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Proposal to the Isolde and Neutron Time-of-Flight Committee

Advanced Time-Delayed coincidence studies of ^{31,32}Mg from the β-decays of ^{31,32}Na

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Abstract

It is proposed to study the lifetime of the 2_1^+ 885.4 keV state in ^{32}Mg by means of Advanced Time-Delayed $\beta\gamma\gamma$(t) method with the precision in the half-life value of about $\pm$1.5 ps. This would be an independent verification of the B(E2; $0_1^+ \rightarrow 2_1^+$) values obtained so far in a few studies using Coulomb excitations at intermediate beam energies. The advantage of time-delayed coincidence measurements is that they are free of corrections used in the Coulex studies, which strongly affect the deduced B(E2) results.

In addition, we propose to study the lifetimes or lifetime limits of other states in nuclei populated in the decays of ^{31}Na and ^{32}Na, specifically focusing on the intruder negative parity band in ^{31}Mg. As a side benefit to this investigation we expect high-quality γ-γ coincidences to reveal new excited states in both ^{31}Mg and ^{32}Mg.

Our results from a brief test-measurement yield a lifetime of $T_{1/2}$ = 10.5(8) ns for the 461 keV state in ^{31}Mg. The model interpretation of this level as the intruder $7/2^-$ state, would thus be confirmed since then the de-exciting 240 keV 7/2- to 3/2- transition would have a collective B(E2) = 11.8(9) W.u., a value close to the B(E2) rate of 14.5 W.u. for the $2_1^+ \rightarrow 0_1^+$ 885.4 keV transition in ^{32}Mg. We expect that the lifetime measurements in ^{31}Mg and new spectroscopic results would help to clarify the nature of the states below 1 MeV in excitation, and specifically the spin/parity assignment of the ground state, which is of strong theoretical interest. Our proposal is highly complementary to other research efforts performed in this mass region at ISOLDE and GANIL. For these studies we request 25 shifts including 1 shift with stable beam.

1. Introduction

The interest in a direct lifetime measurement of the exceptionally low-lying 2_1^+ state in ^{32}Mg, at 885.4 keV, goes back to the early 1990's, when the Advanced Time-Delayed (ATD) $\beta\gamma\gamma$(t) method [1, 2, 3] was introduced at ISOLDE within the IS322 project. However, a detailed investigation of the experimental conditions has revealed a substantially lower yield of ^{32}Na than expected, which was below the sensitivity of the fast timing setup used at that time. Only if the half-life of the level would be about 20 ps or longer, then a time-delayed coincidence measurement would make sense. However, half a year later the team of Motobayashi et al. [4] measured at RIKEN the B(E2; $0_1^+ \rightarrow 2_1^+$) value for ^{32}Mg and the deduced half-life of the level was only 11.5(2.0) ps.

Three factors have changed the situation and motivate the present proposal. The first one is that our fast timing technology has strongly improved its sensitivity limit. Responding to the demand for the lifetime measurements far of stability, we have developed at Studsvik much larger BaF_2 detectors, almost five times in volume in comparison to our standard units, which nevertheless have still a very good time resolution of about 135 ps FWHM for a pair of detectors at ^{60}Co energies, as compared to about 120 ps for the standard units. Moreover, we have refined the time calibration procedures and the technique became well tested at the ISOLDE environment. It is thus feasible to perform measurements at ISOLDE with truly picosecond precision using weak sources, provided these sources are not heavily contaminated with impurities.

Table 1: B(E2; $0_1^+ \rightarrow 2_1^+$) values for ^{32}Mg deduced in the Coulomb excitations at intermediate energies and the deduced level half-life for the 2_1^+ 885.4 keV state.

B(E2; $0_1^+ \rightarrow 2_1^+$) in e^2fm^4	Study by	$T_{1/2}$ in ps
454(78)	Motobayashi et al. [4]	11.5(2.0)
330(70)	Pritychenko et al. [5]	15.9(3.4)
622(90)	Chistè et al. [6]	8.4(1.2)
449(53)	Iwasaki et al. [7]	11.7(1.4)

The second factor, is that there have been a few re-measurements of the B(E2) value for ^{32}Mg by means of Coulomb excitations at intermediate energies. The Coulex of fast Radioactive Ion beams relies on one-step Coulomb excitation mechanism, which is good approximation at intermediate energies. Nuclear excitation can be neglected or is well under control for E1 and E2 in this mass region. The method has an advantage of high experimental efficiency due to large cross sections and the possibility to use a (very) thick target. This can be best demonstrated in the recently measured case of ^{34}Mg [7], where experiment was performed with a weak ^{34}Mg beam yielding only 4 counts per second. Moreover, one collects only simple singles γ-ray spectra. On the side of the drawbacks, one notes possible feeding from higher-lying states, which requires knowledge of the level scheme, and large Doppler shift, which leads to a relatively poor energy resolution.

Inspecting Table 1, one can see some discrepancies. A very significant part of the discrepancies could be related to the corrections needed in these measurements. However, these correction do depend on the experimental structure information of ^{32}Mg, which is limited, or on the information deduced from model calculations. For example the B(E2) value obtained by Pritychenko et al. [5] is 330(70) e^2fm^4 with the feeding correction and 440(55) e^2fm^4 without such a correction. The former value, which is the one adopted by the authors, differs from the value of 622(90) e^2fm^4 obtained by Chisté et al. [6]. A time delayed measurement with a precision of ± 1.5 ps would provide an independent result of strong interest.

Finally, the third factor relates to the new spectroscopic information that the fast timing measurement can provide for the region. Our brief test measurement of running 2 hours in the $\beta\gamma$(t) mode and 14 hours in the $\beta\gamma\gamma$(t) has provided clean contamination-free spectra, which have already revealed new and exciting physics described below. This was, however, an opportunity measurement with a setup poorly prepared for this type of job. A full scale measurement with properly selected detectors, gives thus a clear expectation for more new physics to be revealed.

The physics case

The physics case can be divided into two areas of interest. The first one is the intercomparison of independent techniques of the measurement of the B(E2; $0_1^+ \rightarrow 2_1^+$) in ^{32}Mg, which is a *cause célèbre*. These techniques include Coulex at the intermediate and low energies and the ATD $\beta\gamma\gamma$(t) technique. It is interesting to note that there are still new measurements of Coulex at the intermediate energies coming, which can be simply understood if we consider that the case of ^{32}Mg became now a reference point for these types of measurements in this mass region. One should also note that a Coulex measurement at low beam energies will be performed at REX-ISOLDE.

The second area of interest is related to the nuclear structure of a small but special region near ^{31}Na, which is frequently called "the island of inversion". In this region a strong collapse of semi-magic shell closures far from stability was found, attributed in a shell model context, due to the inversion of the neutron closed-shell configuration and a $2p-2h$ intruder configuration, intrinsically deformed [8]. A summary of the theoretical and experimental studies, in short: current understanding of this region, was recently provided by Caurier, Nowacki and Poves [8], who have also listed current areas of strongest interest. They have pointed out as the area for investigation the limits in the neutron number, N, of the region of inversion. In particular the N=19 may be inside or outside the region depending on the calculation. The experimental situation is also unclear. For example ^{31}Mg situated on the border between the regions (since ^{30}Mg is outside, while the well know case of ^{32}Mg is inside the inversion zone) is an uncertain nucleus. Although, the β-decay studies of Klotz et al. [9] favour the positive parity for the ground state of ^{31}Mg, the experimental data is not firm.

A recent measurement at LISE-GANIL aimed to investigate the nuclear moment of the ^{31}Mg ground state, has revealed [10] the presence of the long-lived I=7/2 state. The spin has been directly determined via the number of resonances seen in a beta-decay Level Mixing Resonance experiment on a pure beam of ^{31}Mg fragments. The experiment was however not conclusive on the fact whether this long-lived intruder state is the ^{31}Mg ground state (which would be in contrast to the β-decay study of Klotz et al. [9]) or if it is an isomeric state. It could even be a γ- or β decaying isomer, reflecting it's resonances in the ^{31}Mg β-decay. All this measurement can claim is that the lifetime of this 7/2 state is of the order of at least 10 microseconds (or more). In context of this experiment (with follow-up measurements already approved in GANIL) a firm assignment of the low-lying states in ^{31}Mg (say below 2 MeV) and measurements of their level lifetimes are in a strong demand.

It is clear that an investigation of the levels in ^{31}Mg from the β decay of ^{31,32}Na is a priority from the point of theoretical and experimental studies. Since our test measurement already provides new and important results on ^{31}Mg, a full and detailed investigation would strongly extend the knowledge of the intruder states in ^{31}Mg and allow for a deeper model interpretation.

Results of the test measurements

We have performed brief test measurements using a time-delayed setup, which consisted of thin β-detector, 2 small (1 inch) BaF_2 detectors and 2 Ge detectors of the efficiency of 80% and 20%, all positioned in a closed geometry around the beam deposition point. The radioactive beam of ^{32}Na was collected at the end of a narrow Al tube. A thin Al window did separate the source from the β detector positioned along the beam line. The γ detectors were positioned at 90 deg to the beam line forming a cross, with the timing detectors placed above and below the tube and Ge detectors positioned horizontally on either site of the tube.

The beam gate was opened 7 ms after the proton pulse and closed 93 ms later. No tape system was needed since the beam of ^{32}Na was very pure and most of the activity decayed out before the next proton pulse arrived. The data were collected in the $\beta\gamma$(t) mode for about 2 hours, and then in the $\beta\gamma\gamma$(t) mode for 14 hours. The proton beam included initially (over night) 7 pulses from the super cycle, and then 6 pulses during the day for the second half of the run.

Figure 1a shows the total β-gated spectrum observed in the 20% detector for the $\beta\gamma$(t) run. We note that it shows a strong 885 keV line in ^{32}Mg in channel $\sim$690. If we select only the γ rays arriving in the first 70 ms (and subtracting an equivalent 220-290 ms spectrum) we obtain spectrum shown in Figure 1b, which constitutes a pure γ spectrum due to the decay of ^{32}Na alone. It shows five γ lines of the energy 50-, 171-, 221- (a weaker line), 240- (in channel $\sim$200) and 885-keV, in channel $\sim$690. The quality of data contrast with the spectra presented in the work of Klotz et al., which are dominated by very strong impurities, but is consistent with the spectra obtained by Guillemaud et al. [11]. The quality of the $\beta\gamma\gamma$(t) data is demonstrated in Figure 1c, which shows the coincidence gate set on the 240 keV line in the 80% detector and projected onto the 20% Ge. Here one can see very clean peaks, up to 20 counts in height, due to the 50-, 171-, and 221 keV transitions, de-exciting the 50 and 221 keV levels in ^{31}Mg from the β delayed neutron emission of ^{32}Na. This should be compared to the work of Klotz et al., where a similar coincidence gate is mixed with the impurity lines. We have obtained several different coincidence spectra, which very firmly assign the 240 keV transition as feeding the 221 keV level from above. A small group of counts in channel 556 in Figure 1c, appear to be significant and show a peak at the energy of 692(1) keV. Similarly, a reversed gate set on the 694 keV peak does appear to show coincidences with the 171, 240 lines. We note here, that the 694 keV transition assigned to the decay of ^{32}Na in the previous studies, was never definitely placed in any level scheme. The analysis of our data is still in progress, but the evidence points out that in the full run a few more states related to the intruder structure in ^{31}Mg could be identified.

We now turn our attention to Figure 2. Figure 2a shows the γ-spectrum observed in the BaF_2 detectors during the $\beta\gamma$(t) run, with the same gating as for the Ge spectrum in Figure 1b. The scale in Figures 2a and 2c is 1 keV/channel thus one can easily identify the full energy peaks due to the 50-, 171-, 221+240- and 885 keV γ-rays reflecting the Ge spectrum of Figure 1b. In the $\beta\gamma$(t) time spectrum (Fig. 2b) started by a β ray in the fast timing β detector and stopped by a γ-ray in the BaF_2 detector, we observe a

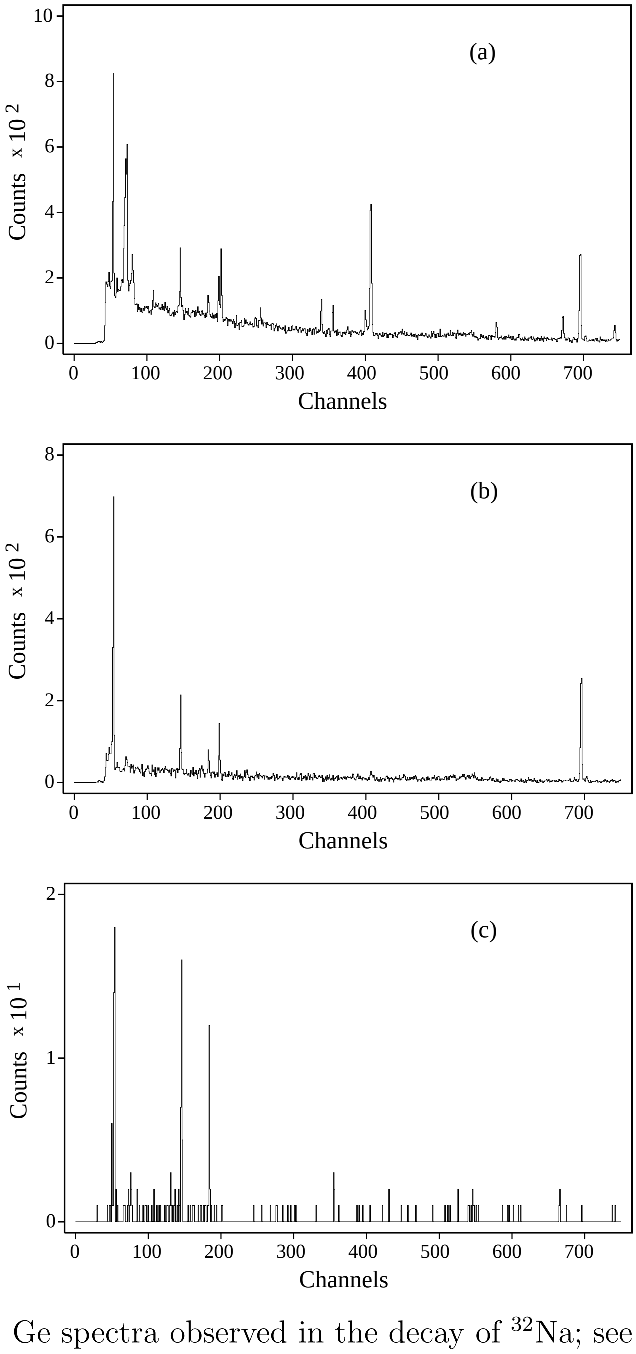

Figure 1: Ge spectra observed in the decay of ^{32}Na; see text for details.

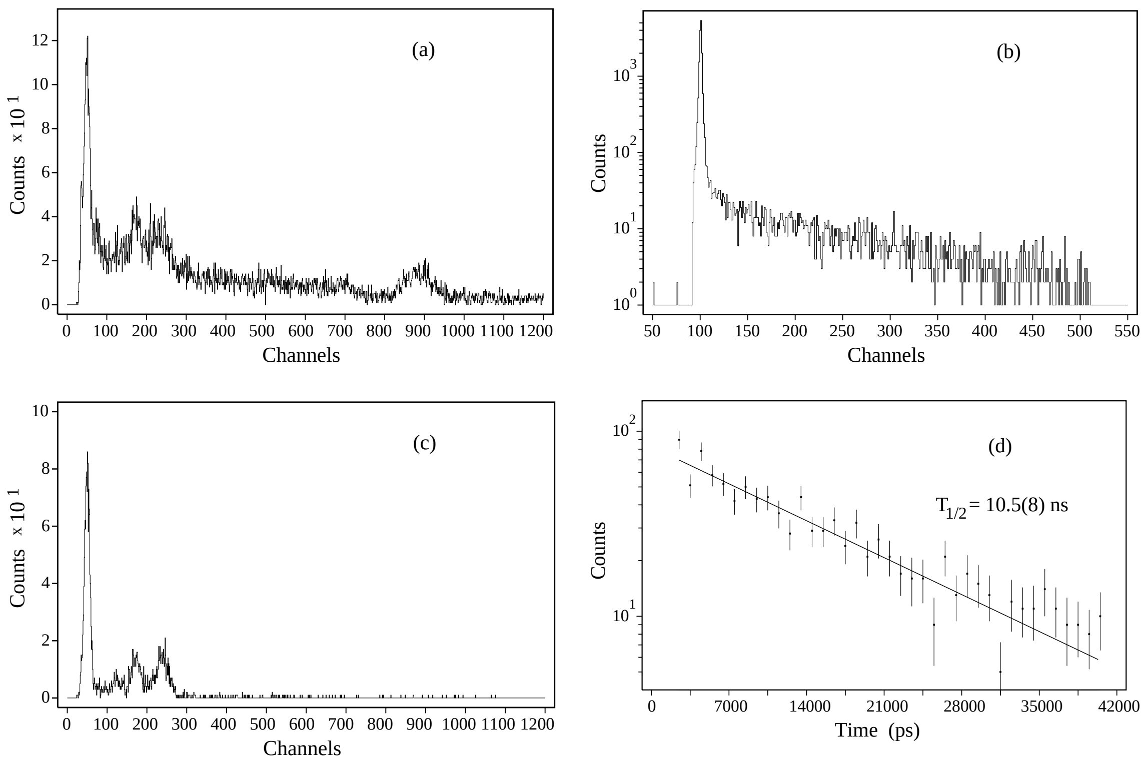

Figure 2: Analysis of the $\beta\gamma$(t) data on the decay of ^{32}Na obtained with the fast timing detectors; see text for details.

semi-prompt time distribution and a long tail due to the level lifetimes in the 5-20 ns range. These long lifetimes are either in ^{31}Mg or ^{32}Mg due to the decay of ^{32}Na, based on the observed Ge spectrum in Figure 1b. In order to identify which γ rays de-excite the ns isomers, we set a gate on the time spectrum well outside the semi-prompt peak, thus from channels 140 to 500 (see Fig. 2b), and observe its coincident energy spectrum in the BaF_2 detector. This coincident spectrum is shown in Figure 2c, where we can easily identify the 50-, 171- and 221+240 keV peaks. We note that the 240 keV line must be present. The energy of the peak is precisely 240 KeV, in a position quite different from the 221 keV energy. Moreover, if the 240 keV line is absent, then the intensity of the 171 peak should be at least twice as large as that for the 221 keV peak, and this is clearly not the case. We also note, that in the work of Klotz et al., a half life of 16.0(2.8) ns was measured for the 50 keV level (thus we should see the 50 keV line in Figure 2c, which we do), but the authors deduced an upper limit of $T_{1/2}\leq$1.4 ns for the 221 keV state. Thus if there is any longer lifetime it should come from the 461 keV level, which de-excites to the 221 keV state via the 240 keV transition. We have then set individually gates on the 50-, 171- and 240 keV peaks (selecting in the latter the higher energy section to minimize the presence of the 221 keV transition). The half-lives deduced for the time spectra gated by the 171 and 240 keV transitions were identical at about 10 ns, while the slope due to the 50 keV peak was significantly longer and consistent with the value measured by Klotz et al. Moreover the normalized χ^2 deduced in the 50 keV case from fitting a straight line, was substancially large than 1.0, which would be consistent with the fact that the 50 keV transition is subjected to feeding from 10 ns isomer at 465 keV in addition to the 16 ns lifetime of the 50 keV level, which alters the time decay spectrum from a straight line on a logarithmic scale. Fitting of the 171 and 240 keV data followed the straight line with a normalized χ^2 of about 0.6. Figure 2d shows the time-delayed sum spectrum gated by the 171+221+240 full energy peaks, which defines the half-life of $T_{1/2} = 10.5(8)$ ns for the 461 keV state in ^{31}Mg.

The results from the test run firmly establish the 461 keV level in ^{31}Mg. In the work of Klotz et al., the 221 and 462 keV states were proposed to be the 3/2- and 7/2- members of the intruder configuration. Consequently, the 240 keV γ ray would be an E2 transition. From our lifetime result we deduce B(E2; 7/2-→3/2-) = 11.8(9) W.u., a value close to the B(E2) rate of 14.5 W.u. for the $2_1^+ \rightarrow 0_1^+$ 885.4 keV transition in ^{32}Mg, which exactly follows the theoretical expectations of enhanced B(E2) rates for the deformed intruder configurations.

Proposed measurements, Experimental Equipment and Methods

The test run has revealed that the ISOLDE beam structure works in our favour. Its almost ideal. The beam intensity is highly concentrated in the first 100 ms, but its temporary counting rate can be easily handled by our system. We do not need any tape system, which means we can work in a close efficient geometry. The test has revealed exactly the conditions expected in the proposed experiment and allow to precisely estimate the beam time requirements.

Our experimental set up will include, as in the test case, five detectors positioned in a close geometry: a β detector, two "large volume" BaF_2 detectors (with the efficiency about 3 times larger than in the test case), and two Ge detectors with the efficiency of 80%. Otherwise the experimental setup will be similar to that used for our test run.

Due to the short lifetime of the 885.4 keV level in ^{32}Mg, the technique will be the centroid shift. We already have experience with measurements with the precision of about 1 ps by centroid shift, see for example [12, 13, 14]. The key to the measurement are the time calibration sources, and for the ^{32}Mg case we have a perfectly matching one in the form of the β decay of ^{88}Rb to ^{88}Sr, where the 1836 keV level of interest has a precisely know lifetime of $T_{1/2} = 0.162(5)$ ps, and the energies in the cascade 898 - 1836 match very closely our energies of 885 - 2152 keV. In addition we will use the source of ^{24}Na decay to ^{24}Mg which has a cascade 2754 - 1368 keV and a very well defined lifetime of the 1368 keV level as $T_{1/2} = 1.35(3)$ ps. Both sources are our standard ones used frequently for the calibrations of the time response of BaF_2 detectors to various interactions of the γ-rays in the crystals.

To obtain an internal cross-check of the procedures, we intend to run two independent and identical measurements for ^{32}Mg. We will start with 8 shifts with the ^{32}Na beam, then 2 shifts of time calibrations (mainly the decay of ^{88}Rb to ^{88}Sr), then a second series of 8 shifts with the ^{32}Na beam followed by 4 shifts with the ^{31}Mg beam (which provides a different population of the states in ^{31}Mg, importantly eliminating the presence of the 240 keV γ ray; this would allow to measure the expected short-lived state at 221 keV in particular). Finally we will close the run with 2 shifts of time calibrations in-beam, and then about 1.5 days of the off-line calibrations with the long-lived source of ^{24}Na to ^{24}Mg collected briefly on-line.

The estimate of the beam time requirement is extrapolated from the test results, and based on large efficiency BaF_2 crystals and a demand that about 10 000 counts will be collected in the time spectra of interest over the total measurement in both the ^{32}Mg case and the calibration ^{88}Sr and ^{24}Mg sources. We assume here that 50% of the proton pulses of the super cycle will be a available. We request a standard UC target with a surface ion-source for the production of ^{24,31,32}Na and ^{88}Rb.

The fast timing detectors and electronics will prepared at Studsvik, and will be provided by the Fast Timing Collaboration Pool of Electronics. Large volume Ge detectors will be provided by the Strasbourg group. We will need the ISOLDE DAQ system. However, we will need the ADC units for timing and Ge-energies with minimum range of 8k but preferentially 16k. We ask for the use of the ISOLDE data acquisition system for the full period of the radioactive beam time and 2 days before and after that for the off-line source calibrations and detector preparations.

6. Summary of beam requests

In total, we request 25 shifts, from which 24 are shifts with radioactive beams.

Nucleus	# of shifts	Separator	Target	Ion source	Min.Intensity (cps)
Stable beam	1	GPS/HRS	UC	WSI	
^{31}Na	4	GPS/HRS	UC	WSI	1x10^{2}
^{32}Na	16	GPS/HRS	UC	WSI	1x10^{2}
^{88}Rb	4	GPS/HRS	UC	WSI	1x10^{4}
^{24}Na	<0.1	GPS/HRS	UC	WSI	1x10^{6}
total	25				

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