Charge radii of magnesium isotopes and transition to a deformed configuration towards N=20

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We present the status of the IS427 experiment and justify the continuation of the studies in accordance with the complete scientific program laid down in the addendum [1] to our original proposal [2]. Thus, we aim to detect the transition to a deformed configuration in magnesium isotopes by laser-spectroscopy measurements of the mean-square charge radii within the entire *sd* shell and beyond. Observing a common parameter for the even-even and odd-mass isotopes would yield a continuous picture of the nuclear-structure evolution throughout the chain and over the borderline of the island of inversion. We will combine for the first time the sensitive β-decay detection with traditional fluorescence spectroscopy for isotope-shift measurements. These studies have the potential to shed additional light on our understanding of nuclear structure away from stability not only for the magnesium species, but also in general.

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MOTIVATION OF IS427

The nuclear shell model has been successful in reproducing the magic numbers and predicting spins of odd-A nuclei, especially for light and intermediate masses. However, heavier nuclei in several regions had to be approached differently, due to collective phenomena associated with nuclear shapes deviating from spherical. The deformed shell model or Nilsson model [3] has been successfully applied in these regions. A natural question is: Does deformation play a role in light nuclear systems? A positive answer has been acquired with the early investigation of the stable ^{20}Ne and ^{24}Mg. The *sd* shell for these nuclei is occupied by only a few protons and neutrons, which induce strong α-type correlations [4] and cause well defined prolate shapes. Advances in the methods for production and extraction of short-lived nuclear species in the last three decades enabled the studies of systems with a filled neutron *sd* shell (N=20) while having the proton *sd* shell almost unoccupied. The onset of deformation in these nuclei was discovered via the extra binding energy and anomalous spin of ^{31}Na [5, 6], which gave reasons to discuss a “collapse of the conventional shell-model ordering in the very neutron-rich isotopes” [7]. Studies of the neighboring N=20 isotones ^{30}Ne [8] and ^{32}Mg [9] also revealed deformed shapes. In terms of the spherical shell model this phenomenon can be understood by taking into account the lower orbitals of the pf shell, which get populated before the *sd* shell is fully occupied, and thus indicating the disappearance of the N=20 shell closure. Several mechanisms have been proposed to contribute to this inversion of the “normal” 0 particle - 0 hole (0p-0h) and “intruder” np-nh states: (i) a

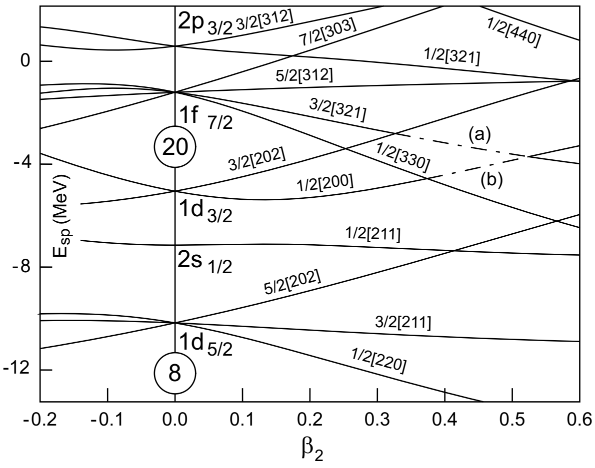

FIG. 1: Nilsson diagram in the (sd-$1f_{7/2}$-$2p_{3/2}$) configuration space. (a), (b) Odd-neutron occupation in the ground states of ^{33}Mg and ^{31}Mg, respectively.

reduction of the shell gap [10]; (ii) an increase in the neutron-neutron and proton-neutron interactions [10]; (iii) the monopole effect of the tensor force [11]. In order to understand the phenomena taking place in this "island of inversion" one has to provide experimental input for further theoretical studies.

Achievements of the IS427 experiment

Neutron-rich isotopes

Experiment IS427 has been very successful in providing information on the nuclear structure of magnesium isotopes and unraveling the causes for the existence of the island of inversion. The spin and magnetic-moment measurement of ^{31}Mg [12]⋆ became a reference point for the continuation of the studies in this region. Calculations using the most recent at that time Hamiltonians for the sd-pf shells could not reproduce the experimentally observed level ordering. The measured spin and magnetic moment correspond to a 2p-2h state, which occurred in all calculations at a considerable excitation energy. With its nearly pure intruder ground state ^{31}Mg is the nucleus in the magnesium chain at which the transition to the island of inversion occurs. This transition is rather unique in the sense that adding a single neutron to ^{30}Mg, whose ground state is well described within the sd shell [13], results in a 2p-2h excitation to the pf shell. Furthermore, mixing with 0p-0h configurations is not necessary to explain the measured quantities. For comparison, the transition to intruder ground states in neon, sodium and aluminum occurs smoothly, with a number of isotopes having mixed wave functions [14–17].

Our measured values of the magnetic moments of ^{27}Mg and ^{29}Mg [18]⋆ are well reproduced by calculations within the sd shell, meaning that the presence of 2p-2h excitations in their ground states can be neglected.

The studies within IS427 continued with the first measurement of the ground-state spin I=3/2 and magnetic moment of a nucleus beyond N=20 in the middle of the island of

⋆ **References with asterisk denote publications derived from IS427.**

inversion [19]*. The ^{33}Mg ground state was shown to have a nearly pure 2p-2h intruder nature, contrary to the earlier suggested 1p-1h configuration and in agreement with the structure of the other isotopes in this region.

The results on ^{31}Mg and ^{33}Mg [12, 18–21]* are also indirectly linked to nuclear deformation. Due to the high density of orbitals in the Nilsson diagram (Fig. 1) the Fermi levels for 19 and 21 neutrons are highly segmented, with each segment belonging to a different Nilsson orbital with a different spin and parity. Thus, based on our spin and parity assignments, it was possible to suggest considerable prolate deformations for both nuclei in accordance with the segments (a) and (b) in Fig. 1. This idea has been investigated further theoretically [22].

Extended target test on neutron-deficient isotopes. Spin and magnetic moment of ^{21}Mg

In our addendum [1] we requested 24 shifts of radioactive beam for measuring the isotope shifts of magnesium over the entire *sd* shell and the nuclear moments of the neutron-deficient isotopes. For the latter we requested an on-line test with a silicon carbide (SiC) target in order to evaluate the yields and investigate the possibilities for suppression of the strong isobaric contamination from sodium. Initially 14 shifts were allocated, 8 for the isotope-shifts measurements on the neutron-rich isotopes and 6 shifts for the target test. A report on the results from the test has been requested for further evaluation of the IS427 demands for radioactive beam.

The test run was performed with a silicon carbide target, number 353, in combination with the resonant-ionization laser ion source (RILIS) and the high-resolution mass separator (HRS). Yield measurements after irradiating the target showed an overwhelming contamination of sodium at mass number A=21 (Tab. I), which prevented determining the production of ^{21}Mg. Nevertheless, the estimated yields of ^{22}Mg and ^{23}Mg (Tab. I) indicated a target behavior in accordance with the expectations.

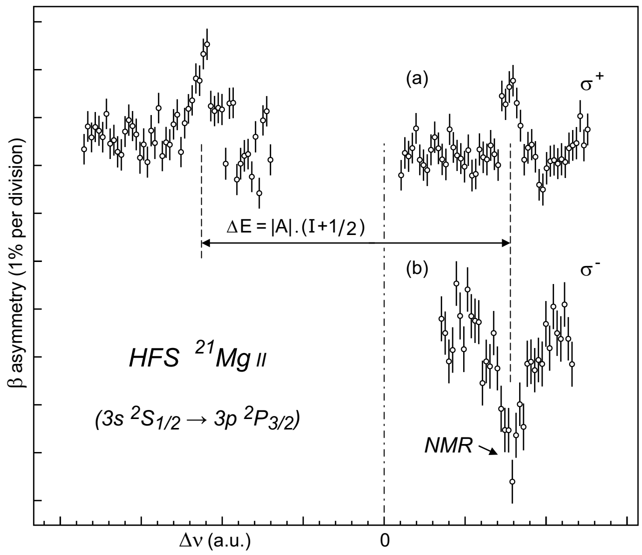

FIG. 2: Hyperfine structure of ^{21}Mg in the D_2 line ($3s\ ^2S_{1/2} \rightarrow 3p\ ^2P_{3/2}$). Nuclear orientation is produced with circularly polarized laser light $\sigma^{\pm}$, (a) and (b) respectively.

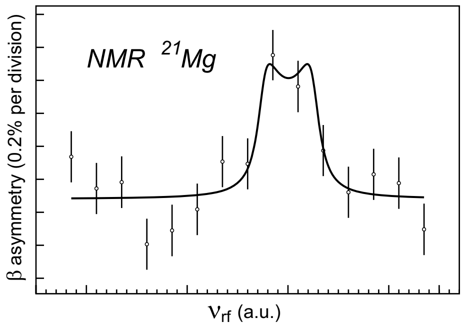

FIG. 3: Nuclear magnetic resonance (NMR) of ^{21}Mg measured with a large frequency modulation.

After the yield measurements, the A=21 beam was guided into the collinear laser spectroscopy setup where the lifetime of the β^+ activity was recorded for different positions of the HRS slits. As expected, at this low mass the resolution of HRS was sufficient for suppressing the sodium contamination to a certain degree. The beam-gate settings were adjusted to match the release of ^{21}Mg, while suppressing the longer-lived ^{21}Na. Finally, a set of degraders was used in front of the β detectors to completely stop the lower-energy particles from the sodium decay. We detected about 1400 particles per proton pulse, which sets a lower limit for the ^{21}Mg yield (Tab. I), since the effect of the slits and our degraders on magnesium can not be precisely estimated. With these improvements, which took about 3 shifts, we established the necessary conditions for meaningful measurements and physics results. In the remaining time the hyperfine splitting in the ground state of the ^{21}Mg ion (Fig. 2) and the nuclear g factor (Fig. 3) were measured for the first time, thus also fixing the nuclear ground-state spin to I=5/2. The spin and magnetic moment of ^{21}Mg are important parameters for studying the mirror symmetry in atomic nuclei, since the properties of its isospin partner ^{21}F (T=3/2) are known. Our preliminary result enables the extraction of the isoscalar magnetic moment, which surprisingly lies outside the empirical limits given by the Schmidt moments. The data analysis and interpretation are in progress.

In order to finalize the measurements on ^{21}Mg we had to calibrate the magnetic field by performing a magnetic resonance on ^{31}Mg. For this purpose we used the first part of our run on the neutron-rich isotopes, which was scheduled in sequence with the test. The remaining beam time was then additionally shortened to about four shifts due to several interventions in the HRS target area and problems with the beam line. Thus, we mainly tried to reach optimized and stable measuring conditions and collected only fragmented data of limited significance. This means we have to recover 4 shifts of our used beam time.

TABLE I: Test yields of proton-rich magnesium and sodium nuclei. The measurements have been taken in May 2007 with silicon carbide target 353 at 490 A and line at 250 A.

	^{21}Mg	^{21}Na	^{22}Mg	^{23}Mg
$\tau_{1/2}$	123(3) ms	22.49(4) s	3.857(9) s	11.317(11) s
ions/μC	$> 3 \times 10^3$	$\approx 4 \times 10^8$	$\approx 1 \times 10^6$	$\approx 1.5 \times 10^7$

Charge radii across the borderline of the island of inversion

The initial proposal [2] which developed into the IS427 experiment suggested the measurement of quadrupole moments of the neutron-rich odd-mass magnesium nuclei in order to obtain a quantitative measure for the nuclear deformation and follow the evolution of the nuclear shape from the *sd* shell through the N = 20 shell closure and beyond. However, the results obtained so far revealed a number of special features in the magnesium species, which prevented the implementation of this program. Our first discovery, the spin I = 1/2 of ^{31}Mg [12]*, meant that this odd-mass isotope has no spectroscopic quadrupole moment. Furthermore, the NMR amplitudes of ^{29}Mg [19]* and ^{33}Mg [18]* prooved to be considerably smaller than the produced asymmetries, likely due to implantation defects in the host crystal. Optical detection of the quadrupole splitting also had to be ruled out due to the unresolved hyperfine structure in the excited atomic state. Thus, the transition to a deformed configuration in the magnesium nuclei is still not well understood.

We propose to detect this onset of deformation in neutron-rich magnesium isotopes and bring IS427 to a natural conclusion by performing laser-spectroscopy measurements of the mean-square charge radii covering essentially all *sd*-shell isotopes, in particular the transition to intruder ground state of ^{31}Mg. Observing a common parameter for the even-even and odd-mass isotopes would yield a continuous picture of the nuclear-structure evolution throughout the chain and over the borderline of the island of inversion. Only fragments of this picture are now available through the Coulomb excitation studies of the even isotopes and the considerations within the Nilsson model for the odd ones. The studies proposed in this addendum have the potential to shed additional light on our understanding of nuclear structure away from stability not only for the magnesium species, but also in general.

NEW EXPERIMENTAL TECHNIQUE

We are aiming to combine for the first time the sensitive β-decay detection with traditional fluorescence spectroscopy for meaningful isotope-shift measurements. This idea naturally evolved from the success in simulating quantitatively [15] 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, our studies of singly ionized magnesium (Mg II) showed a remarkable agreement between theory and experiment [18]*. We are now confident that our knowledge is sufficient for extracting the small field effect in the D_1 line ($3s\ ^2S_{1/2} \rightarrow 3p\ ^2P_{1/2}$) and therefore the changes in the root mean-square charge radii from β-detection spectra even in the light magnesium species.

BEAM-TIME REQUEST

The new technique will allow for measuring the charge radius of ^{31}Mg, whose yield (Tab. II) is below the present limit for classical fluorescence spectroscopy. The even-even ^{32}Mg can not be polarized and hence the sensitive β-detection method can not be applied, but we will explore the conditions for increasing the optical sensitivity by using the pulsed beam structure. This needs a normalization for fluctuating beam intensities, which can be provided by ion counting. In the case of ^{33}Mg, we have successfully applied the β-detection method [19]*, but the precision required for extracting the field shift would demand a dedicated experiment. Thus, we aim to measure the isotope shifts of magnesium nuclei at least in the mass range $22 \le A \le 31$ (with some technical improvements there are good chances to get beyond this range). For this research we request 20 shifts of radioactive beam, which will be used as follows:

• 12 shifts for the neutron-rich isotopes, using a UC_x target, RILIS and GPS;

• 8 shifts for the neutron-deficient isotopes, using a SiC target, RILIS and GPS (possibly HRS);

These 20 shifts include the 16 shifts already requested in our addendum [1] and 4 shifts to be recovered from our last run (see above). Herewith, we assume that ISOLDE will receive at least half of the pulses in the proton cycle at the full intensity. If the number of available pulses is lower, one has to consider proportionally higher number of shifts to complete the studies.

TABLE II: Maximum ISOLDE yields of neutron-rich magnesium isotopes recorded at COLLAPS. The yields of ^{27,28}Mg, given here for completeness, are taken from the ISOLDE database [23]. The measurements of $^{29,\dots,32}$Mg have been taken in May 2004 with uranium carbide target 267 at 730 A and line at 350 A. In later experiments the yields have been typically a factor of up to 3 lower.

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

[1] INTC-P-183, Add. 1, CERN INTC-2006-025 (24 Apr 2006).
[2] INTC-P-183, CERN INTC-2003-038 (24 Oct 2003).
[3] S. G. Nilsson, Kgl. Dan. Viden. Selsk. Mat. Fys. Medd. **29**, No. 16 (1955).
[4] A. Bohr and B. R. Mottelson, *Nuclear Structure*, vol. 2 (W. A. Benjamin, Inc., 1975).
[5] C. Thibault *et al.*, Phys. Rev. C **12**, 644 (1975).
[6] G. Huber *et al.*, Phys. Rev. C **18**, 2342 (1978).
[7] B. H. Wildenthal and W. Chung, Phys. Rev. C **22**, 2260 (1980).
[8] Y. Yanagisawa *et al.*, Phys. Lett. B **566**, 84 (2003).
[9] T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995).
[10] E. K. Warburton, J. A. Becker, and B. A. Brown, Phys. Rev. C **41**, 1147 (1990).
[11] T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).
[12] G. Neyens *et al.*, Phys. Rev. Lett. **94**, 022501 (2005).
[13] O. Niedermaier *et al.*, Phys. Rev. Lett. **94**, 172501 (2005).
[14] H. Iwasaki *et al.*, Phys. Lett. B **620**, 118 (2005).
[15] M. Keim *et al.*, Eur. Phys. J. A **8**, 31 (2000).
[16] P. Himpe *et al.*, Phys. Lett. B **643**, 257 (2006).
[17] P. Himpe *et al.*, Phys. Lett. B **658**, 203 (2008).
[18] M. Kowalska *et al.*, Phys. Rev. C **77**, 034307 (2008).
[19] D. Yordanov *et al.*, Phys. Rev. Lett. **99**, 212501 (2007).
[20] M. Kowalska *et al.*, Eur. Phys. J. A **25**, s01, 193 (2005).
[21] D. T. Yordanov *et al.*, Balk. Phys. Lett. p. 358 (2004), ISSN 1301 - 8329.
[22] I. Hamamoto *et al.*, Phys. Rev. C **76**, 054319 (2007).
[23] `http://isolde.web.cern.ch`.

Publications [12, 18–21] descend directly from IS427.