EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Coulomb excitation of neutron-rich 32,33Mg nuclei with MINIBALL at HIE-ISOLDE

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Abstract

We propose to study the properties of neutron-rich nuclei^{32,33}Mg via Coulomb excitation and transfer reaction experiments using the HIE-ISOLDE facility coupled with the highly efficient MINIBALL array. In the past reliable transition strength values for ^{30,31,32}Mg were obtained at ISOLDE. Higher beam intensities and higher beam energies of HIE-ISOLDE will allow extending these studies to the neighbouring ^{33}Mg isotope and to higher lying states via multiple Coulomb excitation in ^{32,33}Mg. In ^{32}Mg only for the 2^+_1 and 4^+_1 excited states quantum numbers are firmly established. Future multiple Coulomb excitation at HIE-ISOLDE can elucidate the collectivity of the 4^+_1. The high beam energy will allow detecting the 3^-_1 state giving access the size of the $d_{3/2}$-$f_{7/2}$ shell gap. A second 2^+_2 state is predicted to exist on the second excited 0^+_2 state in ^{32}Mg and can be searched for in the proposed experiment. In ^{33}Mg theoretical predictions are made for the transition strength for all inter- and intra-band transitions of rotational states up to excitation energies of 5.2 MeV. A multiple Coulomb excitation experiment with a post accelerated ^{33}Mg HIE-ISOLDE beam would preferentially

populate the 5/2$^-$ and 7/2$^-$ levels. Such an experiment would thus confirm the proposed spin/parity for these levels. Both measurements will be feasible with HIE-ISOLDE beam energies of 5.5 MeV/u and an increased beam intensity which is ten times higher than the now available beam currents.

Requested shifts: 30 shifts
Beamline: MINIBALL + T-REX

Motivation

Despite extensive studies the nucleus ^{32}Mg and the island of inversion [1] remains in the centre of numerous ongoing experimental and theoretical efforts focusing on the evolution of shell structure far from the valley of stability.^{32}Mgitself caused a lot of attention after an anomalously large quadrupole collectivity [2,3] was discovered in this magic nucleus at neutron number N=20. A large B(E2,$0^+ \rightarrow 2^+_1$) value is extracted from a series of Coulomb excitation measurements for ^{32}Mg [3–8]. The first measurement was performed by Motobayashi et al. [3], who reported the value of B(E2)=454(78) e^2fm^4 corresponding to a large deformation of beta=0.512(44).The latest value was obtained with MINIBALL at REX-ISOLDE and yielded B(E2)=434(41) e^2 fm^4 [8]. All these results support the large collectivity suggested by the low excitation energy of the first 2^+ state at 885 keV and pointed to the vanishing of the N=20 shell gap demonstrating at this time that the nuclear shell structure can change in the region far from the stability line. The disappearances of the magic numbers N = 8 [9–12] and N =28 [13,14], as well as the appearance of the new magic number N = 16 [15], have been found in succeeding studies.

The large B(E2) value and the small E(2^+_1) value were interpreted using shell-model calculations by introducing the neutron 2p-2h excitation across the sd-pf shell gap [16–21]. Mean-field calculations result in a spherical shape for the ground state [22,23]. However, it is calculated to be very soft against quadrupole deformation. The low-lying 2^+_1 state is reproduced by the quasi-particle random-phase approximation [24] and configuration mixing with angular momentum projection [25,26].

Excited states in ^{32}Mg

The search for excited states above 2^+_1 in ^{32}Mg have so far been done by using beta-decays, fragmentation reactions, nuclear inelastic scattering, transfer reactions, and Coulomb excitation reactions. Recently the first excited 0^+_2 state of ^{32}Mg was measured employing the ^{30}Mg(t,p) 2n-transfer reaction in inverse kinematics at ISOLDE [27]. Outgoing protons were identified with the T-REX particle detector. Beside the ground state the first excited 0^+_2 state was identified at E_x =1.058 MeV.

An excited state at E_x = 2321 keV provided a potential candidate for either the 3^- or 4^+ state [29,30]. In the beta-decay of ^{32}Na [30], the 2321 keV state is not directly populated, leading to a positive-parity assignment to this state. The authors of Ref. [30] argue that it is the most likely candidate for the 4^+_1 state. This 4^+_1 assignment is consistent with the quadrupole character of the gamma-transition from the 2321 keV state to the 2^+_1 state studied by the gamma-gamma angular correlation in the fragmentation reaction of ^{36}S [31,32]. However, a 3^- assignment for the 2321 keV state was proposed in a nuclear inelastic scattering experiment by considering the similarity between the observed cross section and that for the 3^- state in ^{34}Si [29]. Other spin and parity assignments of 1^-, 1^+, and 2^+ were suggested in an intermediate-energy Coulomb excitation study [4]. Finally, a proton inelastic scattering experiment proved convincingly the 4^+ assignment by measuring the angular distribution for the excitation to the 2321 keV states in ^{32}Mg [33]. Other excited states in ^{32}Mg have been observed by beta-decay experiments. However, definitive spin and parity assignments to all other excited states have not yet been made.

Future experiments in ^{32}Mg

Beyond the 2^+_1 state, the nature of 3^-_1 and 4^+_1 states is crucial in understanding the inversion of the single-particle levels at the N = 20 shell gap and the character of collectivity in ^{32}Mg. The location of the 3^-_1 state reflects the size of the $d_{3/2}$-$f_{7/2}$ shell gap, if the state is of single-particle character. This is measurable by a transition strength which is close to the single-particle value. However, a collective excitation built on the highly deformed ground state would be of even higher relevance. The E2 transition strength between the 2^+_1 and 4^+_1 states gives information on the nature of quadrupole collectivity. The first excited 0^+_2state above the ground state was measured in ^{32}Mg. The new results suggest that the 0^+_2 state is a spherical state coexisting with the deformed ground state and that their relative energies are inverted at N=20. This scenario implies that a distorted rotational band is built on the excited 0^+_2 state in ^{32}Mg and a 2^+_2 state is predicted to exist above the excitation energy of the 0^+_2 state at 1.058 MeV. Dedicated theoretical predictions for this case are made awaiting experimental verification [28].

Inside the island of inversion: ^{33}Mg

While the gross picture of the highly deformed intruder states is established meanwhile from low lying 2^+_1 states and large $B(E2,0^+\rightarrow 2^+_1)$ values in even-even nuclei over a much wider region in the Segre chart than the initial 3x3 square of Warburton et al. [1]; the questions related to the details of the underlying single-particle structure can be preferentially addressed by studying nuclei with odd neutron or proton number. The actual position of the border line where the inversion of levels occurs motivated experiments in the N=19 nucleus ^{31}Mg. In previous theoretical and experimental work this nucleus was classified, to lie outside of the 'Island of Inversion'. However, the direct determination of the spin and the magnetic moment of the ground state in ^{31}Mg were done successfully at ISOLDE [34]. These results have proven that already the ground state of ^{31}Mg has a strongly deformed configuration similar to ^{32}Mg. Predictions of a strongly deformed Yrast rotational band [35,36] motivated an Coulomb excitation experiment in ^{31}Mg by the MINIBALL collaboration.

As a result of this Coulomb excitation experiment in ^{31}Mg the level scheme of ^{31}Mg was extended. Spin and parity assignments of highly collective state were done. The transition probabilities of ^{31}Mg supported the idea that not only the ground state but also excited states are largely dominated by a deformed pf intruder configuration. The result agreed with the assumption that higher lying states in ^{31}Mg are not dominated by pure intruder configurations, but contain an admixture of other particle-hole configurations [37].

From the experimental point of view a similar case like in ^{31}Mg is given at the moment for ^{33}Mg. New measurements of ground state properties of ^{33}Mg at ISOLDE unambiguously determined the spin I=3/2 and a negative g factor g= -0.4971(1) [38]. The quest for the parity of the ground state and the underlying single-particle configuration is described in Ref. [39].

Only four excited states are known in ^{33}Mg (see Fig. 2) and were observed in ▪ -decay, double fragmentation reactions, intermediate energy Coulomb excitation, inelastic proton scattering, and 1nknockout reactions from ^{34}Mg.

Excitation spectra and neutron single-particle configurations of ^{33}Mg were investigated by using antisymmetrized molecular dynamics combined with the generator coordinate method [40]. The results indicate that ^{33}Mg has a strongly deformed $3/2^-$ ground state with a 3p2h configuration. The excitation spectra are qualitatively understood in terms of the Nilsson model and the calculation has shown the coexistence of different intruder configurations within small excitation energy. The normal 1p0h configuration is located at higher excitation energy of 2.1 MeV. Due to the large deformation the intra-band E2 transitions are large for the ground state band. The calculated values are summarized in Table 1.

The measurement of the $B(E2, 3/2^-_1\rightarrow 5/2^-_1)$ and $B(E2, 5/2^-_1\rightarrow 7/2^-_1)$ values should be feasible due to the high intrinsic quadrupole moment of the intruder state.

$J_i^{\square}$	$J_f^{\square}$	B(E2, $J_i^{\square} \rightarrow J_i^{\cdot}$) ($e^2fm^4$)
$3/2^-{}_1$	$5/2^-{}_1$	282
$3/2^-{}_1$	$7/2^-{}_1$	154
$5/2^-{}_1$	$7/2^-{}_1$	147
$5/2^-{}_1$	$9/2^-{}_1$	194
$7/2^-{}_1$	$9/2^-{}_1$	92

Table 1 *Calculated E2 transition probabilities for the ground state band in ^{33}Mg [40].*

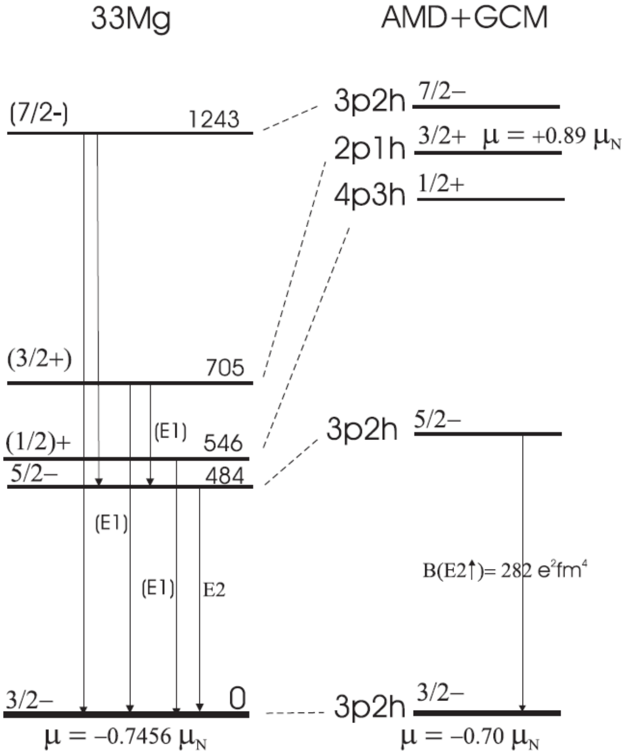

Fig. 2: *Level scheme of ^{33}Mg (left) and results from a calculation based on antisymmetrized molecular dynamics combined with the generator coordinate method. The Figure is taken from [39]; additional theory results are also published separately in [40].*

Experimental setup and count rate estimate

The experimental instrument used with HIE-ISOLDE will be the MINIBALL array for in-beam • -ray spectroscopy. The array consists of 24 6-fold segmented, encapsulated, HPGe detectors arranged in 8 triple cryostats. The detectors are mounted on an adjustable frame. The central core and six segment electrodes of each detector are equipped with a preamplifier with a cold stage and a warm main board. The charge integrated signals are subsequently digitized and analyzed online and onboard the DGF-4C CAMAC card. In addition to the MINIBALL array the charged particle detectors of the T-REX configuration will be employed consisting of a CD-type double-sided silicon strip detector (DSSSD) and segmented Si barrel detectors. The DSSSD detector thickness of 500 μm allows stopping completely the scattered ions. The high segmentation of the detectors allows for a kinematical reconstruction of the events and covers an angular range from 15°to 77°. Solid angle coverage of 30% is used for the count rate estimate [41].

The proposed MINIBALL experiments with unstable beams of ^{32,33}Mg isotopes at HIE-ISOLDE are from the ISOLDE point of view comparable with previous experiments employing ^{30,31,32}Mg beams. The ISOLDE yield values for Mg isotopes are 3 x 10^4 ions/μC for ^{32}Mg and 3 x 10^3 ions/μC for ^{33}Mg [42]. However, the yields available at HIE-ISOLDE should be slightly higher than the quoted value due to recent improvements in the RILIS laser technique. The accelerator efficiency for the complete HIE-ISOLDE chain from REX-trap to the MINIBALL target was estimated to be 5%. A beam intensity of ^{32}Mg and ^{33}Mg at the secondary target inside the MINBALL of I(^{32}Mg) = 2000 ions/s and only I(^{33}Mg)=200 ions/s, respectively, can be expected with a PSB proton beam current of 1.4 μA.

Coulomb excitation will be done at 'safe' energies of 5.5 MeV/u below the Coulomb barrier of a ^{196}Pt target. A distance of closest approach of 52.0fm is calculated for the incoming ^{33}Mg ions hitting the ^{196}Pt target nuclei with an energy of 5.5 MeV/u at an angle of 77° in the laboratory. According to the work of Cline [43] the 'safe' Coulex criterion requires distances of $d > R_p + R_t + 5$ fm = 16.2 fm. The target thickness can be chosen very thick with 7.5 mg/cm^2 at this high beam energy. Nevertheless the energy differences between the kinetic energy of scattered beam and target nuclei allows for a clear separation between the scattering partners in the particle detectors.

The most relevant improvements of the proposed measurements with respect to the previous result obtained e.g. for ^{33}Mg at MSU are: (i) the high energy resolution of the MINIBALL HPGe detectors, (ii) the enlarged energy range for gamma-ray detection, which is going down in a reliable and controlled way to a lower threshold of 50 keV and the (iii) good efficiency of the 8 triple cluster detectors of MINIBALL.

The cross sections for the excitation of excited states in ^{32,33}Mg were calculated with the Coulomb excitation code CLX. A beam energy value of 5.5 MeV/u was used. The cross section for projectile excitation was integrated for particle detection in the solid angle range in the CM system of $\Delta\theta_{CM}$=25°-115°. These angles are covered by the particle detectors in the laboratory frame by $\Delta\theta_{Lab}$=15°-77°. For gamma-ray detection the measured energy dependent gamma-efficiency was included. Effects of the gamma-ray angular distribution were neglected in the estimate. As target material ^{196}Pt was used with a thickness of 7.5 mg/cm^2.

For ^{32}Mg the B(E2) value for the $0^+_1 \rightarrow 2^+_1$ transition was taken from experiment [44]. CHFB+LQRPA calculations [28] give a value of 288 e^{2}fm^4 for the excitation strength of the next excitation step to the 4^+_1 state. The excitation to a possible 3^- state at an energy of 2858 keV was assumed to occur with a strength of about 5 W.u. Additional excitation to a distorted rotational band built on the excited 0^+_2 state in ^{32}Mg was taken into account with $B(E2,0^+_1 \rightarrow 2^+_2)$ = 45 e^{2}fm^4, i.e. an order of magnitude less than the excitation of the deformed first 2^+ state.

For the calculation of the Coulomb excitation cross sections of ^{33}Mg the calculated excitation strengths, given in Table 1, were used in combination with the experimentally deduced level scheme presented in Figure 2. Due to the branching of the gamma-decay of the $7/2^-$ state, both decay lines to the $3/2^-$ and $5/2^-$ state, respectively, need to be observed.

At moment both experiments would suffer from low beam intensities. Due to the low primary ISOLDE yield, almost all yields in the photo peak lines are approaching the detection limit even for a 120 hours experiment. Thus, the success of the proposed measurements will clearly rely also on an intensity upgrade for the neutron-rich Mg isotopes at HIE-ISOLDE. The final ISOLDE yields should exceed the now available yields by at least a factor of ten to be able to detect gamma-decays of higher lying states after multiple Coulomb excitations. The count rate estimate shown in Table 2 is based on the improved future HIE-ISOLDE yield.

Summary of requested shifts:

In conclusion, we request 10 days of beam time for Coulomb excitation of the magnesium isotopes ^{32,33}Mg. Increased HIE-ISOLDE beam intensities are required to perform these measurements. Considering the individual cases for each nucleus we ask for 5 days (15 shifts) of ^{32}Mg- and 5 days (15 shifts) of ^{33}Mg post-accelerated HIE-ISOLDE beam at the MINIBALL target.

	Primary ISOLDE yield (ions/μC)	beam intensity at MINIBALL (ions/s)	Transition/ energy (keV)	B(E2) ↑ values e^2fm^{2L} *theory **assumed	integrated Coulex x-section (mbarn)	Events in the photo peak Count rate in hours		shifts
						Cts/h	Cts/ 120h	
^{32}Mg	3×10^5	2×10^4	$2_1^+ \rightarrow 0_1^+$ 885 keV	454	1110	150	18000	**15**
^{32}Mg	3×10^5	2×10^4	$4_1^+ \rightarrow 2_1^+$ 1436keV	288*	500	5	600	
^{32}Mg	3×10^5	2×10^4	$3_1^- \rightarrow 2_1^+$ 1973keV	2500**	10	1	120	
^{32}Mg	3×10^5	2×10^4	$0_1^+ \rightarrow 2_2^+$ 2550keV	45**	40	2.5	300	
^{33}Mg	3×10^4	2×10^3	$5/2_1^- \rightarrow 3/2_1^-$ 485keV	282*	795	16	1920	**15**
^{33}Mg	3×10^4	2×10^3	$7/2_1^- \rightarrow 3/2_1^-$ 1243 keV $7/2_1^- \rightarrow 5/2_1^-$ 758keV	154* 147*	350	2 2.5	240 300	

***Table 2**: Rate estimates and beam time request which are base on an increased primary ISOLDE yield. At the moment a reduced intensity of 3×10^4 ions/μC is available for ^{32}Mg and 3×10^3 ions/μC for ^{33}Mg*

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DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the	Availability	Design and manufacturing
MINIBALL + T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL + T-REX installation.

Additional hazards: n.p.