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How sharp is the transition into the N=20 island of inversion for the Mg isotopes ?

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Abstract.
The N=20 island of inversion is an excellent playground for testing shell model calculations. The Mg chain is a region of shell evolution still far from being well understood. In this paper we present preliminary results of a single-neutron knockout experiment from ^{31}Mg performed at GANIL to study the structure of ^{31}Mg and of the core ^{30}Mg. The level scheme and longitudinal momentum distributions were mesured and spectroscopic factors were deduced. Negative parity states arise at low energy and the spectroscopic factor for the isomeric 0^+_2 in ^{30}Mg was determined to be smaller than foreseen in the standard picture. The preliminary

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experimental results are compared to state-of the art shell model calculations revealing opposed interpretations.

1. Introduction

The N=20 island of inversion is a region of sudden changes in shell structure where intruder configurations become dominant in the ground state wave function of several neutron-rich nuclei with atomic numbers in between Z=10 and Z=12. Over the past years, large-scale shell model calculations have been very succesful in describing the main properties of the nuclei around this region [1] and predicting new islands of inversions [2]. However, just recently a newly developed interaction, EEdf1 [3], that reproduces as well most of the electromagnetic properties of the nuclei around the N=20 region, predicts an increase of particles in the pf shell and holes in the sd shell over the Z = N = 20 shell gap. In particular along the Mg chain, nuclei at the border of the island of inversion are ideal to investigate the enhancement of $np - nh$ excitations across the N=20 shell gap. Energy levels are important but overlap functions are key inputs in the calculations. Therefore, a single-neutron knockout experiment from ^{31}Mg was performed at GANIL to study the structure of ^{31}Mg and of the core ^{30}Mg.

2. Experimental details

The experiment was performed at the GANIL coupled cyclotron facility. A primary beam of ^{36}S incident on a ^{12}C production target was used to produce a cocktail beam, analysed and purified using the SISSI device and the ALPHA spectromer [4]. The secondary beam of ^{31}Mg at $\sim$ 55 MeV/u impinged on a 171 mg/cm^2 ^{12}C target placed at the entrance of the SPEG spectrometer [5]. An array of 8 segmented EXOGAM clovers of high purity Ge detectors [6] surrounded the target. The array was arranged in a configuration with two rings at 45° and 135° polar angles with four clovers detectors each. The photopeak efficiency of the array was measured to be 3.3% at 1.3 MeV and the energy resolution, after Doppler correction, was 2.7%.

3. Results

The add-back reconstructed and doppler corrected γ-ray spectrum detected in coincidence with ^{30}Mg is shown in Fig. 1. Transitions previously reported [7, 8, 9, 10] can be clearly seen at: 799, 954, 985, 1482, 1816, 1898, 1975 and 3534 keV. A weak transition not reported before at 1660 keV is also visible. Furthermore, a peak at $\sim$ 300 keV corresponding to the known isomeric 306 γ-ray, coming from the 1789 keV level and decaying into the 1482 keV 2^+_1 state, is also observed. This state was reported to have a half-life of 3.9(5) ns based on fast timing measurements $\beta\gamma\gamma(t)$ [11]. The line shape shown by the forward energy spectrum in Fig. 2 reflects the isomeric nature of the state and agrees well with the reported value of the lifetime. The number of counts below each transition N$_\gamma$, was obtained in a statistical fit of the γ-ray spectrum to GEANT4 simulations. The γ-ray intensities for each transition, I$_\gamma$, are then calculated from the ratio of the efficiency corrected photopeak counts N'_γ, and the number of residual knockout cores. Branching ratio for the direct population of each level, b, has been obtained after feeding correction, assuming the level scheme proposed in Fig. 4.

For the isomeric state, the branching ratio was deduced only from the E2 radiative contribution since the branching ratio between the E0 and E2 transitions is shown to be small $\sim 1.4\ 10^{-2}$, as deduced from the partial lifetime of the E0 decay ($\tau(E0)$=396 ns) measured by Schwerdtfeger et al. [12]. Besides, the non-radiative contribution of the E2 transition was found to be negligeable (internal conversion coefficient α_{tot}=9.1 10^{-4}). The exclusive cross section for

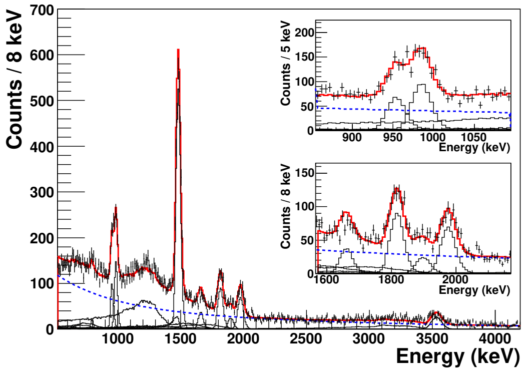

Figure 1. The γ-ray energy spectrum ($E\gamma > 500$ keV) compared to Geant4 simulated line shapes for each transition (black lines). The total fit (red line) includes also a continuum background of an exponential function (blue dashed line), where the slope and scale parameters are left free to vary in the fit.

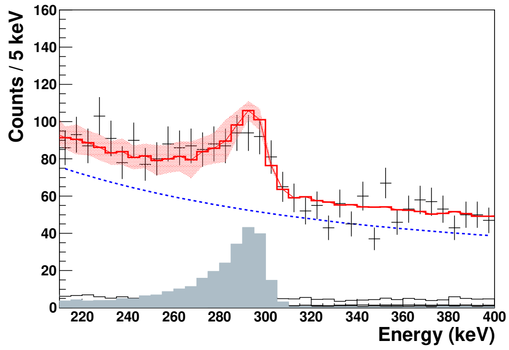

Figure 2. The γ-ray energy spectrum ($E\gamma < 500$ keV) reconstructed using the post-target velocity ($\beta_{post} = 0.303$) and using only the EXOGAM clovers in the forward array owing to a higher sensitivity to the lineshape. The grey histogram shows a simulated isomeric transition at ~ 300 keV with a lifetime of 3.9(5) ns

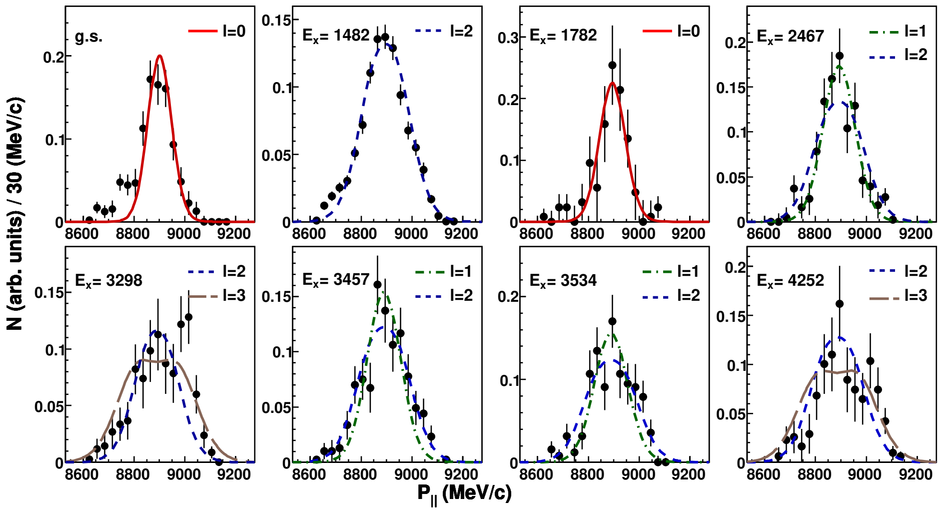

Figure 3. Experimental momentum distributions (solid marker) compared to eikonal-model calculations with ℓ= 0, 1, 2 and 3 (red solid, blue short-dashed, green dot-dashed, and brown long-dashed lines, respectively) for the states in ^{30}Mg. The theoretical lineshapes have been convoluted with the experimental resolution and are normalized to the best fit of data.

each state is given by the product of the branching ratio and the inclusive cross section ($\sigma_{inc} =$ 90(12) mb).

The exclusive longitudinal momentum distributions for the ground state and for the states at: 1482, 1782, 2467, 3298, 3457, 3534 and 4252 keV are presented in Fig. 3. The ground state momentum distribution was obtained by subtracting away the exclusive momentum distributions for the excited states shown in Fig. 3. The eikonal model calculations [13, 14] have been folded with the experimental filter including the beam spread, energy loss and angular straggling, and

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the resolution of the spectrometer and are compared in Fig. 3 to the experimental results.

The experimental shape of the ground state distribution is reproduced with a s-wave, whereas the first excited state at 1482-keV is in agreement with a l=2 value. Despite the low statistics of the momentum distribution gated on the isomeric transition at 300-keV, the narrow shape is consistent with an assignment of l=0. The momentum distribution for the state at 2467-keV was obtained applying a narrow gate on the high-energy side of the 985-keV photopeak and the shape is compatible with l=1 since $\chi^2_\nu(l = 1) = 1.0$ whereas $\chi^2_\nu(l = 2) = 1.6$. For the state at 3298-keV, the distribution is broad and in best agreement with a l=3 value ($\chi^2_\nu(l = 3) = 1.9$ and $\chi^2_\nu(l = 2) = 2.8$). The distribution gated on the 1975-keV transition is best described by a l=2 value ($\chi^2_\nu(l = 2) = 0.8$ and $\chi^2_\nu(l = 1) = 2.2$) and that to the state at 3534-keV is consistent with l=1 and l=2 ($\chi^2_\nu(l = 1) = 1.9$ and $\chi^2_\nu(l = 2) = 2.0$). The level at 4252 keV exhibits a broad distribution compatible with a l=3 orbital ($\chi^2_\nu(l = 3) = 1.4$ and $\chi^2_\nu(l = 2) = 1.6$). Spectroscopic factors were deduced from the ratio between the exclusive cross section for each state and the corresponding single-particle cross sections computed using the eikonal formalism [13, 14]. Tentative assignments of the spin-parity of the levels were based on the rules of gamma decay (see text). The results discussed above are summarized in Fig. 4.

4. Discussion

Figure 4 shows the preliminary experimental results compared to state-of-the-art shell model predictions using both microscopically derived interactions from chiral effective field theory, EEdf1 [3], and phenomenological theories with the newly available SDPF-U-MIX interaction [1]. No quenching [16] has been applied to the predicted spectroscopic factors of both theories.

Knocking a neutron out the $2s_{1/2}$ orbital in ^{31}Mg leads to the population of $0^+_{1,2}$ states in ^{30}Mg. These correspond to the measured ground and isomeric state at 1782(5). Given the upper limit obtained for $C^2S(0^+_1)$=0.42(8), the experimental result is in agreement with both theories but with completely different descriptions. While the SDPF-U-MIX interaction describes the ground-state wave function of ^{30}Mg as dominated by $0p - 0h$, the newly developped, ab initio-type, EEdf1 interaction, produces much enhanced np-nh excitations, indicating that this nucleus belongs to the island of inversion. However, the moderately low $C^2S(0^+_2)$ obtained here suggests a more complex structure rather than the conventional interpretation of this state as being purely 2p-2h. The deduced spectroscopic factors for both $0^+_{1,2}$ are in good agreement with the results from the EEdf1 interaction and only the $C^2S(0^+_1)$ agrees well with the SDPF-U-MIX.

Removing a neutron from the $1d_{3/2}$ orbital in ^{31}Mg populates spins and parity states of $(1,2)^+$ in ^{30}Mg. The first 2^+_1 state at 1482 keV in ^{30}Mg shows a relatively large strength of 0.44(13) in agreeement with the EEdf1 interaction. Assuming some population to the 2^+_1 state could come from dynamical excitation of the core, the resulting spectroscopic factor is thus an upper limit and also consistent with the SDPF-U-MIX interaction. The next 2^+_2 is placed at 3457-keV since 1^+ states are expected at higher energy. Fusion-evaporation measurements employing a $^{14}C(^{18}O, 2p)$ reaction of Deacon et al. [8], have assigned this state to be a 4^+ based on an angular ratio $R_{ang} < 1$ for the 1975-keV γ-ray, however in a direct knockout process from ^{31}Mg, the neutron had to be removed from the $1g_{9/2}$ orbital and the shape of the momentum distribution is clearly not compatible with $l = 4$. Therefore a 2^+_2 assignment is made for this state, in line with the results from [10]. The spectroscopic factor is rather large, 0.48(7), and no equivalent strength for positive parity states is found in shell model calculations at these energies. The large spectroscopic factor found here evidences a substantial overlap with the ground state wavefunction of ^{31}Mg pointing to the intruder nature of the 2^+_2 state. This result is supported by the large β and γ-branching ratios observed in [10].

Negative parity states can also be populated when knocking a neutron out the fp-shell. The state at 2467-keV shows a l=1 shape, thus spin and parities of $(1,2)^-$ are possible. However,

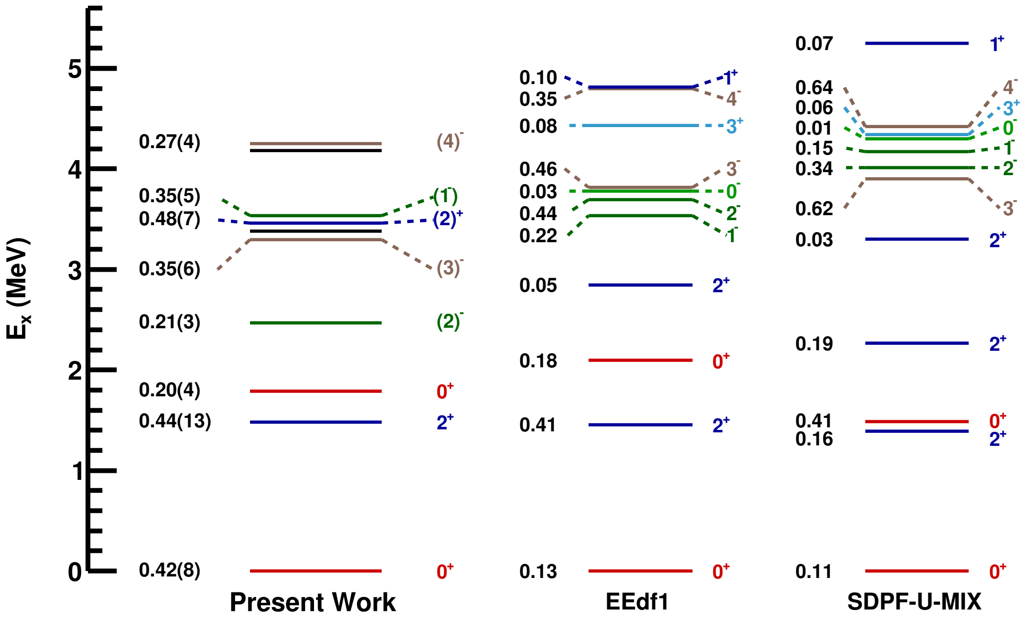

Figure 4. Experimental level scheme of ^{30}Mg (first column) compared to shell model calculations using the EEdf1 and SDPF-U-MIX interactions (second and third column, respectively). Spin and parity assignments are displayed on the right and the spectroscopic factors on the left of the levels.

based on the branching scheme, this state must surely be the 2^- because otherwise it would decay to the ground state by an E1 rather than to the 2^+. This is unexpected according to shell model calculations that predict these negative parity states at much higher excitation energy. Despite the experimental C^2S of 0.20(3) being in agreeement with the 1^- state predicted by the EEdf1 and close to the value obtain by the SDPF-U-MIX, the low position in energy for this negative parity state remains a challenge for current theories. An assignment of 2^+ was originally suggested by H. Mach [11], later adopted by [8] and by β-decay measurements from ^{30}Na [10], although with a remarkably weak feeding and large $\log ft$ value for this later measurement. It is also worth to notice here, that according to our spin and parity assingment, the corresponding E1 transition is still in agreement with the upper limit for the lifetime of this state measured in [11] The momentum distribution for the state at 3534-keV is compatible with $l = 1, 2$ which yields a spin-parity assignment of $(1,\ 2)^+$ or $(1,\ 2)^-$. Preference to the l=1 assignment is made based on the direct decay to the ground state. A tentative assignment of 1^- is suggested for this state.

Some occupancy of the $f_{7/2}$ orbital in ^{31}Mg results in $(3{,}4)^-$ states in ^{30}Mg. The distributions of the 3298-keV and the 4252-keV states are both consistent with $l = 3$ shapes and therefore spins and parities of 3^- and 4^- are assigned for these states, respectively. The order is deduced from the typical Weisskopf estimates, that favour a E1 transition from the 3^- to the 2^+ state over a E3 for an anssignement of 4^- for that level. The upper state with $l = 3$ is a 4^- in agreement with a M1 transition to the 3^- state. A remarkably good agreement is found with the EEdf1 interaction while the predictions from the SDPF-U-MIX interaction overstimate the experimental results. The difference might come from the approximately 30% $3\hbar\omega$ configurations present in the predictions with the EEdf1. Shimoda et al. [10] however, suggested a 2^+

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assignment for the state at 3298-keV, (found at 3.302 MeV). Based on the measured logft > 6.5 in the β-decay experiment, this transition could still be first-forbidden in agreement with our assignment of 3^-. We also note that a tentative assignment of 4^+ has been made in a 2-neutron removal measurement [15].

We have studied single-neutron removal from ^{31}Mg using the SPEG spectrometer and the EXOGAM array for gamma-ray detection. Inclusive and exclusive cross sections and momentum distributions for the populated states in ^{30}Mg have been measured. The two 0^+ states have been measured simultaneously allowing us to extract information on the mixing in ^{30}Mg. The low spectroscopic factor of the 0_2^+ suggests a different structure from the well established 2p2h configuration of the ground state of ^{31}Mg. The large spectroscopic factor found for the 2_2^+ state points to the intruder nature of this state. The results obtained for the 2.467-MeV state are intriguing because negative parity states are expected at higher excitation energy. A comparison of the present ^{30}Mg results with two new shell model calculations, using state-of-the-art interactions, shows two plausible and quite different scenarios. The EEdf1 interaction suggests that many-particle many-hole configurations dominate the low-lying structure of ^{30}Mg and therefore would place ^{30}Mg into the N=20 island of inversion. On the contrary, the SDPF-U-MIX interaction supports a picture of shape coexistence with a dominant spherical configuration in the ground state of ^{30}Mg. The present data suggest that the transion into the island of inversion in the Mg chain is more complex than expected.

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