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Proposal to the INTC Committee

Shape coexistence in the "island of inversion": Search for the 0_2^+ state in ^{32}Mg applying a two-neutron transfer reaction

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Abstract: We aim to study the structure of neutron-rich nuclei in the "island of inversion" where intruder fp-orbitals favouring deformed states compete with the normal spherical sd-orbitals. In particular, we search for the spherical 0_2^+ state in ^{32}Mg which should coexist with the deformed ground state but has not been observed so far. We propose to populate this state by a (t,p) two-neutron transfer reaction with a ^{30}Mg beam at around 2 MeV/u from REX-ISOLDE impinging on a tritium-loaded Ti target. The γ-rays are detected by MINIBALL and the particles by our new set-up of segmented Si detectors. The results will shed new light on the breaking of the shell closure at $N = 20$ in this region.

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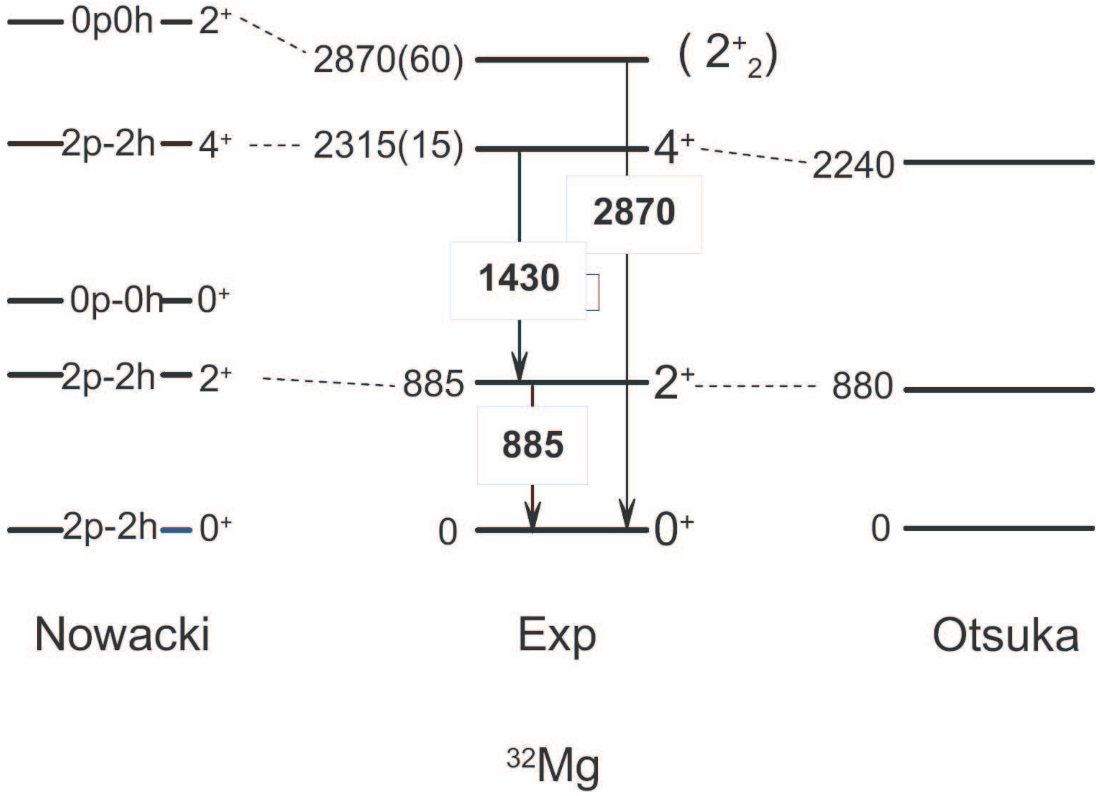

Figure 1: *Partial level scheme of* ^{32}*Mg: experimental levels (middle) compared with theoretical predictions by F. Nowacki and T. Otsuka (diagram taken from [1]). Note that other experiments have observed instead of the decay of the 2870 keV state to the ground state only the decay to the* 2^+_1 *state [23].*

1 Physics case

Although it has been discovered already more than 30 years ago, the structure of nuclei within the "island of inversion" [2, 3], a region of nuclei with deformed ground states in the sea of spherical *sd*-nuclei, is still not fully understood. The gross features of this inversion are interpreted as effect of a residual interaction derived from the tensor part of the nuclear force [4, 5]. The intruder *fp*-orbitals are lowered with respect to the normal *sd*-orbitals and excitations of neutrons to the *fp*-orbitals are energetically favoured. This breaking of the shell closure at $N = 20$ and the, hence, open shells for both neutrons and protons lead to deformed states.
At the north-west coast of the island, Coulomb excitation experiments done at "safe" energies at REX-ISOLDE [6, 7] as well as with intermediate energy beams [8, 9] established consistently a nearly spherical ground state for ^{30}Mg and a deformed ground state for ^{32}Mg. Hence, the former is outside whereas the latter is inside of the "island of inversion". The region has been studied extensively also by theory in the last years. A good agreement has been achieved with modern large scale shell model calculations using either the conventional shell model [10, 11], mean field calculations including correlations with the

GCM [12], or newer approaches, like the Monte Carlo Shell Model (MCSM), involving the new residual interaction mentioned above [13, 14, 15, 16].
However, there are still surprises. In an experiment performed at ISOLDE it was found that ^{31}Mg, the nucleus right on the shore of the island, has a $1/2^+$ ground state in contrast to all theoretical predictions [17, 18]. A possible interpretation has been found only recently [19]. It was concluded that the ground state and the first excited state in ^{31}Mg are largely dominated by 2p-2h intruder configurations (93% and 95% of the wave function, respectively) with a fp-shell occupancy close to 2. The collective and single-particle properties of ^{31}Mg have been studied in 2007 at REX-ISOLDE with "safe" Coulomb excitation (IS410) [20] and a one-neutron transfer reaction (IS454) [21].
In order to study the formation of this island in more detail, the migration of the relevant states along isotopic chains is of particular interest. Concerning the even Mg isotopes, further information comes from the excited 0^+ states. The ground state of ^{30}Mg has predominantly a normal 0p-0h sd-shell configuration and excitations to the fp-shell lead to excited states like a 0^+_2 state with 2p-2h configuration. Going to ^{32}Mg the inversion occurs and the 2p-2h intruder configuration from the fp-shell becomes the ground state and the 0^+_2 state has the normal 0p-0h configuration.
In 2007, in a measurement performed at ISOLDE the E0-decay of the 0^+_2 state in ^{30}Mg to the ground state has been observed for the first time verifying that both states have different deformations [22]. Such coexistence of states with different deformation is also expected for ^{32}Mg, but the nearly spherical 0^+_2 state, the pendant to the ground state in ^{30}Mg, has not been observed so far.
The aim of the proposed experiment is to populate the 0^+_2 state in ^{32}Mg by a two-neutron transfer reaction. The two-neutron transfer reaction starting from the normal ground state of ^{30}Mg is expected to favour the population of its analogue in ^{32}Mg, the excited 0^+_2-state which has a similar particle-hole structure. This state is practically not reachable in Coulomb excitation and its population has neither been observed in the β-decay of ^{32}Na nor in heavy-ion induced reactions [23].
From such a study a deeper understanding of the residual interactions relevant for the nuclear structure in this mass region can be gained.

2 Experimental method

2.1 Proposed experiment

We propose to utilise a (t,p) two-neutron transfer reaction to populate the 0^+_2 state in ^{32}Mg. Nuclear states with a similar particle-hole structure have a large overlap of their wave functions which corresponds to large spectroscopic factors and hence large cross sections. Starting from the nearly spherical ground state of ^{30}Mg, a two-neutron transfer reaction will therefore populate selectively the spherical 0^+_2 state in ^{32}Mg.
In a shell model picture we would expect a transfer of a neutron pair into the sd-shell: $^{30}\text{Mg}\otimes(sd)^2$, which corresponds to the spherical 0p-0h configuration in ^{32}Mg. Transfer to fp-orbitals will lead to highly excited 2p-2h configurations rather than to low lying states. Furthermore, low-spin states on top of the 0^+_2 state with similar structure like the second 2^+ state shown in Fig. 1 may be populated too.

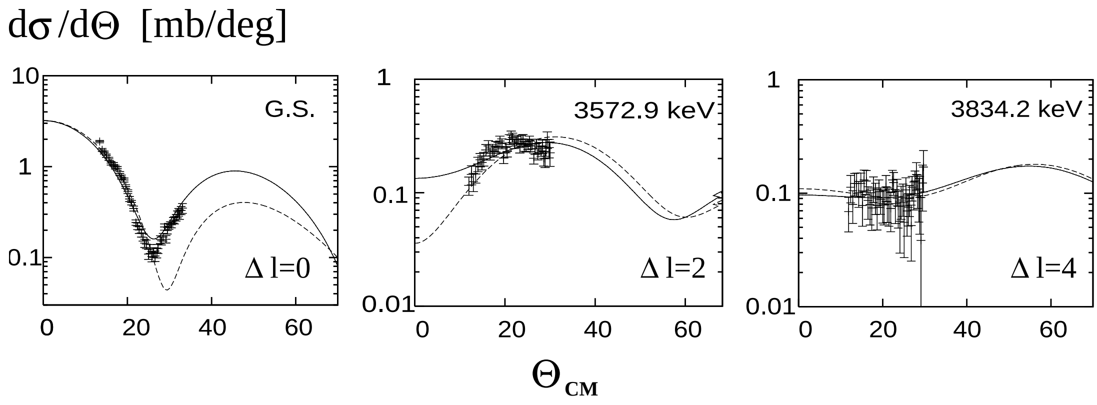

Figure 2: *Examples for experimental and calculated cross sections for the protons emitted from the reaction $^{3}H(^{40}Ar,\ ^{42}Ar)^{1}H$ at 2.25 MeV/u [30].*

Of course, not only the transfer of a correlated neutron pair but also the sequential transfer of two neutrons via intermediate states in ^{31}Mg has to be considered. However, the same argument for a selective population of states with similar configurations holds true. In two sequential one-neutron transfer reactions also states with $^{30}\mathrm{Mg}\bigotimes(sd)(fp)$ configurations could be populated.

The experiment will be performed in inverse kinematics. The projectile-like nuclei are forward focused in the laboratory system and cannot be measured with current equipment (a 0°-spectrometer for HIE-ISOLDE is under development). We will measure the energies and angular distributions of the protons emitted from the (t,p) reaction. Since the energy resolution obtained for the protons is usually not sufficient to disentangle states which differ by less than some 100 keV in excitation energy, the states populated in the reaction, except for the ground state, can be identified also by their characteristic γ-decay which is measured in coincidence with protons. The transferred orbital momentum leading to the spin assignment of a state is determined from the angular distribution of the particles. In particular, the characteristic shape for a $\Delta\ell = 0$-transfer enables to identify 0^+ states.

The measured cross sections and angular distributions will be analysed in the framework of the DWBA by applying the codes CHUCK3 [24] or FRESCO [25]. The optical potentials needed for this analysis can be scaled regarding the mass of the projectile and the beam energy from values fitted to experiments with stable beams applying a well established formula [26]. The optical model parameters can be pinned down also from the analysis of the (t,d) reaction and the elastically scattered tritons. Furthermore, the results for ^{31}Mg obtained in the (d,p) reaction (experiment IS454 [21]), i.e. the spectroscopic factors for one-neutron transfer, will be helpful for the understanding of the sequential neutron transfer.

The results of such an analysis are the excitation energy, the transferred orbital momentum, and possibly the relative spectroscopic factors. Additional information on the spin and parity assignment to a level may come from the multipolarity of the γ-rays extracted from their angular distribution. The obtained values have to be compared with predictions by the recent shell model codes mentioned above.

A similar investigation has already been proposed previously, applying a radioactive ^{10}Be target [27]. The reaction has been tested with a stable ^{26}Mg beam at the tandem accelerator at Köln. It was found that the cross section for two-neutron transfer was roughly an order of magnitude lower than expected from calculations [28, 29], a fact which is not yet understood. Hence this reaction is not feasible with the beam intensities available at REX-ISOLDE. We propose instead to use a tritium-loaded Ti foil as target. The details and the radiation safety concerns for such a target will be discussed in Section 4.

2.2 Test experiment with a stable Ar beam

In order to demonstrate the feasibility of using a tritium-loaded Ti foil as target for transfer reactions we performed an experiment at HMI Berlin with a stable ^{40}Ar beam [30]. The set-up consisted only of a DSSSD Si detector (CD) in backward direction for the protons and two PIN diodes as beam monitors in forward direction, but no γ-detection. Fig. 2 shows the angular distribution of the protons originating from the population of the $0^+_{\rm gs}$, 2^+_1, and 4^+_3 states in ^{42}Ar. The experimental data are compared with DWBA calculations performed with CHUCK3 [24]. The optical model parameters have been taken from the analysis of the same reaction but performed in normal kinematics [31] and adapted to the much lower beam energy of $E_{\rm Lab}$ = 2.25 MeV/u used in the experiment [30]. In particular, the angular distribution allows to distinguish clearly the $\Delta\ell = 0$ transfer from the other channels. The good agreement demonstrates that the description of the two-neutron transfer process is well under control. It has to be mentioned that the process of (d,p) and (t,p) reactions has been studied already extensively also in theory, e.g. see [32].

2.3 Direct vs. fusion-evaporation reactions at 2 MeV/u

A drawback of the use of such a target is the low beam energy of around 2 MeV/u. A limiting factor are protons emitted from fusion-evaporation reactions between the Ti of the target and the beam. Since this is a crucial point and calculations for the fusion cross section just at the barrier have shown to be unreliable, the optimal energy has to be determined experimentally using a pure Ti target. In fact, in our test experiment at HMI it was found that we had to decrease the beam energy down to 2.25 MeV/u, somewhat lower than the $\approx$ 2.5 MeV/u predicted by the PACE code [33]. For the reaction ^{30}Mg with Ti the beam energy has to be limited to around 2 MeV/u. E.g. already at an energy of 2.5 MeV/u the cross section for proton evaporation after the fusion of ^{30}Mg and Ti is predicted to be around 280 mb, hence orders of magnitude higher than the cross section for the transfer reaction (see the following Subsection).
Concerning the optimal beam energy, it would be preferable to go to beam energies around 3 MeV/u where the cross section for transfer is maximal, at least for one-neutron transfer, [34] and the angular distributions are more pronounced compared to 2 MeV/u.
A beam energy of 2 MeV/u is low compared to the higher energies normally used in order to assure that the levels are populated only by direct reactions like transfer and not by fusion-evaporation reactions with the tritium. A fusion reaction as statistical process usually populates, after particle emission, high-lying states where the level density is large (Q-value for fusion of ^{30}Mg with tritium is 14.6 MeV). Therefore, the experimental

signature is very different from that of a direct reaction: statistical energy spectrum of the protons and feeding of low-lying states mainly by cascades of γ-rays. Requiring in the analysis coincidences of γ-transitions with discrete proton lines having the correct kinematics enables to minimise contributions from non-transfer processes. Hauser-Feshbach-calculations also show that at 2.2 MeV/u such compound contributions should be small for neutron-rich nuclei. This can be understood due to the fact that the separation energy increases with neutron number for protons and decreases for neutrons. Therefore, the emission of protons compared to neutrons is suppressed [35]. In fact, calculations with PACE predict that no protons at all will be emitted after the fusion of tritium and Ti at 2 MeV/u.

2.4 DWBA calculations for the proposed experiment

The Q-value for the ^{3}H(^{30}Mg, ^{32}Mg)^{1}H reaction is slightly negative (-0.295 MeV) [36]. Since the Q-value window has a width of a few MeV around the optimal Q-value for neutron transfer of ≈ 0 MeV the population of relatively low-lying states is still favoured. Other reaction channels, like (t,d) ($Q = -3.88$ MeV), have strong negative Q-values, which make them disfavoured or even forbidden. Additionally, because of the negative Q-values and mass transfer from the target nuclei none of them is observed in backward direction (in the laboratory system).

Fig. 3 shows the differential cross sections calculated with the CHUCK3 code for the reaction ^{3}H(^{30}Mg, ^{32}Mg)^{1}H including both one-step and two-step transfer processes. Clearly, transfer channels with $\Delta\ell = 0$ populating 0^{+} states can be distinguished from those with $\Delta\ell = 2$ populating 2^{+} states by their different angular distributions. The spectroscopic factors used in this calculations have been set simply to unity. This is approximately correct for the transfer between states of similar particle-hole structure, as for the one-step transfer from the ground state of ^{30}Mg to the 0^{+}_{2} state in ^{32}Mg, and has been observed experimentally in reactions with stable Mg and Si targets [37, 38]. As already mentioned before, for the ground state and the first excited state of ^{31}Mg a large 2p-2h contribution is predicted and, consequently, small spectroscopic factors for the one-neutron transfer starting from the ground state of ^{30}Mg are expected. However, setting the spectroscopic factors for these states to zero, the total cross section to populate the 0^{+}_{2} state in ^{32}Mg drops only by 10%. Since the population of these states has been observed in the (d,p) reaction [35, 39], the later assumption is anyway too pessimistic. The dominant part of the cross section is due to the one-step transfer of a correlated pair of neutrons and the population of the 0^{+}_{2} state in ^{32}Mg is rather insensitive to the structure of intermediate states in ^{31}Mg.

The main uncertainty is the choice of the optical potential parameters which are here extrapolated from values used in the analysis of similar reactions with stable Mg and Si targets [37, 38]. However, it has to be mentioned that also in the analysis of reactions with stable targets the choice of the optical potential parameters is not unique. We performed DWBA calculations assuming different parameter sets and found that the results shown in Fig. 3 are most sensitive to the depth of the imaginary potential of the (d,p) reaction on ^{31}Mg. By changing its value the importance of the two-step transfer processes can be increased and the total cross section can be up to an order of magnitude larger.

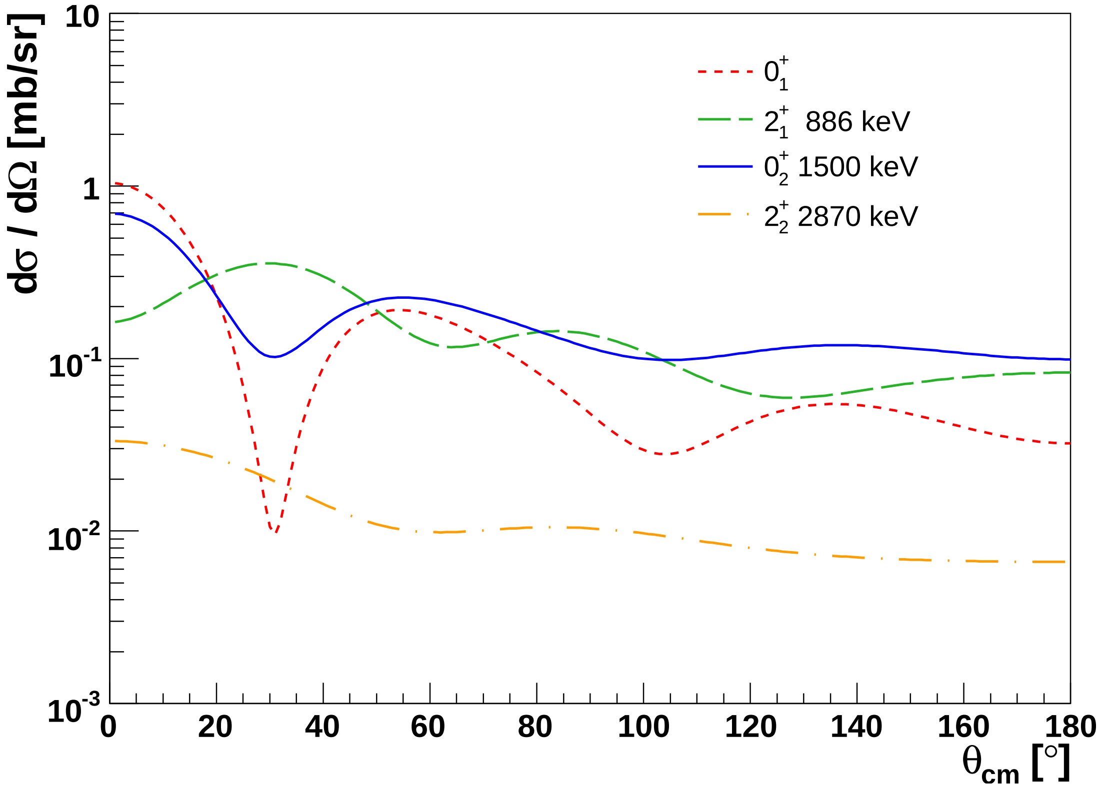

Figure 3: *Cross section for the population of states in ^{32}Mg versus the CM angle for the proposed reaction at 2 MeV/u calculated in the DWBA approximation.*

Conclusively, the estimates shown in Fig. 3 have to be considered as lower limits for the expected cross sections.

2.5 Perspectives for further experiments

The demonstration of the feasibility to perform two-neutron transfer reactions at REX-ISOLDE will open a broad range of future experiments:
Shape coexistence is present in many parts of the nuclear chart. For example, the double or triple coexistence of 0^+ states of different deformation within sometimes less than 1 MeV energy difference in the region of neutron deficient Hg/Pb/Po isotopes is a fascinating phenomenon whose microscopic nature is still not fully understood, see e.g. [40]. Since some of these elements have been recently produced and post-accelerated by REX-ISOLDE, e.g. for experiment IS452 [41, 42], transfer reaction studies complementary to decay spectroscopy or Coulomb excitation will become feasible also for these heavy nuclei. Furthermore two-neutron transfer reactions are a valuable tool to probe nuclear features like pairing. The cross section for two-neutron transfer is enhanced for the transfer from or onto a superfluid nucleus, see e.g. [43, 44, 45]. Therefore it can probe shell closures (no superfluidity) as well as changes in the pairing correlations which are expected for loosely bound neutrons in very neutron-rich nuclei.
Finally it has to be mentioned that the transfer reaction programme, although already

a number of valuable experiments can be performed at low beam energies, will profit particularly from the upgrade to higher energies in the HIE-ISOLDE project.

3 Experimental procedure

3.1 Set-up

The set-up consists of the MINIBALL array to detect γ-rays in coincidence with particles detected by our new array of segmented Si detectors with nearly 4π angular coverage shown in Fig. 4 which is described in the following.
The array comprises two double-sided segmented Si detectors (DSSSD), so-called CD detectors, in forward and backward direction and a barrel of eight planar detectors around 90°.
The forward CD detector consists of two layers, thus it acts as a $\Delta E - E$-telescope. The ΔE-detector (thickness 300 μm) has four quadrants, each of them is segmented in 16 annular stripes (ϑ-coordinate) on the front and in 24 radial segments (ϕ-coordinate) on the back. The E-detector (thickness 1500 μm) is segmented only in 4 quadrants. The backward CD detector has the same segmentation as the forward ΔE-detector, but a thickness of 500 μm.
The four forward detectors of the barrel are also $\Delta E - E$-telescopes. The ΔE-detector (thickness 140 μm) is segmented in 16 stripes perpendicular to the beam axis. Positional information along the stripes can be obtained from the charge division on a resistive layer. The E-detector is not segmented and has a thickness of 1000 μm. The four backward detectors are thick E-detectors (500 μm) and segmented as the ΔE-detectors in forward direction.
The use of $\Delta E - E$-telescopes in forward direction enables the identification of light particles (p,d,t,α). The energy resolution for the protons ranges from 250 keV to 2 MeV depending on angle and energy. The angular resolution is typically below 5°.
In order to reduce the high count rate from elastic scattering of both Mg beam and target nuclei, i.e. tritons and Ti, an Al foil is mounted in front of the forward detectors. This foil stops all heavy ions, but the tritons only around 90°.
From the angular distributions in the laboratory system (see Fig. 6), a coverage of the region around 90° seems to be desirable in order to improve the sensitivity on the transferred orbital momentum. Therefore, it is currently under discussion to modify the arrangement of the barrel detectors aiming to cover on two sides of the barrel the region around 90°. But this will only be possible on the cost of a reduced total efficiency. Additionally, it would require the use of a tilted target reducing the number of positions available on the target ladder.
The electronics of the Si detector is somewhat different to the one previously used. The signals from the CD detectors (in 2007 only the backward CD detector was available) are fed via multiplexers into ADC modules, whereas the signals from the barrel detectors are fed directly to ADC modules. This scheme has been proven to work accurately during several tests performed at the MLL (Garching) and the actual experiment IS454 at REX-ISOLDE.

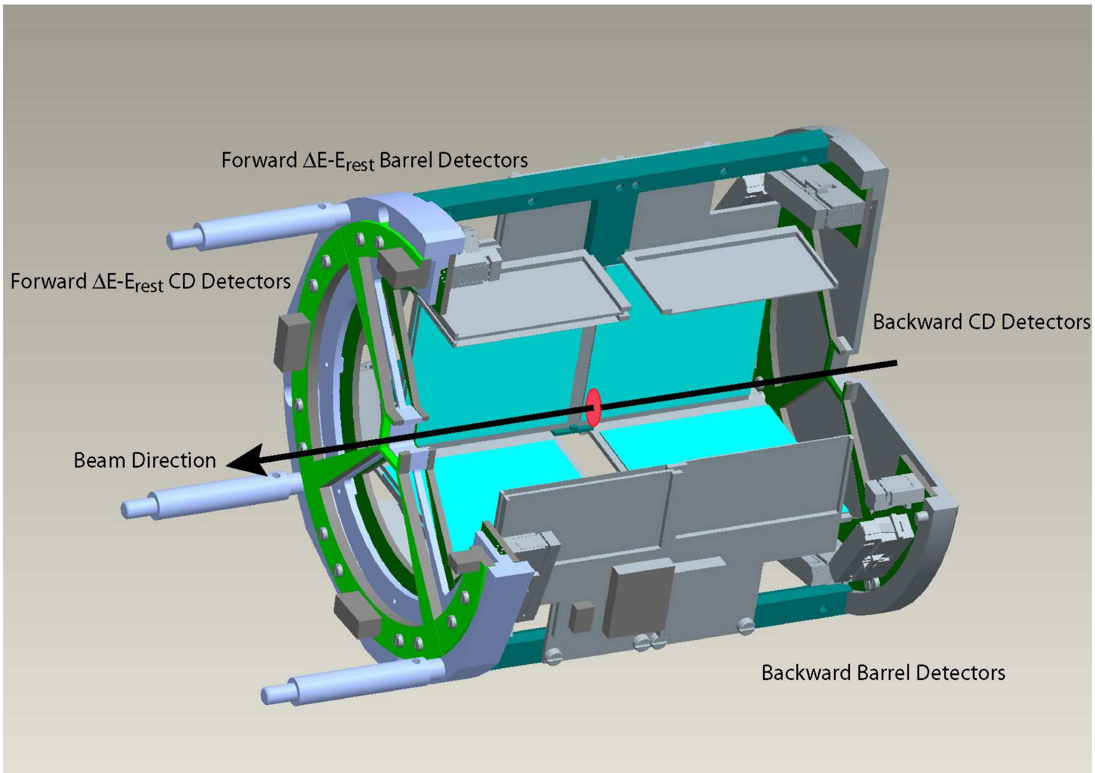

Figure 4: *New array of Si detectors.*

The drawing in Fig. 4 shows the arrangement of the Si detector array as it has been implemented into GEANT4 [46] for simulation. The array is mounted inside a new scattering chamber. Additionally, a segmented diamond detector on the target ladder which can be moved at target position and an active collimator with four PIN diodes in front of the chamber for beam focusing have been included. This set-up as major upgrade of the instrumentation available at REX-ISOLDE has been used for the first time in the run of experiment IS454 in October/November 2007. It has been funded by TUM, KU Leuven, University of Edinburgh, and CSNSM Orsay.
During the run of experiment IS454 electrons from β-activity deposited in the scattering chamber have been identified as a potential problem. In forward direction, these electrons can be clearly separated using the $E - \Delta E$-information because their energy loss in both detectors is small. Whereas in backward direction this separation has been done only by the trigger threshold. Since the Q-value of the proposed experiment is slightly negative, the protons emitted in backward direction have very small energies and the separation from the electrons will be difficult. Therefore the particle detector array will be upgraded by further detectors behind the Si detectors in backward direction which will deliver a further ΔE signal from electrons allowing to identify them. Several technical solutions like a scintillator with avalanche diode read-out or a Si detector are currently under consideration.
The ^{30}Mg isotope is produced with a standard UC_x/graphite target, ionised by the RILIS, and post-accelerated by the REX-ISOLDE facility. For breeding in the EBIS at time well

below the $T_{1/2}$ = 335 ms of ^{30}Mg is sufficient. The daughter of its decay, ^{30}Al, has a $T_{1/2}$ = 3.6 s and decays to the stable ^{30}Si. From the experience of the runs of experiment IS410/IS454, we expect mainly ^{30}Al isobaric contaminations of the beam. ^{30}Na has not been observed in the IS454 run.
Since Mg beams are not pure beams, the composition of the beam has to be determined in order to identify lines originating from transfer or fusion reactions with beam contaminants. The composition of the beam will be determined using the well established methods listed in the following:

- An additional Ge detector behind the beam dump measures the decay of the implanted beam particles.
- Analysing the different release curves of the isotopes from the ISOLDE target after the impact of the proton pulse.
- A Bragg chamber constructed by the TUM group allows to identify mass and charge of the beam particles [47]. In particular, this detector allows also to identify contaminants in the beam which have long lifetimes or are even stable and, therefore, offers information complementary to the beam dump detector.
- A shutter in front of the laser of the RILIS can be closed every second supercycle of the PS Booster ("Laser ON/OFF"). Without the laser the isotope of interest is reduced in the beam and the counting rate decreases correspondingly. Additionally, the number of decays in the beam dump is reduced.

3.2 Analysis

The excitation energy of 0_2^+ state will be determined from the energies of the protons emitted from the reaction and, in case, the coincident γ-rays if observed. As already discussed, the identification to be a 0^+ state relies mainly on the angular distribution of the protons.
Fig. 5 shows the energies of protons in the laboratory system emitted from the ^{3}H(^{30}Mg, ^{32}Mg)^{1}H reaction at 2 MeV/u to the four states of ^{32}Mg shown in Fig. 1 (middle). This simulation has been done with our GEANT4 [46] implementation of the set-up [21]. The angular coverage of the detector is indicated. Clearly, the populated states can be separated. For simplicity, only the 0^+ and 2^+ states shown in Fig. 3 have been included in this simulation. It has to be noted that three further states in ^{32}Mg at 2117 keV, 2315 keV, and 2551 keV, hence all at excitation energies above 2000 keV, are experimentally known [23].
If or if not the population of the 0_2^+ state can be seen already in the proton spectra depends, of course, on its excitation energy. For a range from around 1100 keV to around 1900 keV, the theoretical prediction is around 1400 keV, this is possible. An advantageous feature is that the 2_1^+ state in ^{32}Mg is expected to be populated much weaker than the 0_2^+ state because of the different particle-hole structure, as discussed before. Therefore, the protons corresponding to the population of states below 2000 keV predominantly will belong to the population of the 0_2^+ state.

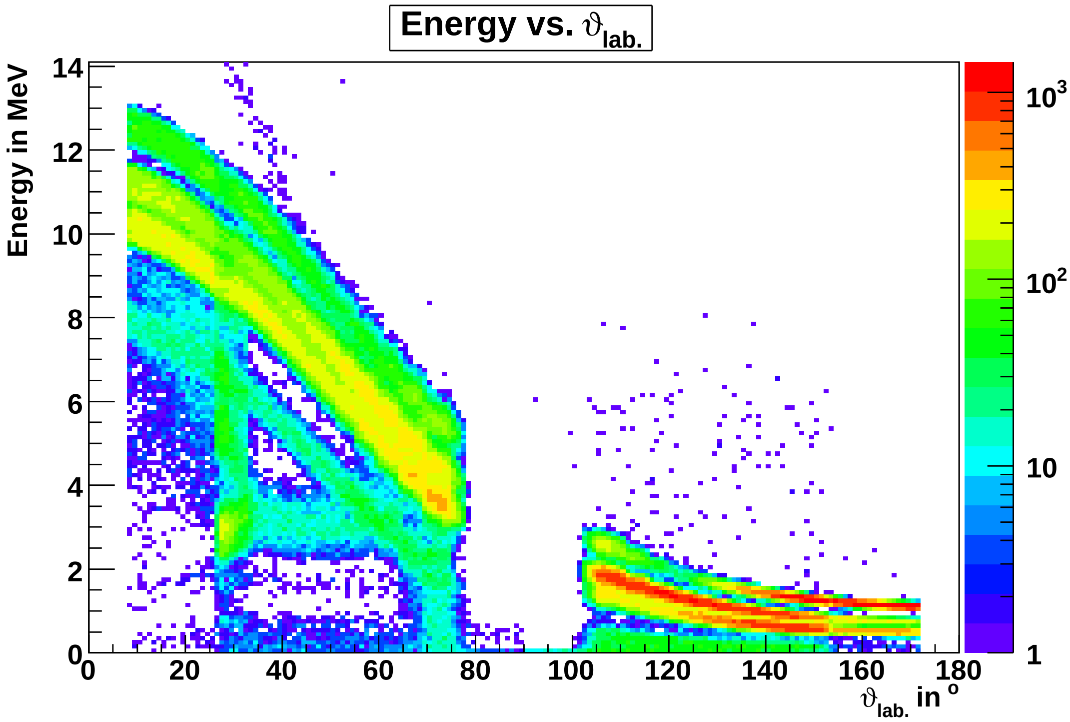

Figure 5: *Simulation of the energies of the protons emitted in the reaction* $^3H(^{30}Mg, {}^{32}Mg)^1H$ *and detected by our new detector set-up (details see text). The angular distributions shown in Fig. 3 have been taken into account.*

Otherwise, one has to rely on the γ-decay to the 2_1^+ state. The lifetime of the 0_2^+ state can be estimated to be around 10 ns assuming that the state is at the expected energy and the transition strength to the 2_1^+ state is around 0.1 W.u.. For smaller transition energies the lifetime will increase and the excited nuclei decay mainly outside MINIBALL, hence the decay will not be observable. It has to be mentioned that the decay of the first excited state in ^{31}Mg with a lifetime of 16 ns has been observed in a (d,p) reaction performed previously with MINIBALL [39].

If the 0_2^+ state does not decay by a γ-transition to the 2_1^+ state, i.e. it only decays via a E0 transition to the ground state, still information can be obtained. After subtracting the protons coincident with the decay of the 2_1^+ state scaled with the efficiency of MINIBALL from the total proton spectrum the remaining protons can be attributed to the population of the 0_2^+ state. Since the efficiency of MINIBALL is not 100%, it is not a good veto detector and this procedure, of course, works only approximately.

If the 0_2^+ state decays by a low-energy γ-transition to the 2_1^+ state which can not be observed, the analysis also possible. A low transition energy would mean a long lifetime and, hence, this decay and the subsequent decay of the 2_1^+ state would happen mainly outside MINIBALL. Practically, the spectra can be analysed as for the case of no γ-transition to the 2_1^+ state.

Transforming the angular distributions shown in Fig. 3 into the laboratory system one obtains the distributions shown in Fig. 6. These experimental angular distributions will

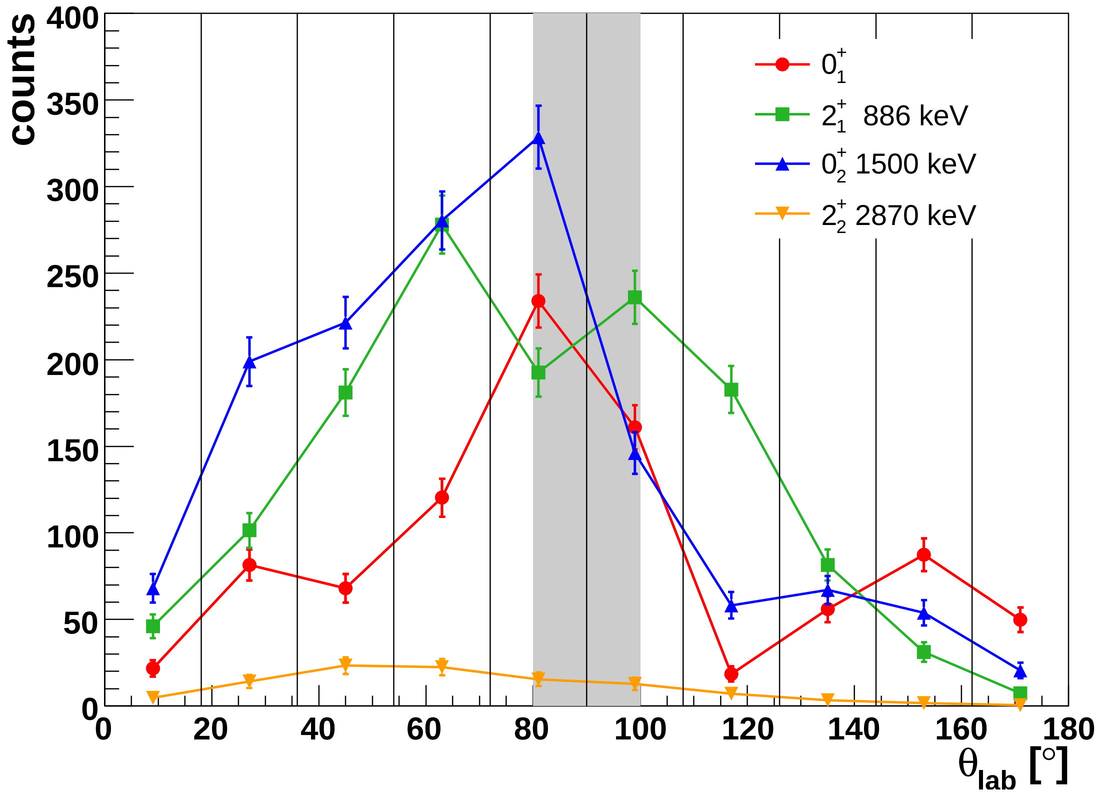

Figure 6: *Statistics per 18° angle bin in the laboratory system (9 days beam time,* 10^5 *part/s). The grey-shaded area is not covered by the current detector set-up.*

be analysed by comparison with calculated angular distributions. It can be seen that the most sensitive area for the angular distribution are the backward angles where the transfer to 0^+ and 2^+ states can be clearly distinguished. However, from a fit to this region a scaling factor can be extracted which then can be applied to the data in forward direction and, therefore, also these data with the higher statistics are of importance for the analysis. Note that the ratios of the count rates before and after the "gap" around 90° differ considerably for the different orbital momentum transfers.

4 Radioactive ^{3}H target

A major challenge of the proposed experiment is the rather unique combination of a radioactive beam with a radioactive target, in our case a tritium-loaded Ti foil.

4.1 Target

A tritium-loaded Ti foil has already used by us in the test experiment at HMI described above. It consisted of a 450 μg/cm^2 thick metallic Ti foil loaded with a atomic ratio ^{3}H/Ti of 1.76 corresponding to a target thickness of 48 μg/cm^2 ^{3}H. The activity was at the time of production 26 GBq.

For the proposed experiment we have ordered a new target of the same thickness but with a smaller area. The activity will be 10 GBq, the value which we are allowed to handle at ISOLDE following CERN Specification N° 4229RP20070405-GD-001 [49].

4.2 Handling and radiation safety concerns

Deuterium- and tritium-loaded metallic Ti foils used under vacuum conditions as targets for heavy ion induced transfer reactions have been proven to be very stable.
The existing tritium target mentioned above has been used with an ^{40}Ar beam at 2.25 MeV/u and $6 \cdot 10^8$ part/s at the HMI (Berlin). The rate of scattered tritium nuclei was monitored during the whole run. No reduction indicating a loss of material in the target has been observed. Additionally, after the experiment the filter in front of the vacuum pumps exhibited no radioactivity.
Similar targets, but loaded with deuterium instead of tritium, worked well and reliably in several experiments (see e.g. [30, 48]) even at higher beam intensities (see below) than available at REX-ISOLDE. It was found by a RBS experiment performed at the MLL (Garching) that only at intensities around 5 pnA hence more than three orders of magnitude higher than intensities, available at REX, a loss of deuterium was observed.
Based on our experience at HMI we propose the following mounting procedure for the target. The target will be extracted from the originally welded container and mounted on a target ladder in a glove box, e.g in the "hot" target laboratory at LMU (Garching). The whole target ladder will mounted in a vacuum-tight container and transported to CERN. The mounting of the ladder into the scattering chamber can be done using a protection shield, e.g. made of transparent plastic which is sufficient to absorb the low-energy radiation emitted from the decay of ^{3}H, avoiding any radiation for the user. After the experiment, the ladder will be extracted the same way from the scattering chamber and inserted back into the transport container.
In the very unlikely case that the target foil breaks within the scattering chamber during the experiment, no tritium gas will be evaporated since it remains within the Ti foil. In the worst case, fragments of the foil may fall down, but will remain within the chamber. In such a case of a broken target, the entire scattering chamber will be closed vacuum-tight, transported back and decontaminated in the glove box at Garching by removing the target and potentially fallen down fragments.

5 Rate estimate and beam time request

We would like to study excited states in the neutron-rich isotope ^{32}Mg populated by a two-neutron transfer reaction. In particular, the so far experimentally unobserved spherical 0_2^+ state, which coexists with the deformed ground state, will be populated preferentially. The proposed experiment will be the basis of the PhD project of K. Wimmer.
As it can be seen from Fig. 3, the average cross section for the population of the 0_2^+ state is estimated to be in the order of 0.1 mb/sr. Assuming a beam intensity of 10^5 part/s as it has been obtained during the run of experiment IS409/IS410 in September 2007, this translates into a proton rate of around 4 counts/h taking into account the solid angle covered by the particle detector. For an angular distribution these counts have to be

distributed over 10 angle bins, hence the count rate is in the order of 0.4/h. In 9 days of beam time, more than 700 counts will be collected. Distributing these statistics over 10 angle bins the expected statistics can be seen in Fig. 6. The statistical error will be below 15% even for the bins with low statistics.
In case that the γ-rays are needed the number will be a factor of 10 lower, since the average efficiency of MINIBALL is around $\epsilon_{\mathrm{MINIBALL}} = 10\%$ for γ-energies of interest between 100 keV and 1400 keV. In this case, it will depend strongly on the background in the spectra if it is still possible to extract a meaningful information from the obtained angular distribution.
Additionally, we ask for 3 shifts to prepare the beam.

We request in total 30 shifts (10 days) of beam time.

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