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New structure information on ^{30}Mg, ^{31}Mg and ^{32}Mg

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*In the memory of Weronika Płóciennik deceased on December 25, 2004.
She was a young and talented researcher in experimental and theoretical physics.*

Abstract. The fast timing $\beta\gamma\gamma(t)$ method was applied to investigate the level lifetimes in ^{30,31,32}Mg. Levels in Mg have been populated in β and β-delayed neutron emission of Na at the ISOLDE facility. From the $\gamma\gamma$ coincidences a number of new states have been identified and new level schemes were constructed for ^{30,31,32}Mg. The following preliminary half lives have been determined: $T_{1/2} = 3.9(4)$ ns for the 1789 keV state in ^{30}Mg, $T_{1/2} = 133(8)$ ps and 10.5(8) ns for the 221 keV and 461 keV states in ^{31}Mg, respectively, and $T_{1/2} = 16(4)$ ps for the 885 keV level in ^{32}Mg. The 1789 keV level was established as a candidate for the intruder 0^+ configuration in ^{30}Mg with a possible strong $E0$ branch to the ground state.

PACS. 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.30.+t $20 \leq A \leq 38$

1 Introduction

A number of recent experiments using a variety of advanced probes has been focused on the structure of exotic Mg nuclei and nuclei in their close vicinity. This region is called "the island of inversion" [1,2] where the shell model configurations are strongly rearranged. Despite many experimental attempts on these exotic nuclei there remains a number of issues still to be resolved. A very active research program in the heavy Mg region is carried out at the ISOLDE facility at CERN using complementary techniques. At this conference the results on the Coulomb excitation on ^{30}Mg have been reported by Scheit *et al.* [3] and the laser spectroscopy and β-NMR results on ^{31}Mg were presented by Kowalska *et al.* [4]. Here we discuss preliminary findings from fast timing measurements using the Advanced Time Delayed $\beta\gamma\gamma$(t) Method [5] on ^{30,31,32}Mg.

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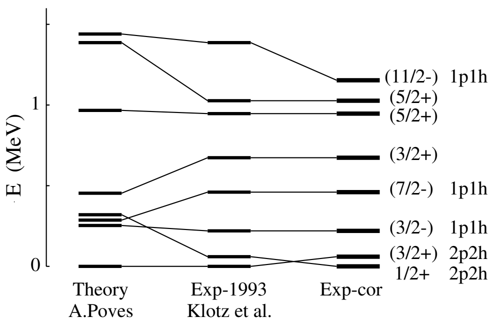

Fig. 1. Schematic representation of the level scheme of ^{31}Mg. The experimental results obtained by Klotz *et al.* [2] are shown in the middle, their theoretical interpretation [2] is illustrated on the left hand side, with the configuration assignment on the far right. The current status is shown on the right hand side (Exp-cor) and includes the ground state spin assignment of $1/2^+$ [4,6] and a new candidate for $11/2^-$.

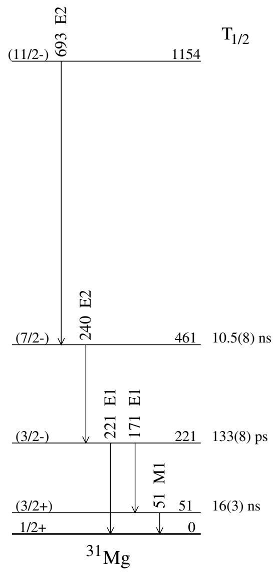

Fig. 2. A partial level scheme of ^{31}Mg and preliminary level lifetimes established in this work, except for the 51 keV level, which is taken from [2]. The suggested spin/parity assignments for the excited levels and transition multipolarities are model dependent [2] although supported by the observed transition rates.

The isotopes ^{30,31,32}Mg are the key nuclei located at the border of "the island of inversion". In particular, the nuclei of ^{30}Mg and ^{31}Mg are expected [1,2] to exhibit coexistence of spherical and intruder configurations, yet it is not clear how to classify the excited states observed at low excitation energy into members of these configurations. Our aim was to obtain new information that would better characterize the excited states in ^{31}Mg and to search for a candidate for the intruder 0^+ state in ^{30}Mg. Another objective was to verify information on the excited states in ^{32}Mg populated by the β decay of ^{32}Na and to measure the half-life of the first excited 2^+ state in ^{32}Mg by the time-delayed method. This state is located at only 885 keV indicating that the ground state in ^{32}Mg is dominated by the intruder configurations. As discussed in [3], there are discrepancies in the $B(E2)$ values reported for ^{30}Mg and ^{32}Mg, thus a direct lifetime measurement would yield an independent $B(E2)$ value for ^{32}Mg.

2 Experimental setup

The time-delayed $\beta\gamma\gamma(t)$ experiment, IS 414, was performed at the ISOLDE facility at CERN. The setup [5] included a thin plastic scintillator as a β detector, which provided uniform time response to β rays of different energies, two fast response BaF_2 detectors for γ-rays, and two large volume Ge detectors, whose high energy resolution allowed to select γ cascades. The fast response detectors were prepared at the OSIRIS mass separator at Studsvik in Sweden. The levels in ^{30}Mg and ^{31}Mg were populated in the β and β-delayed neutron emission of ^{30}Na and ^{31}Na, and ^{31}Na and ^{32}Na, respectively, while the levels in ^{32}Mg were populated in the β decay of ^{32}Na. The neutron-rich Na isotopes were produced by 1.4 GeV proton induced reactions in a UC_x graphite target. For ^{32}Na, the beam gate was opened about 8 ms after the proton pulse and closed about 100 ms later. The source strength of ^{32}Na was about 50–100 dps. No tape system was used since the activities mostly decayed out before the next proton pulse arrived after 2.4 s on the average. The Na ions were deposited onto an aluminum foil in front of the β detector. Other detectors were placed in a close geometry. The data were collected mainly as triple coincidences involving β-Ge-Ge, which allowed to construct the decay scheme, and β-Ge-BaF_2 coincidences for lifetime measurements.

3 Results for ^{31}Mg

Figure 1 on the right hand side (Exp-cor), shows the current status of the interpretation of the levels in ^{31}Mg. It includes a new possible location of the 1p1h $11/2^-$ state coming from our coincidence data, and the new $1/2^+$ 2p2h configuration of the ground state established in refs. [4,6]. The aim of the study was to verify the expected long lifetime (of the order of 11 ns) for the 461 keV level, which was suggested [2] to be $7/2^-$ de-excited by a collective $E2$ transition, and a short one (of the order of 50 ps) for the 221 keV state expected to be $3/2^-$ and depopulated by $E1$ transitions. The 461 and 1154 keV levels are populated in the β-delayed neutron emission of ^{32}Mg, while the other states are populated in the β decay of ^{31}Na.

The new results are illustrated in figs. 2-4. If the model interpretation of levels in ^{31}Mg shown in fig. 1 is correct then, the 461 keV state is the 1p1h intruder and the 240 keV γ-ray is the collective $E2$ $7/2^- \to 3/2^-$ transition. Indeed, its $B(E2) = 67(6)\ e^2\text{fm}^4$ compares very closely to the value for the 2p2h intruder state in ^{32}Mg of $B(E2; 2^+ \to 0^+) = 67(14)\ e^2\text{fm}^4$ taken from ref. [7] (other $B(E2)$ values measured for ^{32}Mg are even higher, see [3]). On the other hand, if it is a spherical configuration then it would follow more closely the $B(E2)$ value

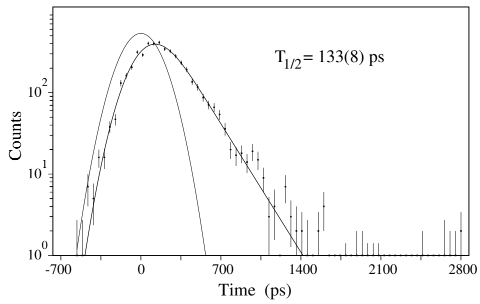

Fig. 3. Time-delayed $\beta\gamma(t)$ spectrum due to the lifetime of the 221 keV state in ^{31}Mg measured in the β decay of ^{31}Na. It was gated in Ge on transitions feeding the 221 keV state from above and by the 221 and 171 keV transitions recorded in the BaF_2 detector. The lifetime value was determined from slope fitting. A Gaussian curve at $T = 0$ shows the prompt time response used in the fitting.

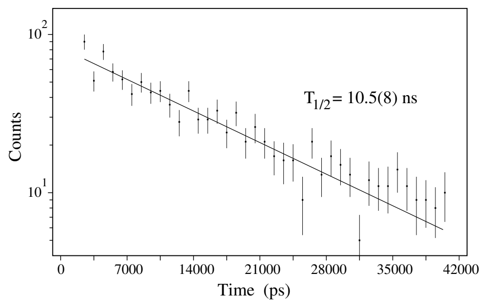

Fig. 4. Time-delayed $\beta\gamma(t)$ spectrum due to the lifetime of the 461 keV state in ^{31}Mg; measured in the β-delayed neutron decay of ^{32}Mg. It was gated on the 240, 221 and 171 keV transitions recorded in the BaF_2 detector. The lifetime value was determined from slope fitting.

for the "core" nucleus of ^{30}Mg, for which the $B(E2; 2^+ \rightarrow 0^+) \sim 40\ e^2\text{fm}^4$ was measured by Scheit *et al.* [3].

According to the interpretation given in ref. [2] (and corrected for the ground state spin/parity of $1/2^+$) the 171 and 221 keV transitions are $E1$, with the predicted reduced transition rate of $B(E1; 3/2^- \rightarrow 3/2^+) = 8.4 \times 10^{-4}\ e^2\text{fm}^2$ and $B(E1; 3/2^- \rightarrow 1/2^+) = 3.4 \times 10^{-3}\ e^2\text{fm}^2$, respectively. Assuming the $E1$ multipolarity, the measured values are $4.6(5) \times 10^{-3}\ e^2\text{fm}^2$ and $9.1(9) \times 10^{-5}\ e^2\text{fm}^2$ for these transitions. Considering the difficulty in the shell model predictions of the $E1$ rates, the observed agreement is very good. To summarize, our experimental results closely confirm the model interpretation of the observed states in ^{31}Mg, albeit do not provide a unique identification. Nevertheless, the measured lifetimes provide strong constraints on any alternative interpretation of these states.

4 Results for ^{30}Mg

While investigating the states in ^{31}Mg from the β decay of ^{31}Na, we have established a long lifetime for the 1789 keV in ^{30}Mg populated in the β-delayed neutron

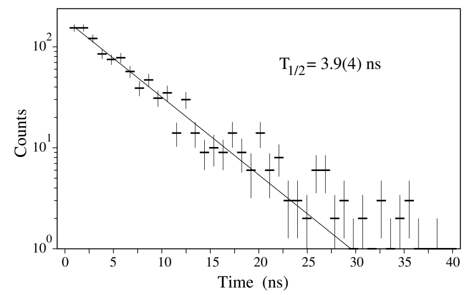

Fig. 5. Time-delayed $\beta\gamma(t)$ spectrum due to the lifetime of the 1789 keV state in ^{30}Mg measured in the β-delayed neutron decay of ^{31}Mg. It was gated by the 306 keV γ-ray in Ge and by the 1482 keV transition recorded in BaF_2. The lifetime value was measured from slope fitting.

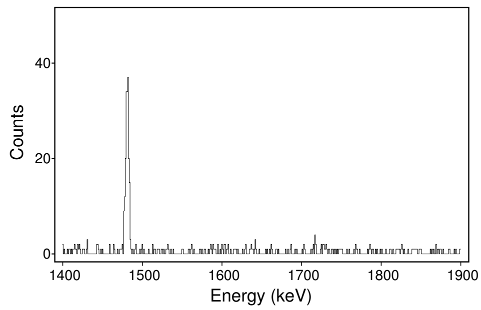

Fig. 6. A partial $\gamma\gamma$ coincidence spectrum gated by the 3178 keV γ-ray, which feeds the 1789 keV level in ^{30}Mg from above. It shows no trace of the 1789 keV line in channel 1280, which should be about 1/4 of the strong 1482 keV line seen in channel 1060, if the 1789 keV line de-excites the 1789 keV level.

emission of ^{31}Na, see fig. 5. Although a long lifetime makes the 1789 keV state a natural candidate for the intruder 0^+ state, yet such assignment was contradicted by the 1789 keV γ-ray previously reported to de-excite the 1789 keV state to the ground state, *e.g.*: see [2]. On the other hand the deduced limits on transition rates are not in agreement with the other possible positive parity assignments, while states of negative parity are definitely not expected at such low energy. Our investigation of the decay scheme of ^{30}Mg from the β decay of ^{30}Na using $\gamma\gamma$ coincidences, has established a new placement for the 1789 and 1820 keV transitions. The 3178 γ-ray feeding the 1789 keV level from above shows no coincidences with the 1789 keV line (fig. 6), while the 1789 keV γ-ray is in strong coincidences with the 1482 and 1820 keV lines (fig. 7). This defines the 1789-1820-1482 keV cascade and new levels at 3302 and 5091 keV, although the latter may actually be the same as the already established and close-lying state at 5093 keV [2]. Figure 8 summarizes the current situation in ^{30}Mg. Below 3.3 MeV there are only 3 known excited states: 2^+ 1482, (0^+) 1789, and (2^+) 2467 keV. There is now an intensity inbalance for the 1789 keV state: with 15.7(10) units of intensity feeding and 11.4(7) units de-exciting the state [2]. The inbalance of 4.3(12) could be due to a systematical error in intensities or a very strong $E0$ transition to the ground state. Both cases

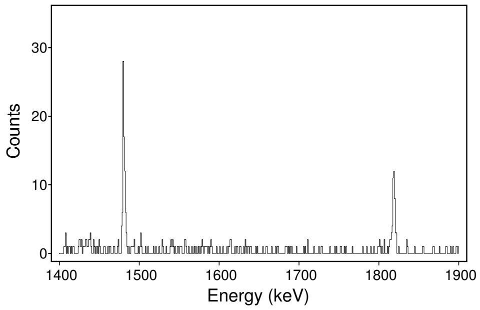

Fig. 7. A partial $\gamma\gamma$ coincidence spectrum gated by the 1789 keV γ-ray in ^{30}Mg. It shows two strong coincidence lines at 1482 and 1820 keV in channels 1060 and 1295, respectively.

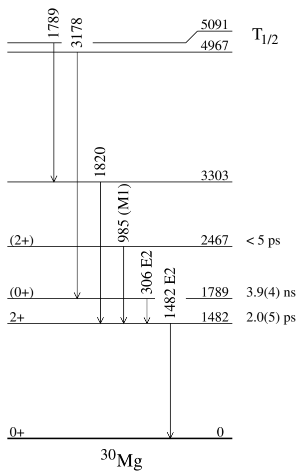

Fig. 8. A partial level scheme of ^{30}Mg and preliminary level lifetimes established in this work. The lifetime of the 1482 keV level is deduced from [4].

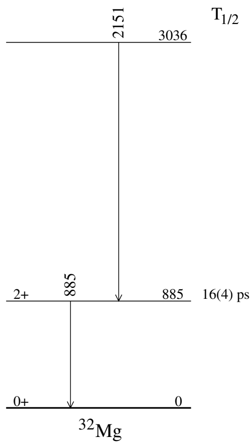

Fig. 9. A partial level scheme of ^{32}Mg showing the key 2151-885 keV two-γ cascade used in the lifetime measurement of the 885 keV level. The 885 keV level lifetime is preliminary.

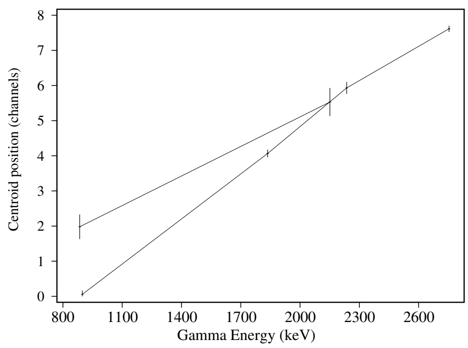

Fig. 10. Centroid shift analysis for ^{32}Mg: time response of the BaF_2 detector for the energy range 898-2754 keV, and the time shift due to a pair of points in ^{32}Mg, at 2151 keV (reference point normalized to the response curve) and at 885 keV. The shift of the latter point from the response curve is due to the lifetime of the 885 keV level.

require further investigation. If the 306 keV line is $E2$, then $B(E2; 2_1^+ \to 0_2^+) = 10.8(11)\ e^2\text{fm}^4$ is slow as would be expected for a transition between intruder collective and normal spherical states; for a comparison, for the 1482 keV line, the $B(E2; 2_1^+ \to 0_1^+) \sim 40\ e^2\text{fm}^4$, see [3]. We also note $B(E2; 2_2^+ \to 2_1^+) \geq 123\ e^2\text{fm}^4$ if a pure $E2$ character is assumed for the 985 keV transition de-exciting the 2467 keV state. Thus most likely the 985 keV transition has a dominant $M1$ component. The de-excitation pattern for this state is somewhat similar to the 2_2^+ state in ^{28}Mg.

5 Results for ^{32}Mg

We report a preliminary lifetime result for the 885 keV in ^{32}Mg. The starting point in the analysis was verification of the level scheme using the $\gamma\gamma$ coincidences. This allowed to established a new decay scheme of ^{32}Na (not presented here). The lifetime measurement of the 885 keV state was done by the centroid shift technique using triple coincidences between β and 885 and 2151 keV γ-rays (see fig. 9) recorded in the β, Ge, and BaF_2 detectors, respectively. The centroid of the time-delayed spectrum due to the β-2151 keV γ-ray coincident with the 885 keV transition recorded in the Ge detector gives the reference point. Then the centroid of the β-885 keV spectrum in coincidence with the 2151 keV transition recorded in the Ge detector is shifted from the reference point (corrected for the time response of the BaF_2 detector, see fig. 10) due to the lifetime of the 885 keV level. Important was to select β sources providing on-line time response calibrations of the BaF_2 detectors for the full energy peaks matching as closely as possible the energies of 2151 and 885 keV, and cascading via levels of precisely known lifetimes. Using the two-point calibrations for the energy pairs 898-1836 keV (^{88}Rb), 1263-2235 keV (^{30}Al) and 1369-2754 keV (^{24}Na), we have established the time response calibration of BaF_2 detector for the energy range from 898 to 2754 keV, see fig. 10. The results presented here for ^{32}Mg are based on 1/3 of data being analysed. The preliminary lifetime of the 885 keV level was found as $T_{1/2} = 16.0(42)$ ps, yielding $B(E2; 0^+ \to 2^+) = 327(87)\ e^2\text{fm}^4$, which is among the lowest values reported [3] for ^{32}Mg almost overlapping with the result from [7].

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