments.

The optical interaction region is kept at a variable electrical potential for tuning the Doppler-shifted laser frequency into resonance. Longitudinal polarization of the total (electronic and nuclear) spin system is created in several cycles of excitation and decay. The optical detection of the emitted fluorescence light as a function of the retardation potential allows to measure isotope shifts and the hyperfine structure of the longer-lived isotopes. A gradually increasing magnetic guiding field is used to rotate and then decouple the spins adiabatically while entering the transverse field of the NMR magnet (about 0.3 T). The ions are implanted into a single crystal placed in the center of this magnet. The β-decay of the polarized nuclei is detected by two scintillation counter telescopes placed between the thin windows of the vacuum chamber and the magnet pole faces. The asymmetry is then defined as the normalized difference between the count rates of both telescopes.

Optically polarized Mg beams

The new frequency doubling installation for 280 nm has been tested and optimized during the summer, and UV-beam powers of up to 60 mW have been reached. In a recent test run, significant amounts of β-asymmetry have been observed for optically polarized beams of ^{29}Mg and ^{31}Mg (figure 5). The actually available power (which is measured to be 25 mW just in front of the collinear beam line) is close to the value needed to produce a maximally polarized ^{31}Mg beam, as demonstrated in figure 6(a).



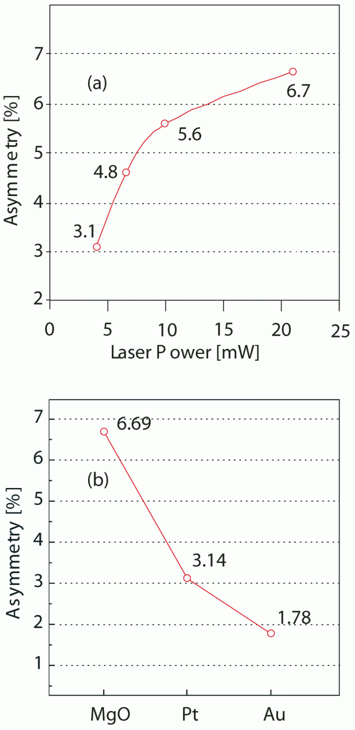


Figure 5: β–decay asymmetry observed for resonantly polarized ^{29}Mg and ^{31}Mg beams, using the optical pumping method with a CW laser.

Figure 6: (a) Dependence of the asymmetry on the laser power in the UV laser beam. (b) Dependence on the implantation crystal.

The observed β-decay asymmetries not only depend on the polarization of the nuclei, but also on the decay schemes (asymmetry parameter) and on the amount of polarization that is maintained after implantation in a suitable crystal. During the 5 shifts of testing, we have also been looking for the best implantation crystal to perform g-factor measurements (so crystals with a cubic lattice structure). The polarization for the ^{31}Mg beam was best maintained in a MgO crystal (a crystal that was also used in our earlier measurements at GANIL), while relaxation effects significantly reduced the observed asymmetry in Pt and Au crystals (fig. 6b).

Feasibility of the experiments

(1) Nuclear hyperfine interaction measurements on polarized beams.

We have demonstrated that it is possible to produce large amounts of polarization in radioactive beams of Mg isotopes, using the UV light produced by frequency doubling of a CW dye laser.

We have demonstrated that the crystal that maintains best the produced spin-polarization, is MgO, a crystal without an electric field gradient, and thus suitable for g-factor measurements on odd Mg isotopes. For quadrupole moment measurements, a MgF_2 crystal with a large electric field gradient (EFG = 70 10^{15} V/cm^2) will be used. This crystal has been used by Matsuta et al. for measuring the quadrupole moment of ^{23}Mg at RIKEN [Mat02].

The yields of ^{29,31,33}Mg beams, produced from a UC_2 target and laser ionized by the RILIS laser ion source have been measured during the test run (table 2). Assuming a β-detection efficiency of about 10%, we can also calculate the amount of laser-ionized Mg isotopes that reached our set-up.

Comparison of the β-count rate with the RILIS lasers ON and OFF, allowed us to estimate the amount of contamination (mainly from surface ionized Na ions) in the ISOLDE beam delivered to our set-up (we used suitable beam gates to cut short-lived contaminants). The results are also presented in table 2.

Table 2: Measured ion rates and β-asymmetries for the neutron rich Mg isotopes produced via laser ionization of radioisotopes produced with a 1.4 GeV proton beam at average intensity of 3.10^{13}protons/puls on a UC_2 target.

Isotope	β-asymmetry	β-counts/puls	OFF/ON ratio	ions/puls
29Mg	2.0(1)%	650.000	7 %	6.5 10^6
31Mg	6.7(1) %	32.000	2 %	3.2 10^5
33Mg	/	800	5 %	8.0 10^3

The combination of a high yield with the large experimentally observed asymmetries will allow to perform precision measurements of the g-factors and quadrupole moments for each of these isotopes, using the β-NMR, β-NQR and β-LMR methods (the best suitable method will be chosen for each case).

Beams of ^{21}Mg and ^{23}Mg could be produced via a SiC target (yields need to be tested).

(2) Measurements of isotope/ isomer shifts

Isotope or isomer shifts of all can be measured using the same laser beam as developed for the polarization. Measurements using either optical detection (for most stable isotopes) or beta-detection (for the isotopes far from stability) can be performed.

This study will be supported by a theoretical development at Leuven, to describe the optical pumping process in a density matrix formalism, starting from the hyperfine interaction and the atom-photon interaction Hamiltonians.

Beam time request.

Rather than making a detailed beam time request, we propose to ask for a total amount of **35 shifts**, to be spread over several runs of 2-4 days, in the coming 2 years. Before each radioactive beam time, about 1 shift of stable beam will be required for beam line, laser, and detector tuning.

Most of the beam time will be devoted to optimizing and carrying out the β-NMR measurements of spins, magnetic moments and quadrupole moments of ^{29}Mg, ^{31}Mg, ^{33}Mg and ^{21}Mg. A calibration of the magnetic field used to determine precisely the g-factors has to be performed in short β-NMR measurements on ^{8}Li, ^{26}Na or ^{20}Na beams which are produced from the same targets by surface ionization. During a changeover time of 1 to 3 shifts (for the laser and the apparatus) the beam can be given to other users.

The isotope shift and hyperfine structure measurements on the even and more abundant odd-A isotopes can be incorporated in the start-up of the runs, when optical reference measurements are anyway performed to determine exactly the laser frequency and to establish a scale for the resonance positions. We may ask for stable Mg beam time of a few shifts to optimize the fluorescence detection and to produce a good hyperfine structure reference spectrum on ^{25}Mg.

We will start with a detailed investigation of the neutron rich odd Mg moments of isomers and ground states, including a detailed study of the hyperfine spectra as well. These beams are now available and have proven to be sufficiently intense.

In the mean time, we hope that beam developments for the neutron deficient Mg isotopes will be performed, such that we can also perform studies on the neutron deficient nuclei, using the same laser beams to polarize them.

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