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Charge radii of magnesium isotopes by laser spectroscopy: a structural study over the sd shell

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We propose to study the evolution of nuclear sizes and shapes over the magnesium chain by measuring the root mean square charge radii of \(^{21}-^{32}\)Mg, essentially covering the entire sd shell. Our goal is to detect the structural changes, which in the neutron-deficient isotopes may originate from clustering, in a way similar to neon \([1]\), and on the neutron-rich side would characterize the transition to the “island of inversion” \([2, 3]\). We will combine, for the first time, the sensitive \(\beta\)-detection technique with traditional fluorescence spectroscopy for isotope-shift measurements and in such a way gain access to the exotic species near the \(N = 8\) and \(N = 20\) shell closures.

keywords: COLLAPS, collinear laser spectroscopy, charge radii, Mg

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INTRODUCTION

In the short history of nuclear physics the magnesium species attracted a substantial amount of attention and experimental efforts. With the discovery of deformed nuclear systems and their improved description by the Nilsson model \([4]\) \(^{24}\)Mg became a landmark in the nuclear chart, representing the lightest nuclei to exhibit this property. Their deformation was attributed to strong \(\alpha\)-type correlations \([5]\), which are in line with the basic concept
FIG. 1: Root mean square charge radii of lead isotopes across the $N = 126$ shell closure [18, 19]. Ground and isomeric states are represented by circles and triangles, respectively. Statistical errors are smaller than the symbols. Systematic uncertainties (correlated) are not depicted.

of the Nuclear Cluster Model and sets them apart from the heavier examples of nuclear deformation. With gaining access to the exotic regions of the nuclear chart, it became possible to test the very basis of our understanding of nuclear structure, the persistence of shell gaps and magic numbers away from the valley of stability. The extra binding energy and anomalous spin of $^{31}$Na [6, 7], which in the classical description has a closed neutron sd shell, suggested a “collapse of the conventional shell-model ordering” [8] and exposed again the idea of deformation in light nuclei. This idea was revisited repeatedly in recent times to explain the $\beta$-spectroscopy and Coulomb excitation of $^{32,34}$Mg [9–11] and, very significantly, the ground-state spins of $^{31,33}$Mg [2, 3]. On the neutron-deficient side, $^{21}$Mg was recently studied [12] to gain an insight of the mirror symmetry in nuclear systems. At present, the magnetic moments of all odd-mass magnesium isotopes in the sd shell are well known [2, 3, 12–15], determined almost exclusively by laser spectroscopy at ISOLDE - CERN. However, apart from the quadrupole-moment measurements of two isotopes, $^{23,25}$Mg [16, 17], their shapes and sizes have not been assessed experimentally until now. Measuring the root mean square (rms) charge radii of magnesium over the sd shell would make an invaluable contribution to an accurate description of this isotopic chain. It also represents a rare opportunity to link together all available studies in terms of a common observable.

PHYSICS MOTIVATION

One of the early attempts to comprehend the atomic nucleus was to describe it as a liquid drop. This model did not comply with the empirical fact that the nuclei have structure. Its basic concept, however, inherited by the droplet model, contributes to a somewhat generic description of the nuclear radii. The lead isotopes for instance (Fig. 1), reveal interesting structural changes, resulting in increased sizes near mid shell $N \approx 104$, odd-even staggering and a kink at the doubly magic $^{208}$Pb. This isotopic chain is a remarkable example of the
sensitivity of the nuclear radius to various aspects of the nuclear interactions, microscopic or collective, e.g. pairing correlations, shell structure, and nuclear deformation. In the lead nuclei, as for other heavy elements, these important effects appear as relatively small corrections to the steady increase of the radii, caused by the scaling of the nuclear volume with the number of nucleons. In the lighter regions of the nuclear chart, where mean-field description is valid to a lesser extent, the nuclear-structure effects may completely override the general trend of changes in the radii. The case of neon [1], with only two protons less than magnesium, is an outstanding example in this respect. In a typical mean-field calculation, e.g. [21], the radii of $^{17}_{\text{Ne}}$ up to $^{22}_{\text{Ne}}$ are much smaller than the experimental values in Fig. 2 and vary smoothly with increasing the number of neutrons. The experimental results are well reproduced with the Fermionic Molecular Dynamics (FMD) approach [22, 23], which includes various types of long-range correlations like halos and clusters. The increase of the charge radius from the semi-magic $^{18}_{\text{Ne}}$ ($N = 8$) to $^{17}_{\text{Ne}}$ is related to the development of a halo component of the wave function with a proton $s^2$ occupation changing from 15% to 40%. The inversed slope formed by the radii of $^{19}_{\text{Ne}}$ to $^{22}_{\text{Ne}}$ is due to admixtures of cluster configurations into their ground states. These admixtures are related to the known deformation properties and decrease with the mass number towards $^{22}_{\text{Ne}}$. Similar effects are very likely to occur near the strongly deformed $^{24}_{\text{Mg}}$, which is known to have a larger charge distribution than the heavier $^{25}_{\text{Mg}},^{26}_{\text{Mg}}$ [18]. With the same neutron-to-proton ratio as an $\alpha$ particle this nuclide, as well as the lighter magnesium isotopes towards $N = 8$, are highly susceptible to influence from cluster configurations.

On the neutron-rich side one expects yet another increase in the magnesium charge radii correlated with changes in the shell structure around $N = 20$. In these neutron-rich nuclei the $pf$ shell is partially populated before the $sd$ shell is complete. In terms of the spherical shell model several mechanisms are proposed to contribute to this inversion of the “normal” zero particle-hole (0p-0h) and “intruder” (np-nh) states: a reduction of the shell gap [24]; an increase in the neutron-neutron and proton-neutron interactions [24]; the monopole effect of the tensor force [25]. The transition to this “island of inversion” in magnesium is a one-step
FIG. 3: Mean square charge radii versus neutron number for the isotopes of argon, potassium, calcium, titanium and chromium as presented in Ref. [20]. Statistical errors are smaller than the symbols in most cases. Systematic uncertainties are not depicted.

process. A single neutron in addition to the sd ground state of $^{30}$Mg [26], results in a 2p-2h excitation to the pf shell into the $^{31}$Mg wave function [2]. For comparison, the transition to intruder states in neon, sodium and aluminum occurs smoothly, with a number of isotopes having mixed wave functions [27–30]. Such a sudden structural change in magnesium would certainly be detected and quantified in a rms charge radii measurement.

The island of inversion is only defined in terms of the spherical shell model, which does not account for variations in the nuclear shape. There is solid experimental evidence for deformation in the even-even isotopes $^{32,34}$Mg [10, 11] from Coulomb excitation studies. On the other hand, the odd-mass $^{31,33}$Mg [2, 3] are indirectly linked to this parameter by considerations in the Nilsson model. Thus, the transition to a deformed configuration in the magnesium nuclei is still not understood. Observing a common quantity for the even-even and odd-mass isotopes, like the rms charge radius, would yield a continuous picture of the nuclear-structure evolution throughout the chain and in particular over the borderline of the island of inversion.

Argon is so far the only element for which rms charge radii have been measured over the $N = 20$ shell closure, with sufficient number of isotopes on both sides to reveal the trend [20, 31] (Fig. 3). Unlike any other shell closure [32–34], and in particular unlike $N = 126$ in the lead isotopes (Fig. 1), there is no shell effect at the magic neutron number 20. This has been explained by a cancellation of monopole and quadrupole polarization of the proton core under successive addition of valence neutrons [31]. Experimental values for the charge radii of $^{31,32}$Mg, whose ground states are based on particle-hole excitations, will provide accurate input for the study of this shell gap away from stability.

Sodium is the only element whose isotope-shift measurements expand between the 8 and 20 neutron shell closures. The existence of only one stable isotope in this chain sets a severe constraint on the accuracy of the radii extracted from optical data [35]. Hence, magnesium,
Charge radii of Mg isotopes

with three stable isotopes for a reference, has the potential to become the first element for which accurate radii are available within the complete \textit{sd} shell.

**NEW EXPERIMENTAL TECHNIQUE**

We aim to combine for the first time the highly sensitive $\beta$-decay detection with conventional fluorescence spectroscopy for meaningful isotope-shift measurements. This idea naturally evolved from the success in simulating quantitatively [28] the nuclear polarization produced by optical pumping as a function of the laser frequency. While these simulations only qualitatively reproduced the hyperfine structure of atomic sodium, for known reasons [28], our studies of singly ionized magnesium showed a remarkable agreement between theory and experiment [13]. We are now confident that our knowledge is sufficient for extracting the small field shift in the D$_1$ line ($3s\,^2S_{1/2} \rightarrow 3p\,^2P_{1/2}$) and therefore the changes in the rms charge radii from $\beta$-detection spectra even for an element as light as magnesium. A sketch of the apparatus in the appropriate configuration is shown in Fig. 4.

![Collinear laser spectroscopy setup (COLLAPS) at ISOLDE - CERN](image)

**FEASIBILITY OF THE EXPERIMENT AND BEAM-TIME REQUEST**

The $\beta$-detection technique will allow for measuring the charge radii of $^{21,31}$Mg, whose yields (Tabs. I and II) are below the present limit for classical fluorescence spectroscopy. These isotopes were previously polarized in the D$_2$ line ($3s\,^2S_{1/2} \rightarrow 3p\,^2P_{3/2}$) [2, 12] and in the case of $^{31}$Mg a remarkable agreement was discovered with simulated spectra in this transition [13]. Hence, our intention to perform the studies in the D$_1$ line, due to the better resolution, does not present a principle challenge. Furthermore, $^{31}$Mg was previously polarized in this transition in search of optimum condition for NMR studies [36]. The measurements on $^{21}$Mg present a greater difficulty due to the isobaric contamination from surface ionized $^{21}$Na (Tab. I), whose $\beta$ radiation would overwhelm the signal of interest. The high-resolution separator (HRS) partly resolves the two isobars as shown in earlier
TABLE I: Test yields of neutron-deficient magnesium and sodium nuclei. The measurements have been taken in May 2007 with silicon carbide target number 353 at 490 A and line at 250 A.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>21Mg</th>
<th>21Na</th>
<th>22Mg</th>
<th>23Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{1/2}$</td>
<td>123(3) ms</td>
<td>22.49(4) s</td>
<td>3.857(9) s</td>
<td>11.317(11) s</td>
</tr>
<tr>
<td>ions/µC</td>
<td>$&gt;3 \times 10^3$</td>
<td>$\approx 4 \times 10^6$</td>
<td>$\approx 1 \times 10^6$</td>
<td>$\approx 1.5 \times 10^7$</td>
</tr>
</tbody>
</table>

TABLE II: ISOLDE yields of neutron-rich magnesium isotopes recorded at COLLAPS. The yields of $^{27-32}$Mg, given here for completeness, are taken from the ISOLDE database [39]. The measurements of $^{29-32}$Mg have been taken in May 2004 with uranium carbide target number 267 at 730 A and line at 350 A.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^{27}$Mg</th>
<th>$^{28}$Mg</th>
<th>$^{29}$Mg</th>
<th>$^{30}$Mg</th>
<th>$^{31}$Mg</th>
<th>$^{32}$Mg</th>
<th>$^{33}$Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{1/2}$</td>
<td>9.458(12) ms</td>
<td>29.91(3) h</td>
<td>1.30(12) s</td>
<td>335(17) ms</td>
<td>233(16) ms</td>
<td>120(20) ms</td>
<td>90.5(16) ms</td>
</tr>
<tr>
<td>ions/µC</td>
<td>$\approx 1.5 \times 10^7$</td>
<td>$\approx 6 \times 10^6$</td>
<td>$\approx 1.2 \times 10^6$</td>
<td>$\approx 4.6 \times 10^5$</td>
<td>$\approx 1.5 \times 10^5$</td>
<td>$\approx 4.2 \times 10^4$</td>
<td>$\approx 5.3 \times 10^3$</td>
</tr>
</tbody>
</table>

measurements [12, 37]. This quality of HRS, however, comes at the expense of longer cycling times. In this respect, the general-purpose separator (GPS) provides much more adequate conditions for frequent mass changes required in isotope-shift measurements relative to a reference isotope. The signal of $^{21}$Mg will be purified with the use of degraders, which will completely stop the $\beta$ radiation [38] from $^{21}$Na ($Q_{\beta} = 3.5$ MeV) and still allow the energetic positrons from magnesium ($Q_{\beta} = 13.1$ MeV) to pass. Furthermore, the timing and beam-gate settings will be adjusted to match the release of $^{21}$Mg, while suppressing the longer-lived $^{21}$Na.

The even isotopes from $^{32}$Mg down to $^{22}$Mg and the longer-lived odd-$A$ isotopes will be studied with conventional fluorescence spectroscopy. An exceptional case is $^{29}$Mg which, depending on the yield, may be feasible only by $\beta$ detection. If the production rate permits the application of both detection methods, we will use this case as a proof of principle for the equivalence of both types of measurements. This will certainly be possible if the yield in Tab. II is reached.

Being based on ratios of count rates, the $\beta$-asymmetry measurements are insensitive to fluctuations in the intensities of the laser ion source (RILIS) and the proton beam, and even to irregularities in the proton sequence, if the half-life is short compared to the 2.4 s repetition time in the proton cycle. In fluorescence measurements such variations are usually averaged out by using a fast continuous scanning mode. This is not possible for $^{32}$Mg with a half-life of 120 ms. In this case one can trigger the measurement by the proton pulse and collect photon counts only during the release of $^{32}$Mg$^+$ ions from the target. This also gives a suppression of stray laser light background. However, a normalization for fluctuating beam intensities will be required, which can be provided by ion counting. The beam of $^{32}$Mg is expected to be pure, considering that contamination by the surface-ionized isobar $^{32}$Na ($\tau_{1/2} = 13.5$ ms) is strongly suppressed due to the very short half-life. The procedure will allow for taking spectra that are undistorted by beam fluctuations and can be analyzed to the accuracy required for extracting the small field isotope shifts. For maximum detection efficiency at the transition wavelength of 280 nm we will introduce new photomultiplier tubes with thin prismatic windows of fused silica and a bialkali photocathode.

In conclusion, we propose to measure the rms charge radii of magnesium in the entire $sd$ shell ($21 \leq A \leq 32$) by combining fluorescence and $\beta$-detection methods for the first time. We request 24 shifts of radioactive beam for the completion of this program, to be used in two experiments as follows:
• 10 shifts for the neutron-deficient isotopes $^{21-23}\text{Mg}$, using a SiC target and RILIS;

• 14 shifts for the neutron-rich isotopes $^{27-32}\text{Mg}$, using a UC$_2$ target and RILIS; (12 shifts have already been approved by the INTC)

Considering all contributing factors (e.g. yields, detection method, isobaric contamination) we estimate that the measurement time in the two experiments will be distributed among the radioactive isotopes in the following manner:

• $^{21}\text{Mg} + ^{22}\text{Mg} + ^{23}\text{Mg} \Rightarrow 6 + 2 + 2 = 10$ shifts;

• $^{27}\text{Mg} + ^{28}\text{Mg} + ^{29}\text{Mg} + ^{30}\text{Mg} + ^{31}\text{Mg} + ^{32}\text{Mg} \Rightarrow 2 + 1 + 4 + 1 + 2 + 4 = 14$ shifts;

Herewith, we assume that ISOLDE will receive at least half of the pulses in the proton cycle at the full intensity of $3 \times 10^{13}$ particles. If the number of available pulses or their intensity is lower, one has to consider a proportionally higher number of shifts in order to achieve the required statistical uncertainties.

This proposal is a natural continuation of our initial project [40, 41], which was carried out with a remarkable success in its nuclear-moments part [2, 3, 12, 13, 36, 42]. A status report [37] was submitted to the attention of the INTC committee and the program was evaluated very positively. Consequently, 12 shifts for the neutron-rich isotopes have already been allocated. Thus, in addition to these we effectively request 2 shifts for the neutron-rich and 10 shifts for the neutron-deficient isotopes in order to extract the rms charge radii along the entire accessible isotopic chain of magnesium and bring the program to a natural conclusion.