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Mg isotopes and the disappearance of magic $N = 20$

Laser and β-NMR studies

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Abstract

Collinear laser spectroscopy and β-NMR spectroscopy with optical pumping were applied at ISOLDE/CERN to measure for the first time the magnetic moments of neutron-rich ^{27}Mg, ^{29}Mg, ^{31}Mg and ^{33}Mg, along with the spins of the two latter. The magnetic moment of ^{27}Mg was derived from its hyperfine structure detected in UV fluorescent light, whereas the nuclear magnetic resonance observed in β-decay asymmetry from a polarised ensemble of nuclei gave the magnetic moment of ^{29}Mg. For ^{31}Mg and ^{33}Mg, the hyperfine structure and nuclear magnetic resonance gave the spin and the magnetic moment. The preliminary results for ^{27}Mg and ^{29}Mg are consistent with a large neutron shell gap at $N = 20$, whereas data on ^{31}Mg show that for this nucleus $N = 20$ is not a magic number, which is also the case for ^{33}Mg, based on preliminary analysis. Thus, the two latter isotopes belong to the "island of inversion".

PACS: **21.10.Hw** - Spin, parity, and isobaric spin; **21.10.Ky** - Electromagnetic moments; **27.30.+t** - $20 \leq A \leq 38$; **32.10.Fn** - Fine and hyperfine structure

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I. INTRODUCTION

Laser spectroscopy and similar techniques have played an important role in investigating the ground-state properties of many exotic nuclei. In our recent experiment we have used the collinear laser spectroscopy and the β-NMR method with optical pumping to probe an interesting region of the nuclear chart around $Z = 10-12$ and $N = 20$ which is characterised by large ground state nuclear deformations inconsistent with a closed $N = 20$ shell [1, 2]. Such behaviour can be explained only by a collapse of the usual filling of the nucleon single-particle levels, thus the region is also known as the "island of inversion". The existence of the "island" carries interesting questions related to its borders, physics mechanism, and connection to other phenomena present far from β stability, such as changing magic numbers [3]. In spite of intensive experimental and theoretical effort the answers to these questions are still not clear.

The nuclei of our interest were neutron-rich Mg isotopes. ^{27}Mg and stable isotopes were studied with classical collinear laser spectroscopy, which uses fluorescence detection. Their isotope shifts allowed us to derive changes in their charge radii, whereas the hyperfine structure of ^{27}Mg gave the sign and value of its magnetic moment. The shorter lived odd-neutron ^{29}Mg, ^{31}Mg and ^{33}Mg are well suited for β-NMR investigations with nuclear polarisation achieved by optical pumping. So far, we performed measurements of their hyperfine structure and nuclear magnetic resonance, all observed in the β-decay asymmetry. Such combined studies gave independently the sign and value of the magnetic moment, as well as the spin, which was unknown for ^{31}Mg and ^{33}Mg.

II. EXPERIMENTAL METHOD

The experiments were performed at ISOLDE/CERN where Mg beams were produced by bombarding a thick UC_2 target with 1.4-GeV protons (about 10^{13} protons/s on average). The Mg atoms were selectively laser ionized with the resonance ionisation laser ion source [4] and the ions were accelerated to 60 keV. Next, the mass separated Mg^+ beams were guided to our laser and β-NMR spectroscopy setup, where they were investigated with cw laser beams. A very suitable transition for resonance excitation with fluorescence detection or optical pumping is the 280 nm line of singly-charged ions from the atomic ground state $^2S_{1/2}$ to one of the two lowest excited states $^2P_{1/2}$ (D_1 line) and $^2P_{3/2}$ (D_2 line), with about

TABLE I: ISOLDE production rates (in ions/s), ground-state spin/parity and electromagnetic moments of neutron-rich Mg isotopes ($Z = 12$) [5–7]. In bold: studied by our group.

	yields	$t_{1/2}$	I^π	μ_I (μ_N)	Q (mbarn)
^{24}Mg		stable	0^+	0	0
^{25}Mg		stable	$5/2^+$	-0.85546(1)	201(3), 199.4(20)
^{26}Mg		stable	0^+	0	0
^{27}Mg	2×10^8	9.5 min	$1/2^+$	**measured**	0
^{28}Mg	3×10^7	20.9 h	0^+	0	0
^{29}Mg	6.5×10^6	1.3 s	$3/2^+$	**measured**	**measured**
^{30}Mg	1×10^6	335 ms	0^+	0	0
^{31}Mg	1.5×10^5	230 ms	$\mathbf{1/2^+}$	**-0.88355(15)**	**0**
^{32}Mg	7×10^4	120 ms	0^+	0	0
^{33}Mg	9×10^3	90 ms	**measured**	**measured**	**measured**

4 ns lifetime.

Beam energy in the range of 10-100 kV and energy spread around 1-2 eV are the main reasons why laser spectroscopy with a collinear propagation of the ion and laser beams is the most suitable laser-based method in ISOL-type facilities, such as ISOLDE. Its primary advantage is the narrow Doppler width, prerequisite of high resolution and sensitivity, whereas another advantage is the possibility to scan across atomic resonances by changing the acceleration voltage and not the laser frequency. Our experimental setup using this configuration is presented schematically in Fig. 1. To allow the collinear geometry the nuclei of interest are guided into the apparatus via an electrostatic deflector and are overlapped with the laser light which enters straight through a quartz window. After passing beam-shaping elements they reach the section where they are post-accelerated using a tunable voltage of maximum $\pm$10 kV.

This part is followed by the excitation region insulated from both sides by thick plastic flanges, where Mg^+ velocity is tuned into resonance with laser light. The last part of the apparatus hosts the implantation crystal surrounded by the NMR coil with thin scintillation β-detectors and the poles of the NMR magnet placed outside the vacuum chamber.

For fluorescence detection, we used two UV photomultipliers on which the photons were collected by quartz lenses and a cylindrical mirror. With this configuration, we obtained the overall efficiency in the range of 1 detected photon per 10^4 ions, compared to the typical background of 3 000 photons per second per 1 mW laser intensity. The low detection effi-

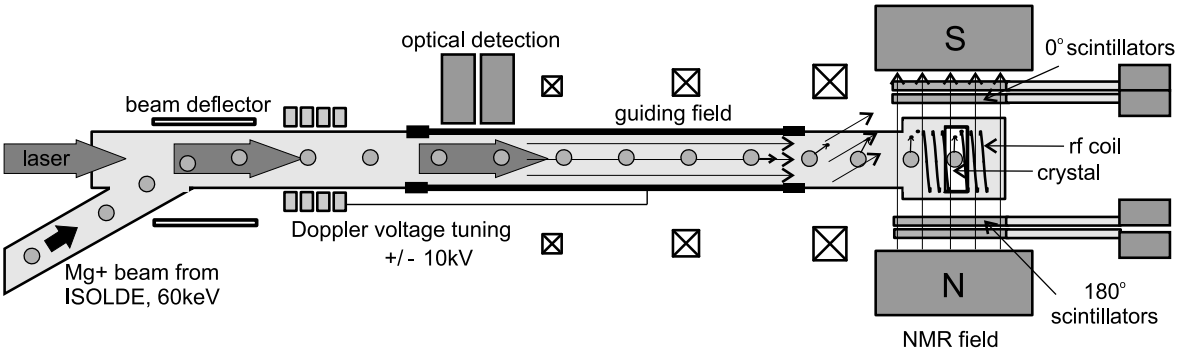

FIG. 1: Collinear laser spectroscopy and β-NMR setup.

ciency and high background (mainly due to scattered photons) limits the use of this method to isotopes produced more abundantly than about 10^6 ions/s, corresponding to longer-lived (or stable) Mg isotopes such as ^{27}Mg or ^{28}Mg (see Table I).

In the case of β-asymmetry detection, the laser light creates nuclear spin polarisation, which is achieved in the optical pumping process [8, 9] in which circularly polarised light polarises the total atomic angular momenta F by inducing transitions between the m_F magnetic sub-levels of the ground and excited state hyperfine multiplets. The theoretical polarisation is lowered due to hyperfine pumping, in which the excited state decays to the other ground state F-level which cannot be excited with the same laser frequency. The optical pumping takes place in the whole isolated section and the quantization axis for σ^+ or σ^- resonance absorption is established by a small longitudinal magnetic field. When the ions reach the fringe field of the NMR magnet, the rotation and subsequent adiabatic decoupling of the nuclear and electron spins takes place. The ions are then implanted into a suitable crystal placed in the centre of the magnet and β-decay electrons are detected in two pairs of thin plastic scintillators, placed at 0 and 180 degrees in front of the magnet poles. When the ions are in resonances with the laser light, the spins are polarised and the intensity of the emitted β particles is asymmetric with respect to the spin direction. For hyperfine structure measurements, the β-decay asymmetry is observed as a function of the acceleration voltage applied to the optical pumping region. On the other hand, for NMR studies the voltage is set at the hyperfine component giving highest β-decay asymmetry and a tunable radio-frequency field (generated by an rf current flowing through a coil placed around the host crystal) is applied perpendicular to the static magnetic field. This detection method is suitable for short-lived Mg isotopes with lifetimes from several milliseconds to several

seconds. Due to a very small background and high efficiency for β detection, measurements with down to several hundred ions/s are possible, as shown for ^{29}Mg, ^{31}Mg and ^{33}Mg (see Table I).

The continuous-wave laser system used for both exciting and optically pumping the ions/atoms of interest consists of an Ar^+ laser (Coherent Innova 400) pumping at 6 W in the multiline visible mode (mainly 488 and 514 nm) a ring dye laser (Coherent 699-21). The ring output is around 700 mW at 560 nm (with Pyrromethene 556 dye as active medium) and it is additionally frequency-doubled in an external cavity (Spectra-Physics Wavetrain) with angle phase matching and BBO as the non-linear crystal. With 5-10% efficiency, on average 20-50 mW of UV light at 280 nm are available. For optical detection as little as 1 mW is needed, whereas for optical pumping the saturation takes place for about 50 mW power [9] and usual measurements are carried out with 10-20 mW.

III. RESULTS

The hyperfine energy of a level with electron angular momentum J and nuclear spin I is, to the first order, given by

$$E_F = \frac{1}{2}AK + B\,\frac{3/4K(K+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}\,, \tag{1}$$

where F is the total angular momentum, $K = F(F+1) - I(I+1) - J(J+1)$, and A with B are hyperfine structure parameters proportional respectively to μ_I and Q. These nuclear moments are easily derived from A and B parameters if reference data exists for at least one isotope. In such a case, e.g. for μ_I:

$$\mu_I = \mu_x\,\frac{A\,I}{A_x I_x}\,, \tag{2}$$

where one neglects corrections due to finite charge and magnetisation distribution of the nucleus, which for Mg are in the order of 10^{-3} [10].

The electromagnetic moments of nuclei can be also derived from NMR measurements. For example, in a cubic host crystal with no quadrupole interaction energy, the Zeeman energy of a nucleus with spin I in a strong magnetic field B_0 is given by

$$E(m_I) = -m_I(\mu_I/I)B_0 = -m_I g_I \mu_N B_0 = -m_I\,h\,\nu_L\,,$$

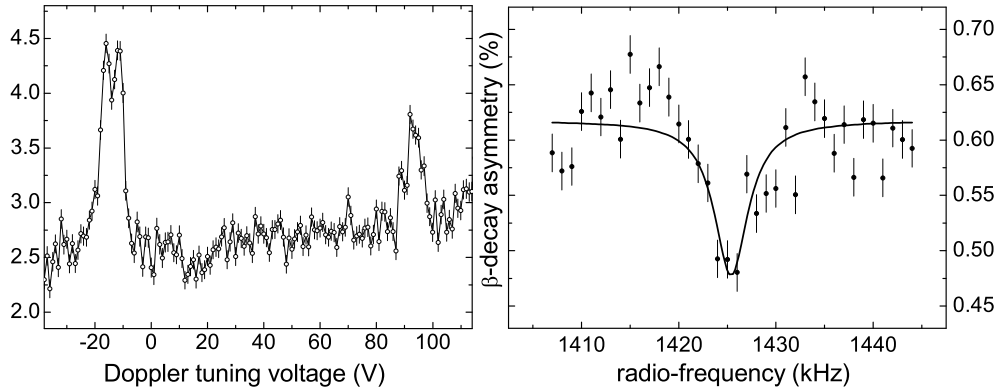

FIG. 2: The hyperfine structure of the D_2 transition (left) and the NMR resonance (right) of ^{29}Mg, observed in the β-decay asymmetry.

where m_I is the magnetic quantum number, g_I is the nuclear g-factor, and ν_L is the Larmor frequency. A radio-frequency field corresponding to ν_L induces transitions between Zeeman levels which can be observed as the NMR resonances. By recording the NMR signal on the nucleus of interest and on a reference nucleus with known μ_I, one can determine the unknown g-factor and magnetic moment by using the relation

$$|g_I| = |g_{ref}|\frac{\nu_L}{\nu_{ref}} \ . \tag{3}$$

If the reference is an isotope of a different chemical element, eqn. (3) has to include additionally the diamagnetic corrections to account for different shielding of the external magnetic field by the atomic electrons.

In the case when the spin of a given nucleus is not known it can be determined by combining information from the hyperfine structure and NMR. For the splitting between the $J = 1/2$ ground-state sub-levels $F = I+1/2$ and $F' = I-1/2$ one obtains $\Delta E = A(I+1/2)$, where the A-factor can be expressed in g_I and the ratio A/g_I known for the reference isotope

$$I = \frac{\Delta E}{g_I}\,\frac{g_{ref}}{A_{ref}} - 1/2 \ . \tag{4}$$

By measuring optically the hyperfine structure of ^{27}Mg and ^{25}Mg, and using the known magnetic moment of the latter (see eqn. 2), we were able to determine for the first time the magnetic moment of ^{27}Mg [11], with an uncertainty below 0.5%. In a similar way, but using the β-asymmetry detection, we recorded the hyperfine structure of shorter-lived ^{29}Mg and derived its magnetic moment, whose precision we increased to 0.15% by β-NMR

measurements (see Fig. 2) [11]. Since the ground-state spins were not known for ^{31}Mg and ^{33}Mg, the analysis in these two cases combined the hyperfine structure and NMR studies. The results comprise unexpected spins and magnetic moment with uncertainty as low as 0.02% for ^{31}Mg [7] and 0.2% for ^{33}Mg [12].

Comparisons with shell model calculations show that in the ground state of ^{31}Mg the neutron shell is open at $N = 20$ [7], which places this nuclide inside the "island of inversion". The analysis for ^{27,29,33}Mg is still not finalised, therefore no values can be presented at this point. However, preliminary results already show that in the ground state of ^{27}Mg and ^{29}Mg $N = 20$ remains a good shell closure [11], which is not the case for ^{33}Mg [12]. Thus, the latter isotope belongs to the intriguing "island".

Future plans in this region of the nuclear chart include isotope shift measurements up to ^{33}Mg, which will yield changes in charge radii for different Mg isotopes, and will thus show deformation areas. These studies will combine the fluorescence detection with the β-decay asymmetry detection.

The above studies are presented in the Ph.D. theses of M.K. and D. Yordanov.

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