Coulomb excitation of Mg-31

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Coulomb excitation of $^{31}$Mg


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The ground state properties of $^{31}$Mg indicate a change of nuclear shape at $N = 19$ with a deformed $j^\pi = 1/2^+$ intruder state as a ground state, implying that $^{31}$Mg is part of the “island of inversion”. The collective properties of excited states were the subject of a Coulomb excitation experiment at REX-ISOLDE, CERN, employing a radioactive $^{31}$Mg beam. De-excitation $\gamma$-rays were detected by the MINIBALL $\gamma$-spectrometer in coincidence with scattered particles in a segmented Si-detector. The level scheme of $^{31}$Mg was extended. Spin and parity assignment of the 945 keV state produced. Spin and parity assignment of the 945 keV state yielded $3/2^+$ for some nuclei be-

1. Motivation

Shell structure is one of the most important frameworks for understanding nuclear structure and the properties of atomic nuclei. Recent experimental and theoretical findings indicate that magic numbers are subject to the proton-to-neutron ratio and new magic numbers are revealed when going to more exotic nuclei. Such a new magic number was proposed at $N = 16$ for some nuclei between $Z = 8$ (oxygen) and $Z = 14$ (silicon) [1,2] and confirmed in recent experiments [3]. The shell model modifications and the occurrence of new magic numbers are traced back to the resid-

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ground state for these nuclei [6]. Later shell model calculations by Warburton et al. [7] showed that the 1f5/2 orbital becomes lower in energy, reducing the sd shell gap and an anomalous inverted level structure was proposed, which is based on 2-particle 2-hole (2pf2h) neutron cross shell configurations in the ground state. Recent shell model calculations trace this phenomenon back to the nucleon–nucleon tensor interaction [8]. Investigations in the following nuclei evince that 29,30,32Ne [9–11], 30,31Na [13,14] and 31–34,36Mg [15–21] are part of this so-called “island of inversion” (see Fig. 1). In the neutron-rich magnesium isotopes Coulomb excitation experiments were performed at REX-ISOLDE, CERN with 30,32Mg, showing a normal sd shell structure for 30Mg [26]. In contrast the large B(E2, 0+ → 2+) value of 31Mg [18,19] demonstrates the strong collectivity of this transition at N = 20 and indicates a deformation of the ground state, caused by this highly deformed pf intruder state. A shape coexistence of this deformed O2g and an excited O2g was observed recently [32].

The N = 19 nucleus 31Mg, at the boundary of the island of inversion, was subject of a recent hyperfine structure and β-NMR measurement by Neyens et al. [15]. The ground state spin and parity of 31Mg were determined to be Jπ = 1/2+ in contradiction to previous β-decay studies that yielded a 3/2+ ground state [33]. Maéchal and collaborators performed a complementary β-decay experiment on 31Mg [16,34] and observed very weak feeding to the 31Al ground state (Jπ = 5/2+) and lowest excited states (Jπ = 1/2+, 3/2+). Both observations agree well with the 1/2+ ground state of 31Mg. The absence of strong β-decay feeding into the lowest lying Jπ = 1/2+, 3/2+ states indicates very different single-particle structures of mother- and daughter-nuclei in agreement with a strong 2p2h component in the 31Mg ground state wave function. These experimental results were supported by shell model calculations in the sd–pf valence space, reproducing the low-lying level scheme of 31Mg remarkably well for the first time [16]. The ground state and the first excited 3/2+ state were found to be largely dominated by 2p2h intruder configurations, and 31Mg has to be placed inside the island of inversion. Furthermore, theoretical results on the collective properties of excited states in 31Mg predict a deformed positive yраст band – built on the 1/2+ ground state – with a collective transition to a J = 5/2+ state just below 1 MeV. A corresponding B(E2, 5/2+ → 1/2+) = 127 e2fm4 value is given [16]. Additional calculations were done by Kimura [35], which yielded an intruder dominated 5/2+ state at 0.89 MeV. The electric quadrupole moment of this strongly deformed and largely collective state was predicted to be Qe = −19.1 e2fm4 and Qπ = −21.6 e2fm4, calculated by the AM+GCM wave function and the rigid rotor approximation, respectively [35].

Three promising candidates for such a 5/2+ state are known between 600 keV and 1400 keV [36], but spin and parity assign-
the beam composition, respectively (Fig. 2). A position sensitive parallel plate avalanche counter (PPAC), could be placed right into the beam axis 1.2 m behind the target for measurement of the beam profile in x and y direction [42]. A Bragg ionization chamber close to the beam dump position allowed permanent monitoring of the beam composition in mass A and charge Z [43]. Data were recorded using particle-$\gamma$ coincidences with a coincidence window of typically 800 ns.

In Coulomb excitation experiments with radioactive ion beams possible beam contaminations have to be carefully investigated, because all beam components contribute to Coulomb excitation of the target material, which is used for normalization. For the extraction of the transition probabilities it was mandatory to monitor and to determine the exact beam composition during the experiment. Different sources of beam contamination were identified: Isobaric contaminants occur by $\beta$-decay of the radioactive $^{31}$Mg during accumulation and charge breeding at REX-ISOLDE. The isobaric contaminant $^{31}$Al, directly produced in the primary ISOLDE target, was surface ionized due to the high temperature of the hot cavity and was not separated completely in the HRS due to the small mass difference ($\Delta m/m = 1/2460$). An additional beam component stemmed from residual argon gas in the REX-Trap and EBIS. After charge breeding, the $^{38}$Ar had almost the same A/q ratio ($q = 11+$) and was accelerated together with the $^{31}$Mg and $^{31}$Al.

The beam composition was carefully monitored during the experiment, using three different techniques: (i) The ratio of laser ionized $^{31}$Mg over surface ionized $^{31}$Al in the beam was checked by switching the laser on and off periodically every 2.5 hours for about 30 minutes. While the laser was on, $^{31}$Mg was elastically scattered into the DSSSD as well as $^{31}$Al. When the laser light was blocked, only the surface ionized contaminant was detected. The fraction R of magnesium in the beam was calculated out of the intensities $I_{on}$ with laser on and $I_{off}$ with laser off as $R = (I_{on} - I_{off})/I_{on}$. (ii) The time dependence of the RIB intensity with respect to the proton beam impact on the primary ISOLDE target was analyzed. Due to their fast release out of the primary target [44] and their short lifetime the $^{31}$Mg ions showed a high intensity only for the first 800 ms after the proton pulse. For $\Delta t > 800$ ms the contaminants dominated the beam composition. (iii) In addition the exact beam composition was determined with help of the Bragg ionization chamber.

Taking into account the $\beta$-decay the accumulated radioactive beam composition of the experiment amounted to 78.9(14)% for $^{31}$Mg within a time window of 800 ms after the proton pulse impact, which was applied in the further analysis of the measured $\gamma$-intensities. Smaller beam fractions were found to be 17.7(9)% for $^{31}$Al and 3.4(5)% for $^{38}$Ar.

3. Analysis

Calibration of all DSSSD segments was done with an $\alpha$-source, containing $^{239}$Pu, $^{241}$Am, and $^{244}$Cm. To calibrate the MINIBALL clusters and to determine their energy dependent efficiency, $^{60}$Co and $^{152}$Eu sources were mounted onto the target frame at the target position. For Doppler correction, all angles of the cluster detectors had to be known exactly. Therefore an angle-calibration measurement was performed, using Doppler-shifted $\gamma$-rays after the neutron pick-up reaction $^{25}$Ne($^{23}$Ne, $^{25}$Ne)$^*$.

Coulomb excitation data analysis commenced by selecting scattered $^{31}$Mg ions, which were identified by the CD detector (DSSSD). The kinematics of the scattered beam or target particles is clearly separated by the measured correlation of particle energy and scattering angle. In the center-of-mass system a scattering angle range of $\theta_{CM} = 21.0^\circ$–66.5$^\circ$ is covered. A time window with $\Delta t_p = 250$ ns between the particle and the $\gamma$-ray was applied to select the prompt Coulomb excitation events and to suppress random coincidences from constant room background, i.e. $\beta$-decay and bremsstrahlung. The prompt Coulomb excitation spectrum for further analysis is particularly clean of any background lines after background subtraction with a long time window $\Delta t_c = 3750$ ns. All observed $\gamma$ lines are due to Coulomb excitation of either beam or target nuclei.

4. Results

Background subtracted $\gamma$-ray spectra observed in coincidence with a scattered beam particle in the CD-detector are shown in Fig. 3. Doppler correction was performed for the detected $^{31}$Mg projectile and the corresponding recoiling $^{109}$Ag target nucleus, respectively. Strong $\gamma$-transitions are observed at 311 keV and 415 keV, depopulating Coulomb excited states in $^{109}$Ag. The two lines at 50 keV and 895 keV, already observed in $\beta$-decay studies of $^{31}$Na [33,45], are assigned to the transitions of a known excited state at 945 keV in $^{31}$Mg. The small Doppler-broadening of the 50 keV line in the spectrum corrected for $^{31}$Mg is due to the long half-live of 16(3) ns [33]. The time of flight between target and CD-detector is only 1.7–3.2 ns, thus these $\gamma$-rays were emitted at rest after implantation in the detector. There is evidence for three more transitions de-exciting states in $^{31}$Mg. Two lines at 623 keV and 673 keV were already established by the $\beta$-decay studies as depopulating transitions of an excited state at 673 keV into the 3/2$^+$ state at 50 keV and the ground state, respectively. The line at 724 keV was observed for the first time in this work. To identify this $\gamma$-transition unambiguously and to place it into the level scheme, information on coincident transitions has been evaluated. Multiple $\gamma$-events, that are in prompt coincidence with a detected beam particle, have been sorted into a $\gamma\gamma$-matrix. The known coincident transitions at 895 keV and 50 keV from a 5/2$^+$ $\rightarrow$ 3/2$^+$ $\rightarrow$ 1/2$^+$ cascade are confirmed by coincidence relations. Despite low statistics of 2–3 counts on a mean background of about 0.02 count/keV, which is in good agreement with the MINIBALL $\gamma$-efficiency of $\sim$10%, the cut spectrum on the 724 keV transition shows clear evidence for coincident $\gamma$-rays at 50 keV, 173 keV and 221 keV (see Fig. 4). These transition energies are all known to belong to the low-energy level scheme of $^{31}$Mg [33,45]. The new 724 keV transition can be inserted clearly into the level scheme of $^{31}$Mg as de-exciting transition of the 945 keV state, feeding a known 3/2$^+$ state at 221 keV [46,47]. The direct decay of the 945 keV state into the ground state was not observed.
In the case of a 1-step excitation via E1 the 945 keV level would have negative parity and the spin would be limited to 1/2 or 3/2. For this assumption GOSIA calculated a reduced excitation probability of $B(E1, 1/2^+ \rightarrow 3/2^-) = 0.224 \text{ e}^2\text{fm}^2$. For de-excitation into the $3/2^+$ state at 50 keV the calculation yielded $B(E1) = 2.13 \text{ e}^2\text{fm}^2$ and $B(M1) = 127 \mu_B^2$ for de-excitation into the $2/2^-$ state at 221 keV, respectively. For a $1/2^-$ state at 945 keV GOSIA calculated excitation probabilities of the same order. All these values are unreasonably high and scenario (ii) can be excluded. Also an excitation via E3 to a $5/2^-$ or $7/2^-$ state would yield a similar disproportionally huge value of $B(E3) \geq 40000 \text{ e}^4\text{fm}^6$. Thus a negative parity state, i.e. scenario (iii), can be excluded.

The remaining possibilities to get consistent values for the excitation of the 945 keV state are the scenarios (iv) and (v): direct (1-step) excitation from the ground state via E2 to a $3/2^+$ or a $5/2^+$ state. Now the full known level scheme of $^{31}\text{Mg}$ up to 1 MeV and all known and newly observed transitions were taken into account for the calculation, with adopted $B(E2)$, $B(E1)$, and $B(M1)$ values for the states up to 500 keV [36,46]. Predicted spectroscopic quadrupole moments $Q_s$ and their reduced matrix elements for the $3/2^+$ and $5/2^+$ states [16,35], so called re-orientation matrix elements, were included into the calculation, using [49]

\[
Q_s^{al} = -\frac{16\pi I(2I-1)}{5(I+1)(2I+1)(2I+3)}\frac{\mu_B^2}{\alpha}\frac{\alpha}{\alpha'},
\]

where $M_{al,al}(E2) = -\langle\alpha'|\mathcal{E}R(E2)|\alpha\rangle$ is the reduced matrix element.

For the 945 keV state the reduced transition probability was calculated to be $B(E2) = 182 \pm 17^{+9}_{-13} \text{ e}^4\text{fm}^4$. Both, the $3/2^+$ and $5/2^+$ scenarios coincide within the error bar. The error bar is dominated by the statistical error on the number of counts in the observed $\gamma$-transitions and the uncertainty on the beam composition.

De-excitation was investigated using the measured branching ratios of $74(12)\%$ for the 895 keV transition, $24(7)\%$ for the 724 keV transition, and an upper limit of $<2.6(8)\%$ for the unobserved direct transition to the ground state. Assuming a $3/2^+$ state at 945 keV its de-excitation would have to proceed via E2 + M1 transitions to the ground state and the $3/2^-$ state at 50 keV, respectively. The investigated branching ratios yield a ground state transition via M1/E2 with a reduced transition probability that is hindered by a factor of about $10^{-4}$ compared to the 895 keV transition. This is very unlikely due to the similar 2p3h configuration of the ground state and the first $3/2^+$ excited state at 50 keV [16]. Thus, scenario (iv), i.e. a $3/2^+$ state at 945 keV can be rejected.

The only remaining possibility is that the 945 keV is a $5/2^+$ state (scenario (v)). Assuming a pure E2 transition to the 50 keV state would imply an unreasonably high $B(E2)$ value of about 2700 $\text{ e}^4\text{fm}^4$ to reproduce the measured intensities. Thus de-excitation to the 50 keV state proceeds via a strong M1 transition with a calculated transition probability range of $B(M1) \approx 0.1 \ldots 0.5\mu_B^2$. These limits depend mostly on the multipole mixing ratio $\delta$ of the transition and its absolute E2 strength. The additional de-excitation to the $3/2^-$ state at 221 keV had to proceed via an E1 transition with $B(E1) > 8.9 \times 10^{-4} \text{ e}^2\text{fm}^2$.

For the 673 keV state, which is a $3/2^-$ state with a 0.1p1h configuration [47], the analysis yielded a reduced transition probability of $B(E2, 1/2^+ \rightarrow 3/2^-) = 21(8) \text{ e}^4\text{fm}^4$. Assuming purely E2 de-excitation from this state as well, the calculation gives $B(E2) = 11(5) \text{ e}^4\text{fm}^4$ and $B(E2) = 24(12) \text{ e}^4\text{fm}^4$ for the 673 keV and 623 keV transitions, respectively. The $B(E2)$ value of the 50 keV transition could not be determined due to feeding and a complex, non-uniform efficiency for these 50 keV $\gamma$‘s in the MINIBALL detectors.
experiment are presented in Fig. 5. For the first time the clear spin and parity assignment was done for the 945 keV state. This 5/2\(^+\) state is part of a strong collective \(K^\pi = 1/2^+\) band in 31Mg.

5. Discussion

The measured level scheme and reduced transition probabilities of 31Mg are compared to results from recently published calculations [16,35]. Both publications predicted a 5/2\(^+\) state at 988 keV [16] and 0.89 MeV [35], respectively, which is in very good agreement with the present results of the 945 keV state in this work (see Fig. 6). Additionally, the 673 keV state is the 3/2\(^+\) state and the head of the \(K^\pi = 3/2^+\) band with a dominant spherical 0p1h configuration [47,35]. A reduced coupling to the deformed 2p3h ground state configuration is in very good agreement with a less collective transition with \(B(E2, 1/2^+ \rightarrow 3/2^+) = 21(8) \, e2\text{fm}^4\) observed in this experiment.

The measured properties of the 945 keV state agree well with the predicted 5/2\(^+\) state of the positive-parity yrast band in 31Mg. Due to its predicted dominant 2p3h configuration the 5/2\(^+\) state has a strong coupling to the deformed ground state with \(B(E2, 1/2^+ \rightarrow 5/2^+) = 182(20) \, e2\text{fm}^4\). Combined with the 1/2\(^+\) ground state and the first excited 3/2\(^+\) state at 50 keV these states form a positive parity yrast band with \(K = 1/2\), connected by almost pure M1 transitions. Measured \(B(M1, 5/2^+ \rightarrow 3/2^+) = 0.1...0.5\mu^2\) and \(B(M1, 3/2^+ \rightarrow 1/2^+) = 0.019(4)\mu^2\) [36] values agree well with shell model calculations done by Marechal [16], that yield \(B(M1, 5/2^+ \rightarrow 3/2^+) = 0.38\mu^2\) and \(B(M1, 3/2^+ \rightarrow 1/2^+) = 0.06\mu^2\), respectively (see Table 1). For electric quadrupole transitions the shell model calculations do not reproduce the measured values. With \(B(E2, 5/2^+ \rightarrow 1/2^+) = 127 \, e2\text{fm}^4\) [16] it is in fact a factor of 2 bigger than the result of the present measurement, that gives \(B(E2) = 61(7) \, e2\text{fm}^4\).

According to the rigid rotor approximation calculations in [35] another comparison with theory is done by assuming a purely rotational \(K = 1/2\) band in 31Mg, given by the sequence 1/2\(^+\) – 3/2\(^+\) – 5/2\(^+\). For transitions within such a rotational band the reduced transition probability is linked to the intrinsic quadrupole moment \(Q_0\) by [49]

\[
B(E2, I_1 \rightarrow I_f)_{\text{rot}} = \frac{5}{16\pi}e^2Q_0^2|\langle I_1 K 0 |I_f K \rangle|^2.
\]

For the 5/2\(^+\) \rightarrow 1/2\(^+\) transition we get \(B(E2)_{\text{rot}} = 69 \, e2\text{fm}^4\) and \(B(E2)_{\text{rot}} = 114 \, e2\text{fm}^4\), calculated with predicted quadrupole moments from shell model and rigid rotor approximation calculations, respectively [16,35]. The result from shell model calculations is in reasonable agreement with the experimental result (see Table 1), whereas the rigid rotor approximation yields a transition strength that is too high by a factor of more than 1.8.

The deduced excitation probability \(B(E2, 1/2^+ \rightarrow 5/2^+) = 182(20) \, e2\text{fm}^4\) can be compared to the \(0^+ \rightarrow 2^+\) E2 strengths in the neighboring even–even magnesium isotopes 30,32Mg. While the excitation \(B(E2)\) values always strongly depend on the different spins of the initial (ground) states, the transition strengths of the de-excitation process will be compared instead. For 32Mg the experimental results, i.e. \(B(E2)\) values, were discussed by [19], including possible feeding contributions. An E2 strength of \(B(E2, 2^+ \rightarrow 0^+) = 89(11) \, e2\text{fm}^4\) is reported without a correction for feeding, and \(B(E2, 2^+ \rightarrow 0^+) = 66(9) \, e2\text{fm}^4\) includes a correction for feeding from a higher lying state [19], which is consistent with [50]. The new \(B(E2, 5/2^+ \rightarrow 2^+) = 61(7) \, e2\text{fm}^4\) of 31Mg compares well with the feeding corrected \(B(E2, 5/2^+ \rightarrow 2^+) = 66(9) \, e2\text{fm}^4\) of 32Mg [19], and exceeds the \(B(E2, 5/2^+ \rightarrow 0^+) = 48(6) \, e2\text{fm}^4\) of 32Mg [26]. This result establishes that deformed pf intruder configurations exist for the ground and low lying states already at \(N = 19\), including a sequence of collective rotational states.

6. Summary

To summarize, we have investigated Coulomb excitation of the unstable odd-N nucleus 31Mg. The properties of a positive-parity yrast band with \(K = 1/2\), built on the 1/2\(^+\) ground state are in good agreement with a 5/2\(^+\) state at 945 keV. The determined \(B(E2)\) and \(B(M1)\) values support this assumption. The increased collectivity is well described by the deformed Nilsson model for excited states in 31Mg. Finally, the quadrupole moment supports...
Table 1
Reduced transition probabilities of the positive-parity $K = 1/2^+$ yrast band in $^{31}\text{Mg}$, compared to recent theoretical predictions. $B(E2)$ values are given in $e^2\text{fm}^4$, $B(M1)$ in $\mu^2\text{N}$. For more details see text.

<table>
<thead>
<tr>
<th>$I_i \rightarrow I_f$</th>
<th>$B(E2)_{\text{exp}}$</th>
<th>$B(E2)_{\text{SM}}$</th>
<th>$B(E2)_{\text{th}}$</th>
<th>$B(M1)_{\text{exp}}$</th>
<th>$B(M1)_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5/2^+ \rightarrow 1/2^+$</td>
<td>$61(7)$</td>
<td>$69^a/114^b$</td>
<td>$-$</td>
<td>$-$</td>
<td></td>
</tr>
<tr>
<td>$5/2^+ \rightarrow 3/2^+$</td>
<td>$20^a/32^b$</td>
<td>$0.1$–$0.5$</td>
<td>$0.38^a$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3/2^+ \rightarrow 1/2^+$</td>
<td>$106^a$</td>
<td>$140^a/145^b$</td>
<td>$0.019(4)^c$</td>
<td>$0.06^a$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ From Ref. [16].
$^b$ From Ref. [35].
$^c$ From Ref. [36].

the idea that for the $N = 19$ magnesium isotope not only the ground state but also excited states are no longer dominated by a spherical configuration. Although the $E2$ strength of the $5/2^+ \rightarrow 1/2^+$ transition in $^{31}\text{Mg}$ is a bit smaller it is comparable to the corresponding $2^+ \rightarrow 0^+$ transition in $^{32}\text{Mg}$. The deviation can be explained by the assumption that higher lying states in $^{31}\text{Mg}$ are not dominated by pure intruder configurations [16,35], but contain an admixture of other particle-hole configurations.

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