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Spin and Magnetic Moment of ^{23}Mg

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A negative magnetic moment of ^{23}Mg has been determined by collinear laser spectroscopy at CERN-ISOLDE. The absolute value is in agreement with previous measurements by nuclear magnetic resonance while the sign points at high-seniority configurations. The result is consistent with shell-model predictions for nuclei with valence nucleons in the sd shell.

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I. INTRODUCTION

Collinear laser spectroscopy was deployed for charge-radii measurements over the magnesium isotopic chain [1]. An important objective was to propagate the study towards both ends of the sd shell where expected cluster configurations on one side and cross-shell excitations on the other would influence the nuclear size. The experiment indeed determined a transition to a deformed configuration at ^{31}Mg , and found a trend of ever increasing radii by the removal of neutrons from the lighter isotopes down to ^{21}Mg . This work combined for the first time fluorescence spectroscopy and laser-induced nuclear orientation for charge-radii measurements. The resulting magnetic moments have never been published, partly because alternative values had already been reported [2–7]. However, ^{23}Mg currently lacks electromagnetic-moments sign determination since it has been examined by nuclear magnetic resonance alone [3, 4, 8]. Furthermore, the associated experimental accuracy is not greater than the one offered by the present study. Apart from its importance from the nuclear-structure point of view ^{23}Mg is also a key probe for the study of fundamental interactions [9] specifically as a group member of the isospin 1/2 nuclei with mirror β transitions [10]. Below we discuss an independent spin and magnetic-moment measurement of ^{23}Mg , and offer an interpretation in terms of the spherical shell model.

II. EXPERIMENT

The experiment was carried out with the collinear laser spectroscopy setup [6] at ISOLDE-CERN. Radioactive nuclei were produced by high-energy protons impinging on a silicon carbide target. Magnesium atoms were resonantly laser ionized [11], accelerated to an energy of 50 keV and mass separated. The ion of ^{23}Mg was excited in the transition $3s\ ^2S_{1/2} \rightarrow 3p\ ^2P_{1/2}$ at 280.35 nm [12] which is free of quadrupole interactions and has a well resolved hyperfine structure. The corresponding ultraviolet light was produced by frequency doubling the output of a stabilized ring dye laser, using Rhodamine 19 as the active medium, pumped at 532 nm. The ion beam was overlapped with a laser beam and directed through an electrostatic lens for post-acceleration. Atomic excitations were detected in the ion-beam fluorescence as a function of the Doppler-shifted laser frequency.

A. Empirical line shapes

Typically, the shape of a spectroscopic line is closely described by the Voigt profile which is a convolution of a Lorentzian function representing the natural absorption profile and a Gaussian component accounting for Doppler broadening due

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FIG. 1. Fluorescence spectra of ^{24}Mg from a UC target (a) and a SiC target (b). The vertical scales are logarithmic.

FIG. 2. Fluorescence spectra of ^{23}Mg (a) and ^{25}Mg (b). The corresponding F quantum numbers are indicated above the individual transition peaks.

to the thermal motion of the atoms in the ion source. Through the years the Voigt profile has been approximated very accurately by the use of explicit mathematical functions for computational ease [13]. In most applications of collinear laser spectroscopy the Voigt line shape is in agreement with the observations, however, additional effects may also play a role. The spectral lines of ^{24}Mg in Fig. 1 illustrate the asymmetric line profile associated with the present study. The two measurements are taken under similar conditions in separate experiments. Both clearly show additional structures at the lower-energy side of the main resonance. It should be noted that the apparent effect in Fig. 1 is exaggerated by the logarithmic scale which has the purpose of magnifying the details at the base of the spectra. Clearly the intruder structures are periodic and seem to resemble the effect of inelastic collisions reported by Bendali and co-workers [14]. In their work a mono-energetic sodium ion beam passed through a sodium vapor for neutralization. Depending on the vapor densities side peaks resulting from multiple inelastic collisions with an energy defect corresponding to the $3s$ - $3p$ energy difference became prominent. The periodicity in our spectra does indeed correspond to a $3s$ - $3p$ excitation in the magnesium ion. However, our measurements do not involve neutralization, therefore the medium causing collisions is likely to be the residual gas in the vacuum beamlines after the point of ionization. In this respect, differences from one experiment to another, such as those in Figs. 1 (a) and (b), could be attributed partly to different vacuum conditions. The collisional excitations reported by Bendali and co-workers represent a particular case of forward scattering where the collision partners are identical atoms. The arrangement in the present work is considerably more complex since molecules and atoms of different masses and “softness” to excitation are involved. A change in the residual-gas density upstream from the ion source may also play a role. Modeling of the exact processes is challenging and would require a dedicated study. In this work we have analyzed the data using a realistic line profile consisting of a main resonance and three equidistant side peaks with positions determined by the $3s$ - $3p$ energy difference in the magnesium ion. High-statistics scans, as the one presented in Fig. 1 (b), have been made throughout the experiment in order to determine the height and the Gaussian width of the individual side peaks relative to the main peak. Subsequently these parameters have been used to fit the isotopes with hyperfine structure. The Lorentzian width, common to all peaks, and the Gaussian width of the main resonance have been maintained as free parameters. With such a line profile we have been able to obtain a very good description of the data, in particular reduced- χ^2 values close to unity have been obtained after fitting.

B. Magnetic moment

The atomic transition in use is free of quadrupole interactions. The relative positions of individual lines are, therefore, determined by the equation:

$$E_F = A \frac{F(F+1) - I(I+1) - J(J+1)}{2}, \quad (1)$$

applied for both the ground and the excited atomic states, where I is the nuclear spin, J are the respective electronic angular momenta, F are the total angular momenta, and A are the magnetic hyperfine parameters. The hyperfine anomaly in singly-ionized magnesium, taking into consideration the data on atomic sodium [15–17], is expected to be small with respect to the experimental uncertainties in this work. The A factors and the nuclear magnetic moments of any two magnesium isotopes are then related through the expression:

$$A \frac{I}{\mu} = \text{const.} \quad (2)$$

The constant essentially represents the average magnetic field per unit angular momentum induced at the origin by the atomic electrons. Its value is always positive allowing for sign determinations of nuclear magnetic moments directly from hfs measurements.

Considering the relative intensities of spectral lines, also known as Racah intensities [19], we have identified the hyperfine components in Fig. 2 and labeled them by the corresponding F quantum numbers. For both isotopes the line doublet starting from the state with the lower angular momentum is also lower in excitation energy. The hyperfine levels of $S_{1/2}$ are therefore inverted with the lower angular-momentum state being higher in energy. This arrangement is characteristic of negative A factors and consequently negative magnetic moments, as evident from the equations above. All experimental results are presented in Tab. I. The reference isotope is the stable ^{25}Mg whose magnetic resonance has been measured relative to ^{14}N [5]. However, we adopt the reevaluated value from Ref. [18] incorporating diamagnetic corrections and later numbers for the proton moment, recently supported by a double Penning-trap measurement [20], and the ^{14}N -to- ^1H frequency ratio [21]. The A factors of ^{25}Mg are consistent with previous studies [6, 22]. The $S_{1/2}$ parameters have been used for determining the final magnetic moment of ^{23}Mg . Without discussing the independent evidence, such as the relative intensities and the isotope shift, the fact that the magnetic moment of ^{23}Mg from this work is in agreement with the result from nuclear magnetic resonance [3] fixes the spin of ^{23}Mg with absolute certainty to $I = 3/2$. Indeed, there can be only one half-integer value that is consistent with the observed $S_{1/2}$ splitting $\Delta\nu = A(I + 1/2)$ and the A factor derived from NMR measurements with the aid of Eq. 2. With regard to the differential hyperfine anomaly in the $S_{1/2}$ state one is able to calculate $^{25}\Delta^{23} = -0.04(8)\%$ according to the definition in Ref. [15] and using the hyperfine parameters in Tab. I, and the known NMR values [3, 18].

III. INTERPRETATION

A negative magnetic moment can not be generated in the neutron sd shell without a $d_{5/2}$ contribution, hence the $3/2$ ground-state of ^{23}Mg must be determined by multi-particle interactions involving that orbital. Such high-seniority configurations are more likely to occur in the middle of the $d_{5/2}$ shell, and indeed the neighboring odd isotopes ^{21}Mg and ^{25}Mg both have ground-state spins of $5/2$ as one would expect from normal coupling. An equivalent spin change also occurs in the respective mirror partners, namely along the $N = 12$ isotonic chain of ^{21}F , ^{23}Na and ^{25}Al . The magnetic moment of ^{23}Mg has been previously discussed in the framework of isospin $1/2$ mirror doublets in the sd shell [3]. To gain a further insight into the configurations involved we have carried out shell-model calculations with the universal sd Hamiltonians USD [23] and USDB [24] using the code NuShellX @ MSU [25]. Experiment and theory are plotted against each other in Fig. 3 for all odd magnesium isotopes in the sd shell, except ^{31}Mg whose ground state involves particle-hole

TABLE I. Hyperfine A parameters from this work and a new value for the magnetic moment of ^{23}Mg .

	I	$A(3p^2P_{1/2})$	$A(3s^2S_{1/2})$	μ/μ_N
^{23}Mg	$3/2$	$-107.4(3)$	$-623.5(3)$	$-0.5366(3)^a$
^{25}Mg	$5/2$	$-103.1(2)$	$-596.4(2)$	$-0.85545(8)^b$
(MHz)				

^a Extracted in the $S_{1/2}$ multiplet; uncorrected for hyperfine anomaly; to be compared with $|\mu(^{23}\text{Mg})| = 0.5364(3)\mu_N$ from NMR [3].

^b Reference magnetic moment of ^{25}Mg [18].

FIG. 3. Ground-state magnetic moments of magnesium isotopes in the sd shell in units μ_N , versus shell model calculations. The respective mass numbers are indicated. The experimental uncertainties are smaller than the dots.

excitations into the pf shell [7]. In line with our previous findings [2, 6], in the beginning of the sd shell the USD interaction generates more accurate results, whereas already by midshell the USDB Hamiltonian is required, particularly for predicting the correct level ordering in ^{29}Mg . In all calculations free g factors have been used. The agreement between theory and experiment is generally good. In the case of ^{23}Mg it is the USD interaction that approaches the magnetic moment closer by the value $-0.52 \mu_N$. As expected, the $d_{5/2}$ orbital is dominant with about 75% occupation for both protons and neutrons. The protons do indeed play an important role since they undergo 2^+ or 4^+ coupling in about 60% of the wave function. The most abundant neutron configurations contain the three valence neutrons in the $d_{5/2}$ orbital coupled to either spin $3/2$ or $5/2$, but those fractions at 16% and 18%, respectively, are not large. In reality the wave function is very fragmented and a dominant configuration can not be highlighted. As to the magnetic moment of ^{31}Mg , a very close match with the USDB value $-0.83 \mu_N$ of the lowest $1/2^+$ state in ^{29}Mg has been previously pointed out [26, 27]. This is consistent with the picture of a cross-shell excitation of two paired neutrons which do not contribute directly to the magnetic moment. If the corresponding point was to be added in Fig. 3, similarly to the other cases it would lie close to the identity line.

IV. SUMMARY

In brief, we have studied ^{23}Mg by high-resolution collinear laser spectroscopy. An empirical approach to the observed spectroscopic line shapes has been discussed. The ground-state spin $3/2$ has been confirmed and a negative magnetic moment has been measured, thus highlighting the importance of high-seniority configurations. The absolute value is found consistent with previous studies by nuclear magnetic resonance. The odd magnesium isotopes in the sd shell have been investigated in the framework of the spherical shell model using the well-known universal sd Hamiltonians. The calculation on ^{23}Mg , indeed points to a strong $d_{5/2}$ contribution from both protons and neutrons and only a minor occupation of the neutron $d_{3/2}$ shell.

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