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Proposal to the INTC Committee

Study of single particle properties of nuclei in the region of the "island of inversion" by means of neutron-transfer reactions

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Abstract: We are aiming at the investigation of single particle properties of neutron-rich nuclei in the region of the "island of inversion" where intruder states from the fp-shell favour deformed ground states instead of the normal spherical sd-shell states. As first experiment, we propose to study single particle states in the neutron-rich isotope ^{31}Mg. The nucleus will be populated by a one-neutron transfer reaction with a ^{30}Mg beam at 3 MeV/u obtained from REX-ISOLDE impinging on a CD_2-target. The γ-rays will be detected by the MINIBALL array and the particles by a newly built set-up of segmented Si detectors with a angular coverage of nearly 4π. Relative spectroscopic factors extracted from the cross sections will enable us to pin down the configurations of the populated states. These will be compared to recent shell model calculations involving new residual interactions. This will shed new light on the evolution of single particle structure leading to the breaking of the magic number $N = 20$ in this region.

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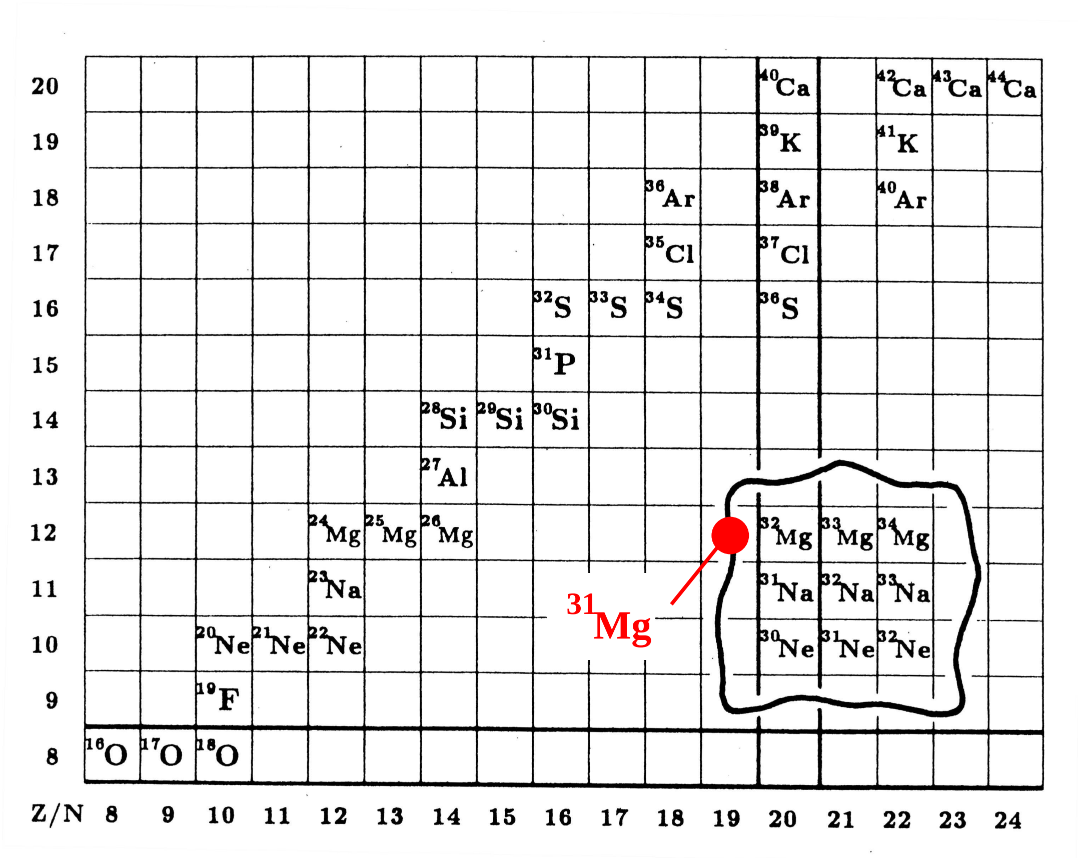

Figure 1: *"Island of inversion", the tentative borders are taken from Ref. [4] (apart from the "island" only stable nuclei are shown). The red dot marks ^{31}Mg.*

1 Physics case

For the last 50 years, the shell model has described successfully the existence of magic numbers for both neutrons and protons in stable nuclei. The advent of radioactive beams enables investigating whether these magic numbers will persist or be altered in nuclei with extreme isospin, notably in neutron-rich nuclei, and will provide a deeper insight into the residual interactions, which are relevant for their local occurrence.
The magic shell closure at $N = 20$ for stable nuclei, e.g. in ^{40}Ca, disappears going to neutron-rich nuclei. E.g. ^{28}O is not even bound. Moreover, the last bound Oxygen isotope ^{24}O exhibits features of a doubly-magic nucleus, hence $N = 16$ has become a magic number. Theoretically, this evolution can be explained by the monopole part of the tensor force, an attraction between protons and neutrons occupying spin-orbit-partner orbitals [1, 2]. As protons start to occupy the $d_{5/2}$-orbital from F to Ca, the $d_{3/2}$-orbital for neutrons is lowered. The $N = 16$ closes and the $N = 20$ gap opens.
In between, no closed shell exists and neutron excitations to the fp-shell are energetically favoured for nuclei within the so-called "island of inversion" [3, 4], a region of nuclei with deformed ground states in the sea of spherical sd-nuclei. The lowering of intruder

fp-orbitals with respect to the sd-shell causes an inversion of spherical and deformed single particle configurations, allowing the latter to become the ground states. First experimental evidence came from anomalies in the binding energies for nuclei around $A \approx 32$ [3, 4]. However, the shores of this island are neither experimentally nor theoretically well established.

Direct experimental evidence for the deformed ground state of ^{32}Mg came from both low $E(2^+)$ *and* the large $B(E2; 0_{\rm gs} \to 2^+)$ determined in intermediate energy Coulomb excitation [5]. However, later results for this $B(E2)$ value, all obtained in intermediate energy Coulomb excitation, differed by nearly a factor 2 and made a conclusion on the structure of this nucleus impossible.

At REX-ISOLDE, the isotopes ^{30,32}Mg have been studied in "safe" Coulomb excitation. The obtained $B(E2)$ values show that ^{30}Mg is outside and ^{32}Mg is inside of the "island of inversion" [6, 7]. These results are in good agreement with modern large scale shell model calculations using either the conventional shell model [8, 9, 10] or newer approaches, like the Monte Carlo Shell Model (MCSM), involving the new residual interaction mentioned above [11, 12, 13, 14]. They also agree well with the most recent results obtained in Coulomb excitation at intermediate energies [15]. Conclusively, the ground state of ^{32}Mg indeed can be described by a $2p$-$2h$-configuration promoting two sd-neutrons to intruder fp-orbitals, hence by breaking the $N = 20$ shell.

With Coulomb excitation mainly the collective properties of nuclei are studied. Nevertheless the obtained results are very well described by modern large scale shell model calculations, there is an increasing interest to investigate also the single particle structure of nuclei around the "island of inversion" which allows to test the predictions from shell model calculations more directly.

In particular, ^{31}Mg may be right on the shore of the "island of inversion" and it is therefore of particular interest to study the transition from normal to intruder configurations which happens between ^{30}Mg and ^{32}Mg. Experimentally, ^{31}Mg, like other odd-even and odd-odd nuclei in this region, has been investigated mainly in g-factor measurements of the ground state with laser and β-NMR spectroscopy, β-decay, and inelastic proton scattering. In Fig. 2 (left), the currently available spectroscopic information on ^{31}Mg is shown (taken from [16]). The previously known transition at 1214.9 keV has been assigned to a new level at 1435.9 keV based on γ-γ-coincidences measured with MINIBALL at REX-ISOLDE following a one-neutron transfer reaction (experiment IS410, see below). It is worth to mention that recently the collective properties of the odd isotopes ^{29,31}Mg have been studied also in "safe" Coulomb excitation [17].

The theoretical description of the odd ^{31}Mg is much less satisfactory than of the neighbouring even Mg isotopes. In Fig. 2 (right), the experimental levels for which at least a tentative spin assignment is known are compared with various shell model calculations. In particular, the spin $I^{\pi}_{\rm gs} = 1/2^+$ of the ground state, established from its magnetic moment measured at ISOLDE [18, 19], has been a challenge. Shown are results obtained with the MCSM ("mixed np-nh") and the conventional shell model with ("2p-2h and 1p-1h") and without ("0p-0h") breaking $N = 20$ and including excitations to the fp-shell. Obviously, none of the calculations was able to reproduce the experimental results.

Only very recently, an adjustment of the monopole part of the interaction for the fp-shell brought an improved reproduction of the observed level scheme, as it is demonstrated in

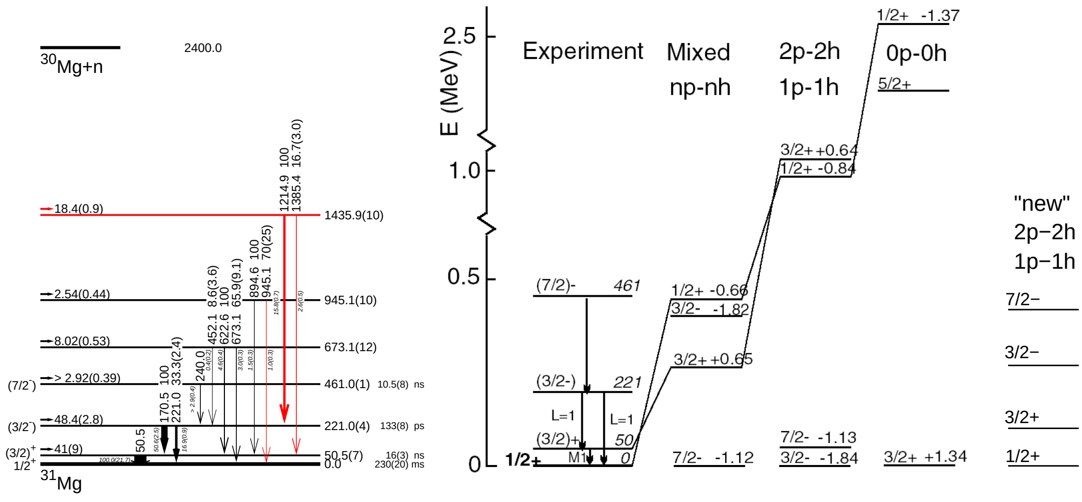

Figure 2: *Present situation for ^{31}Mg (taken from Refs. [16, 18, 20]): experimental information and different predictions from large scale shell model calculations (for details see text).*

the rightmost part of Fig. 2 ("new 2p-2h and 1p-1h") [20]. The result is that the ground state and the first excited state are largely dominated by 2p-2h intruder configurations (93% and 95% of the wave function, respectively) with a fp-shell occupancy close to 2. Hence, there is a sudden transition from normal to intruder configurations adding one neutron to ^{30}Mg and ^{31}Mg would thus be clearly inside of the "island of inversion".
Interestingly, this behaviour is different for the neighbouring Na isotopes where this transition is much smoother. ^{29}Na e.g. has a 50% content of the intruder configuration in the wave function of the ground state [21]. For Al isotopes, no significant intruder content is found for the ground states of ^{31,32}Al [22, 23] whereas for ^{33}Al neither experimental [24, 25] nor theoretical results [8, 9, 12, 26] on the intruder content of the ground state wave function are consistent.
Since our current understanding of this interesting region of the nuclear chart is still based on scarce experimental information, it is obvious that more measurements are needed. In particular, the sensitivity of the level structure of ^{31}Mg on the details of the interactions used in shell model calculations, as it is demonstrated in Fig. 2, motivates the study of the single particle structure of this nucleus. The aim of the experiment proposed here is to obtain such information, in particular for excited states, by a one-nucleon transfer reaction. This is complementary to both results from Coulomb excitation and the measurement of the magnetic moment of the ground state. New information on the structure of ^{31}Mg will further challenge modern shell model calculations and, eventually, improve the understanding of the underlying physics which causes the existence of the "island of inversion". It is planned to extend this study in the future with further transfer experiments in this region. The ^{2}H(^{32}Mg, ^{33}Mg)^{1}H reaction is a challenge due to the small beams intensities currently available. More understanding of the mechanism of the level migration, in particular of the intruder $f_{7/2}$ level, can be gained by the study of nuclei still

outside of the island, e.g with the ^{2}H(^{28}Mg, ^{29}Mg)^{1}H reaction. The two-neutron transfer reaction starting from normal ground state of ^{30}Mg is expected to favour the population of its analogue in ^{32}Mg, the excited 0_2^+-state, which is practically not reachable in Coulomb excitation.

2 Experimental method

Nucleon transfer reactions are a well established tool for the investigation of the single particle structure of nuclei. Relative spectroscopic factors extracted from transfer cross sections are a measure for the occupation numbers of single particle configurations (particles or holes). These can be directly compared to results from shell model calculations. Additionally, the neutron-pair transfer will allow the study of pairing correlations. The transferred orbital momentum leading to the spin assignment of a state is determined from the angular distribution of the particles.

We propose to study the single particle structure of the neutron-rich isotopes in the region of the "island of inversion" by neutron transfer reactions in inverse kinematics. The projectile-like nuclei are forward focussed in the laboratory system and cannot be measured with current equipment (a 0°-spectrometer for REX is under development). We will measure the energies and angular distributions of the protons emitted from the (d, p), or in the future (t, p) reactions in coincidence with high-resolution γ-rays. The study of single particle properties of Na and Mg isotopes in this region was already part of the experiments IS379 [27] and IS410 [28] at REX-ISOLDE.

The states populated in the reaction are identified by their characteristic γ-decay, 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. As an example, Fig. 3 (left) shows part of the γ-spectrum from ^{31}Mg obtained in coincidence with protons emitted in the reaction ^{2}H(^{30}Mg, ^{31}Mg)^{1}H measured at 2.2 MeV/u at REX-ISOLDE. In the right part of the figure, the obtained angular distributions of the protons in coincidence with the 171 keV and 222 keV transitions depopulating the level at 222 keV are shown.

The measured cross sections and angular distributions will be analysed in the frame of the DWBA applying the codes CHUCK [29] or FRESCO [30]. The optical potentials needed for this analysis can be scaled regarding mass of the projectile and beam energy from values fitted to experiments with stable beams applying a well established formula [31]. On the other hand, also the analysis of elastically scattered deuterons allows to fix the optical potential.

As an example, in Fig. 3 (right) the experimental angular distributions are compared with DWBA calculations assuming different orbital momentum assignments to the level at 222 keV in ^{31}Mg. Additionally, different optical potentials are used. It is obvious, that the limited angular coverage of the existing set-up at REX-ISOLDE didn't allow to interpret the measured angular distributions unambiguously [32, 33, 34]. However, the analysis still continues, e.g. the feeding of this state by γ-decays of higher-lying states has not been taken into account yet.

We propose to repeat this experiment using a significantly improved set-up which includes a newly built array of Si detectors for particle detection with nearly 4π angular coverage

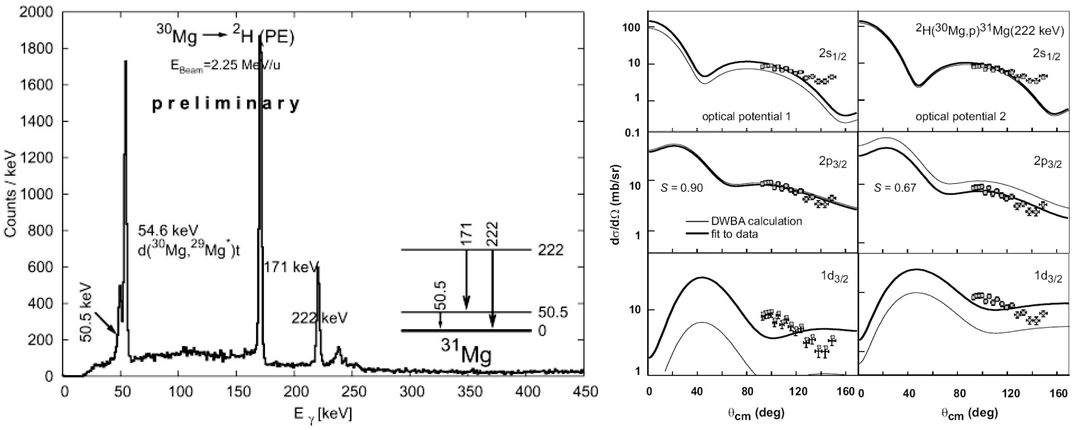

Figure 3: *Partial γ-spectrum from ^{31}Mg (left) and the angular distributions of the protons in coincidence with the 171 keV transition compared with different DWBA calculations, for details see text (right) [32, 33, 34].*

whose technical implementation will be presented in the next section in detail. First we discuss in the following the requirements coming from the proposed experiment.

Fig. 4 (left) shows the simulated angular distributions of protons in the laboratory system emitted from the ^{2}H(^{30}Mg, ^{31}Mg)^{1}H reaction at 3 MeV/u. Input for this simulation were theoretical angular distributions calculated by H. Lenske [35]. Shown is the transfer to the four states of ^{31}Mg shown in Fig. 2 (right). It was assumed that the wave functions contain pure configurations.

It can be seen that the angular distributions with different orbital momentum transfer ℓ can be clearly distinguished. The angular distributions for values $\ell = 0$ and $\ell = 1$ do not differ significantly in both the forward and backward direction, but in the region around 100°-130° the difference is obvious. In contrast to these small orbital momentum transfers, the larger values $\ell = 2$ ($d_{3/2}$ at 50.5 keV) and $\ell = 3$ ($f_{7/2}$ at 461 keV) exhibit a steady decrease from 75° crossing the "blind" area of the detector. However, for $\ell = 2$ the count rate at 75° and at 105° is nearly equal whereas it drops by more than a factor of 2 for $\ell = 3$. The general trend is that the maximum is shifted the more forward (in the lab system) the larger the values ℓ is. It has to be mentioned that because of the lower beam energy the angular distributions in general are less pronounced than angular distributions measured at 5-10 MeV/u.

Results of such an analysis are the excitation energy, the transferred orbital momentum, and the relative spectroscopic factor. Additional information on the spin and parity assignment to a level comes 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 beam energy of 3 MeV/u is still 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 Deuterium. A fusion reaction as statistical process usually populates, after particle emission, high-lying states where the level den-

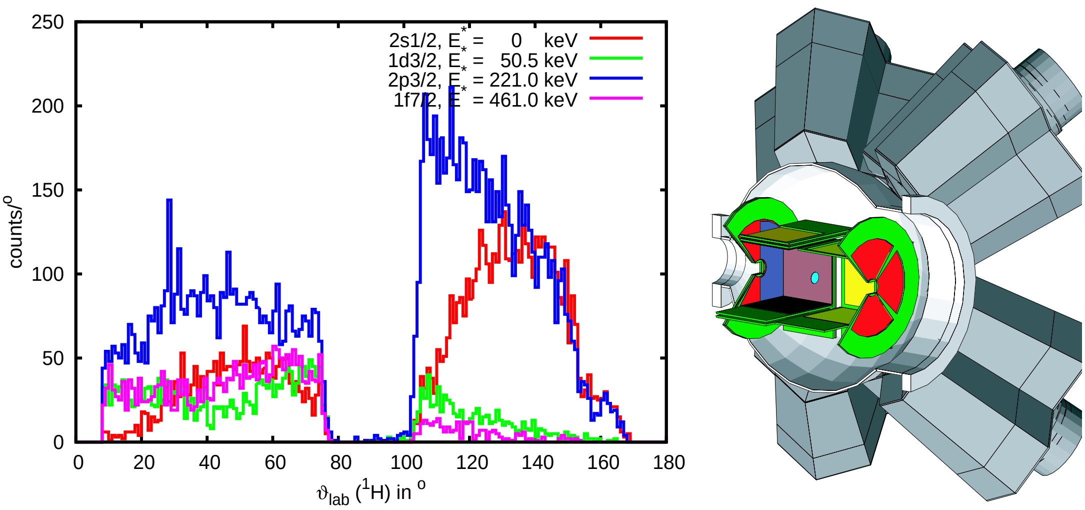

Figure 4: *Simulation of the angular distribution of the protons emitted in the reaction* $^{2}H(^{30}Mg,\ ^{31}Mg)^{1}H$ *and detected by our new detector set-up (details see text Sec.3).*

sity is large (Q-value for fusion of ^{30}Mg with Deuterium is 15.3 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 even 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 [34].
Finally, we would like to mention that we plan for the future also to investigate two-neutron transfer reactions applying a Tritium-loaded Ti target. Such a target has been tested last year successfully in an test experiment with stable Ar beam [36].

3 Experimental set-up

The set-up consists of the MINIBALL array to detect γ-rays in coincidence with particles detected by a newly built array of segmented Si detectors for particles.
This 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 (1000 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 (deuterons and C) an Al foil is mounted in front of the forward detectors (50 μm in front of the CD and 15 μm in front of the barrel). This foil stops all scattered Mg nuclei from the beam and above $\approx 65°$ also all deuterons and C from the target. Since in the range 65°-90° deuterons and C cannot be separated, neither by $\Delta E - E$ nor by their different absolute energies, this region yields no useful information on elastic scattering anyhow. Below 65° deuterons and C can be separated by their different energies or $\Delta E - E$ (deuterons at small angles have enough energy to reach the E-detector).
Fig. 4 (right) shows the arrangement of the Si detector array as it has been implemented into GEANT4 [37] for simulation. The array is mounted inside a new scattering chamber which is shown also in the figure.
The electronics of the new Si detector will be different to the one previously used. The preamplifier signals are fed via multiplexers into DGF modules. In total for the 476 channels 10 DGF modules are needed. The use of DGF modules assures the full compatibility with the existing DAQ of MINIBALL.
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 [38]. 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.

The new Si detector array including the electronics will be funded by TU München (Germany), KU Leuven (Belgium), CSNSM Orsay (France), CERN (Switzerland), and the

UK groups involved in MINIBALL and will be used for transfer reaction studies in the neutron-rich Ca ($Z = 20$) and Ni ($Z = 28$) region as well.

4 Proposed experiment

The ^{31}Mg isotopes will be populated by a one-neutron transfer reaction with a CD_2-target (deuterated PE foil), i.e. ^{2}H(^{30}Mg, ^{31}Mg)^{1}H. Alternatively, also Deuterium-loaded Ti foils could be used. Such targets worked well in several experiments (see e.g. [36, 39]), but the fusion cross section of the beam with the Ti is larger compared to the C of the CD_2-target. The Q-value for this reaction is positive (0.18 MeV). Other reaction channels like (d,t) ($Q = -0.04$ MeV) or (p,d) ($Q = -4.07$ MeV) have negative Q-values, therefore and because of the mass transfer to the target nuclei none of them is observed in backward direction (in the laboratory system).
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. The breeding time in the EBIS will be between 12 ms and 18 ms to reach charge state 9^+ which fits well to $T_{1/2} = 335$ ms of ^{30}Mg. 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, we expect mainly ^{30}Al and very few ^{30}Na as isobaric contaminations of the beam.
Concerning the optimal beam energy, it is preferable to go to beam energies around 3 MeV/u where the cross section for transfer is maximal [40] and the angular distributions are more pronounced compared to 2.2 MeV/u. A limiting factor for the beam energy is the fusion of the beam with the C or, in case, Ti of the target, and, but to a much lesser extent and anyway unavoidable, with the Deuterium. Protons emitted from such reactions can swamp the spectra if the cross section is much larger than for the transfer. This would make the intended analysis unfeasible. At 2.2 MeV/u no significant background in the light particle spectra from fusion is seen. In experiment IS379, besides the protons also the emission of α-particles emitted after a fusion reaction of the Na beam and the Deuterium in coincidence with a characteristic γ-ray has been observed. Going to 3 MeV/u, we expect from PACE [41] calculations that the cross section for fusion of the beam and the C of the target increases only slightly ($\approx 35\%$) and, therefore, the obtained spectra are expected to be of the same quality.

5 Beam time request

We would like to study the single particle properties of the neutron-rich isotope ^{31}Mg populated by a one-neutron transfer reaction. In order to extract the relevant spectroscopic information good statistics in proton-γ-coincidences are necessary.
The efficiencies are $\epsilon_{\text{part}} = 62\%$ for the particle detector and an average $\epsilon_{\text{MINIBALL}} = 8\%$ (γ-energies between 50 keV and 1400 keV are of interest, see Fig. 2) for γ-detection in the photopeak with MINIBALL. Since some of our γ-rays are at low energy it is essential that bremsstrahlung emitted from the 9-gap resonator of REX is shielded effectively.
Conservatively, we estimate a beam intensity on target of $5 \cdot 10^4$ s^{-1} for ^{30}Mg based on the experience from several runs of experiment IS410. The target will be a CD_2 foil

(deuterated PE foil) of 5 μm thickness.
The highest single rate from elastic scattering is expected for the forward barrel with an average total rate around 45 Hz. Currently the beam intensity is concentrated mainly in the first some 20 μs of each EBIS pulse and the instantaneous rate is much higher, up to 100 kHz depending on the duty cycle of the EBIS. Since this rate is shared between the channels of the four barrel detectors, even this rate can be handled without pile-up problems. However, if available, we would like to use the slow extraction from the EBIS to reduce the instantaneous rate. Background from light particles, in particular protons and α's, emitted after the fusion reaction of the beam and the C in the target is expected to be low.
Aim of this experiment is to measure angular distributions of the protons in coincidence with γ-rays also for the weakly populated $(7/2^-)$- and the $(3/2^+)$-states (see Fig. 2). Since the lifetimes of these two states are long, only a part of the γ-rays from their decay will be detected. A particular efficiency correction has to be applied as it has been done in the analysis of the data obtained by experiment IS410 [16]. Supposing for these states a cross section of around 100 mb as it is predicted by theory, the rate is about 36 h^{-1} for γ-p-coincidences. Since we intend to measure angular distributions, the rate will be in the order of some 0.1 counts per hour and 1° (depending on the angle). In order to obtain statistics comparable to the statistics in the simulated spectrum shown in Fig. 4, 7 days of ^{30}Mg beam at 3 MeV/u are needed. Additionally, we ask for 3 shifts to prepare the beam.

We request in total 24 shifts (8 days) of beam time.

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