EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Nuclear Shell Evolution in the Island of Inversion Studied via the $^{28}Mg(t,^{30}Mg)p$ reaction

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Abstract

The goal of this proposal is to resolve the current puzzle concerning the microscopic understanding of nuclear structure physics in the "Island of Inversion" around neutron-rich N=20 nuclei. We propose to measure cross sections $\sigma(0^+_{1,2})$ for the population of 0^+_1 and 0^+_2 states in ^{30}Mg after two-neutron transfer $^{28}Mg(t,^{30}Mg)p$. Depending on the actual amount of neutron (sd) and neutron (fp) configurations at the "shore" of the Island of Inversion, the ratio $\sigma(0^+_2)/\ \sigma(0^+_1)$ can become larger than one, and is predicted to be the most extreme value throughout the chain of neutron-rich magnesium isotopes. The data are important to resolve the current discrepancies concerning experimental data on two-neutron transfer into ^{32}Mg, previously measured at ISOLDE, indicating that intruder configurations are not dominant in the ground state of ^{32}Mg, in conflict to the existence of an Island of Inversion.

Requested shifts: 20 shifts
Beamline: MINIBALL + T-REX

In the so called "Island of Inversion" around ^{32}Mg, the ground states of nuclei exhibit a larger binding energy than expected from simple models. Extra binding energy can stem from an onset of deformation. Indeed, the systematics of excitation energies and B(E2) values in the Mg isotopes suggest a softening of the N=20 shell closure and it was suggested [1,2] that the nuclear tensor force has a major influence. In an intuitive picture, the T=0 proton-neutron tensor interaction is attractive for protons in "spin up" ($j_>$) orbitals and neutrons in "spin down" ($j_<$) orbitals, or vice versa. Otherwise, a repulsive interaction results. Going towards Mg isotopes, protons are removed from the $1d_{5/2}$ orbital, which lowers the N=20 gap between neutron $1d_{3/2}$ ($j_<$) and neutron $1f_{7/2}$ ($j_>$). The enlarged model space for neutrons leads to strong quadrupole correlations [3], which are pushed by the presence of quasi-SU(3) configurations both for proton and neutron orbitals. The gain in binding energy due to quadrupole correlations is large enough to overcome the spherical gap at N=20 and leads to dominant (2p-2h) configurations in the ground state of nuclei in the IOI.

On the other hand, the B(E2) value of ^{32}Mg can be explained without assuming dominant $(fp)^2$ configurations in ^{32}Mg [4]. Also, calculations do exist, which successfully describe the IOI without making (explicit) use of the tensor force. In the deformed Nilsson model, shell evolution in the IOI appears due to the characteristic features of weakly-bound orbits with small angular momentum [5]. In case of N=20, the neutron $p_{3/2}$ orbital is pushed down relative to the close lying neutron $f_{7/2}$ orbital. In this case, the onset of deformation around ^{32}Mg can be understood as a Jahn-Teller effect. Also, pairing interactions (dominant in the T=1 channel) were found to be essential to explain the onset of deformation at N=20 towards Mg isotopes [6]. Detailed experimental information for nuclei near or in the Island of Inversion is needed in order to pin down the underlying nature of nuclear shell evolution towards neutron-rich nuclei. This will drastically improve the predictive power of nuclear structure models, needed as an input for r-process modelling.

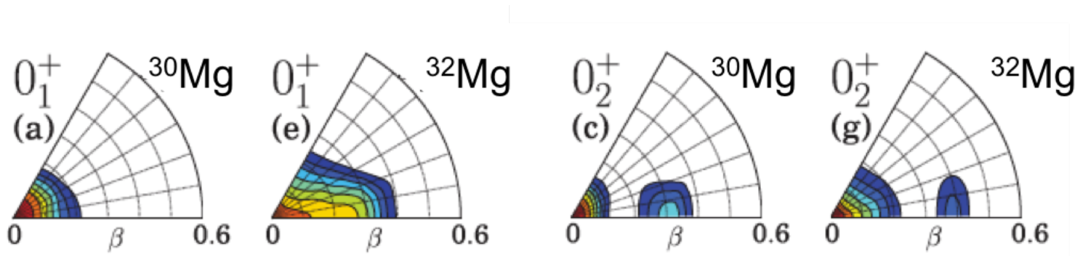

Fig 1: Vibrational wave functions squared, resulting from solving the five-dimensional quadrupole-collective Schrödinger equation. The simple picture of the "Island of Inversion" is not supported in this calculation. Adapted from [8]

An experimental break-through was the discovery of an exceptional low-lying 0^+_2 state after two-neutron transfer in inverse kinematics in ^{32}Mg [7] using MINIBALL and the T-REX silicon array. The fact that an additional 0^+_2 state is found at such low energy clearly indicates an erosion of N=20. However, the structure and amount of intruder configurations in the states 0^+_1 and 0^+_2 is of actual debate and the presence of an "Island of Inversion", i.e. dominant intruder configurations in the ground state wave function, is questionable. Large-scale shell model calculations predict dominant (2p2h) and (4p4h) neutron (fp) configurations in the 0^+_1 state of ^{32}Mg, whereas the 0^+_2 state has a distinct (0p0h) character (see e.g. [3]). This is different from the conclusions in [8]: solving the five-dimensional quadrupole-collective Schrödinger equation for ^{30}Mg, the shape coexistence picture that the deformed excited 0^+ state coexists with the spherical ground state approximately holds, but large-amplitude quadrupole-shaped fluctuations dominate in both the ground and the excited 0^+ states in ^{32}Mg (see fig. 1)

Things are complicated by the conclusion of [9], that the large measured ratio of $\sigma(0^+_2)/\sigma(0^+_1)$ = 0.62(6) in ^{32}Mg after two-neutron transfer [7] suggests only a small amount of intruder configurations in its ground state [9], i.e. no inversion takes place at ^{32}Mg. The conclusion is based on a mixing scenario of (sd) and (fp) neutron (0p0h) and (2p2h) configurations and depends in a sensitive way of the cross section ratio $\sigma(fp)^2/\sigma(sd)^2$ for the two-neutron transfer in pure (fp) or (sd) states. This ratio mainly depends on the unknown amount of neutron $(p_{3/2})^2$ contributions in the $(fp)^2$ wave function. The ratio is estimated from an analysis of the measured absolute cross section $\sigma(0^+_1)+ \sigma(0^+_2)$. As a result, the ground state of ^{32}Mg is found to be dominated by neutron (sd) "spherical" configurations by 81%, in strong contrast to the common belief. The results of [9] are confirmed by the work of [10] in more detailed calculations. Instead, the excited 0^+_2 state is assigned dominating deformation-driving configurations. These analyses certainly are oversimplifications and based on measured absolute cross sections which may be effected by systematic errors. Also, large scale shell model calculations predict important contributions from 4p4h excitations in the ground state of ^{32}Mg. On the other hand, the author argues that the results are rather stable with respect to "small" changes. These findings have dramatic consequences on our understanding (and actually on the existence) of the IOI. It is thus of importance to understand two-neutron transfer cross sections in this region of the nuclear chart in more detail.

In case of the very exotic ^{32}Mg experiment, cross sections could only be determined from proton detection using T-REX. Statistics was unsufficient to purify spectra using gamma gates. Furthermore, the excitation energy resolution was limited by the poor performance of T-REX position-sensitive strip detectors and, as a result of the low beam energy of 1.8 MeV/u, by the low-energy recoiling protons. The main goal of this proposal is to gain more detailed data on two-neutron transfer in this region, involving both the sd and fp neutron configurations. We propose to measure cross sections $\sigma(0^+_{1,2})$ for the population of 0^+_1 and 0^+_2 states in ^{30}Mg after two-neutron transfer ^{28}Mg(t,^{30}Mg)p. The ^{30}Mg at the "shore" of the Island of Inversion plays a special role: there is common agreement that the ^{30}Mg reflects the case of a pure (sd) groundstate and a rather pure neutron (fp) excited 0^+ state. Using mixing amplitudes deduced from the measured E0-decay of the 0+2 state in ^{30}Mg, the author in [9] predicts an exceptionally large ratio $\sigma(0^+_2)/\sigma(0^+_1) > 1$ for the two-neutron transfer ^{28}Mg(t,^{30}Mg)p. This is caused by the pure (fp) character of the 0^+_2 state in ^{30}Mg, strongly favored by two-neutron transfer. First of all, the measurement allows us to benchmark our understanding of two-neutron transfer cross sections in this region of the nuclear chart, based on well understood wave functions in ^{28}Mg. This also allows to study the possible influence of $s_{1/2}$ in the definition of the removal pair [10]. Furthermore, if this unusually large ratio is experimentally verified, this will form a direct proof of the presence of shape coexistence at the "shore" of the Island of Inversion and yields a precise way to extract the mixing amplitudes. Moreover, the above mentioned ratio $\sigma(fp)^2/\sigma(sd)^2$ for ^{30}Mg can be extracted, specifying the amount of neutron $(p_{3/2})^2$ configurations in the IOI. This would pin down the microscopic structure of the deformation driving configurations in the IOI, thus helping to understand its origin in better detail and judge on the relative importance of the tensor force and the Jahn-Teller effect. For this it is also of fundamental importance to identify the shape-coexisting structure on top of both 0^+ states in ^{30}Mg. In case the tensor force indeed plays a pivotal role, the mixing will develop in a specific way as a function of spin and excitation energy. Various experimental candidates for excited 2^+ and 4^+ states in ^{30}Mg do exist which will be probed using the two-neutron

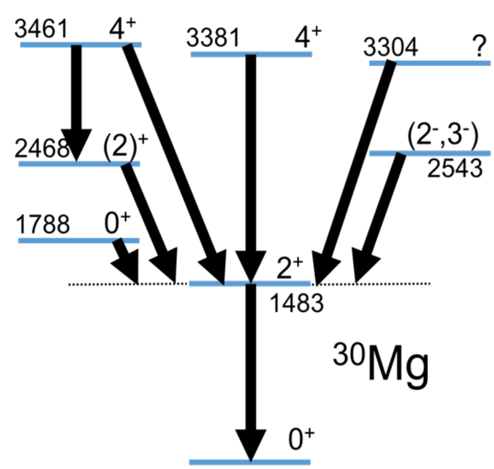

Fig 2: Known experimental levels in 30Mg up to 3.5 MeV excitation energy and its strongest decays.

transfer reaction. The case presented here is a unique chance in the sense that cross sections are expected to be unusually high for these configurations.

Of special importance is the (2^+) state at 2468 keV as well as the doublet of 4^+ states at 3379 keV and 3455 keV, whose cross sections can be measured on the basis of gamma-gated MINIBALL spectra, only. Of great importance is also the low-lying $(2^-,3^-)$ state at 2542 keV in ^{30}Mg which can not be explained by the shell model [11] and indicates once more that microscopic insight into the ^{30}Mg nucleus is needed. In our two-neutron transfer experiment we will extract the l-transfer into this state. Earlier experiments using two-neutron transfer into ^{28}Mg showed a strong population of the lowest-lying octupole-collective 3^- state, which will guide the search for such a state in ^{30}Mg.

Additional information will stem from the strong (t,d) reaction channel, populating the ^{29}Mg nucleus. Due to different Q-values and the different reaction mechanism compared to a suggested ^{28}Mg(d,p) experiment using the solenoid spectrometer (HELIOS-type) which will become available at ISOLDE, relative cross sections for the population of states in ^{29}Mg can be dramatically different, giving additional insight into the structure of states in ^{29}Mg.

The experiment utilizes the updated T-REX silicon array together with MINIBALL and the available tritium target. The identified transferred protons will be used to reconstruct the Q-value spectrum for ^{30}Mg. The Q-value of the ^{28}Mg(t,^{30}Mg)p experiment is 1.53 MeV, which is well suited for this experiment: proton energies in backward direction are sufficiently high to be detected using T-REX while cross sections quickly drop for higher lying states which may influence the results due to feeding.

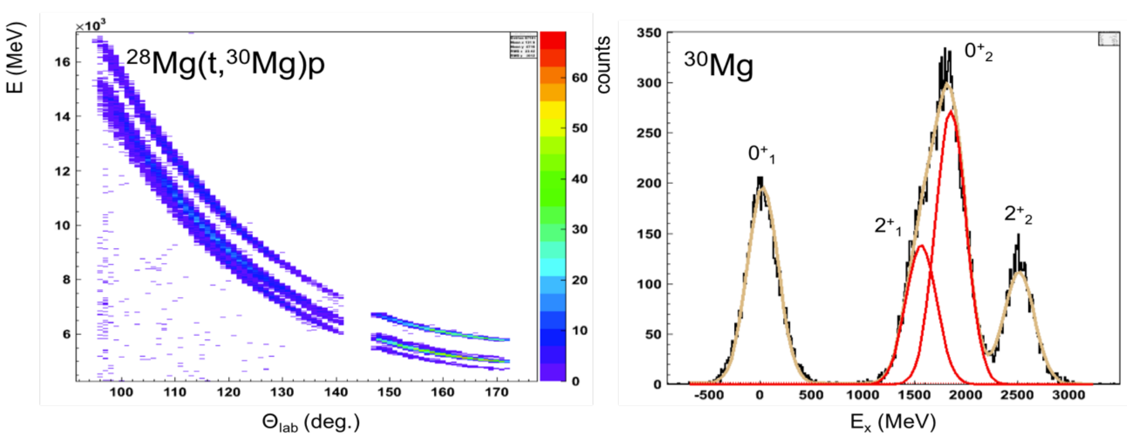

Fig 3: Left: Geant4 simulation of energy of transferred protons vs. proton scattering angle after two-neutron transfer into ^{30}Mg using the T-REX geometry. Right: Q-value spectrum of ^{30}Mg using T-REX after two-neutron transfer without gamma gate.

Based on DWBA calculations we performed a detailed Geant4 simulation for the proposed experiment both at 1.8 MeV/u and 5.5 MeV/u using the T-REX silicon detector geometry and the ^{3}H+Ti target, including multiple scattering of beam and recoiling light particles. The resultant Q-value spectrum for 5.5 MeV/u is shown in Fig. 3. The 2^+_1 and 0^+_2 states are not fully resolved, but, thanks to the expected large cross section of the 0^+_2 state, the spectrum can be disentangled and cross sections can be deduced in this direct way using a beam energy of 1.8 MeV/u. However, due to the limited Q-value resolution, it is essential to cross check the result using MINIBALL gated spectra. This also allows to identify contributions from possible beam contaminants, other reaction channels and background contributions from delta electrons in T-REX, which can change the relative cross sections significantly. The lifetime of $T_{1/2}$=3.9(4) ns of the 0^+_2 state in ^{30}Mg is sufficiently short so that most gamma rays emitted from the 0^+_2 state will decay insight the MINIBALL target chamber. The impact on the MINIBALL efficiency for these delayed gammas can be precisely determined using Geant4 simulations and 1.8 MeV/u beam energy, which is important in order to extract $\sigma(0^+_2)/\sigma(0^+_1)$ using

MINIBALL-gated spectra. Note that the delayed gamma ray emission of the 0^+_2 state will effect the MINIBALL Doppler correction for this line, resulting in a broader peak. However, thanks to the low gamma ray energy of this transition the absolute shifts are small and the line can be used for a clean gate, still.

This experiment also wants to make use of the higher energies now available at HIE ISOLDE. The resultant higher proton energies allow to detect about 50% more protons in forward direction based on dE-E techniques. Also, the sharp distribution of the momentum matching for transfer reactions in neutron-rich nuclei give slightly larger cross sections into ^{30}Mg. More importantly, the small Q-values and the large spatial extension of wave functions in neutron-rich Magnesium isotopes lead to an energy-momentum dependence of the cross sections which is very different from those known for transfer reactions on well bound systems [12]. The HIE ISOLDE upgrade allows to inspect this effect in neutron-rich systems for the first time, yielding a new and alternative way to study the compositions of wavefunctions and e.g. extract the amount of $f_{7/2}$ and $p_{3/2}$ intruder orbitals in both the spherical and deformed shapes in ^{30}Mg.

On the other hand, at HIE ISOLDE energies, new challenges arise. Due to the higher velocity the uncertainty on the effective MINIBALL efficiency for the decay of the 0^+_2 state becomes larger. The bigger problem arises from fusion reactions on the titanium layer (1.4b at 5.5 MeV/u). This results in 0.8 emitted proton per fusion reaction. The energy and angular distribution of fusion protons is more isotropic compared to transfer protons but can not be completely disentangled in T-REX. Although a gamma-gated analysis can still be performed, a suppression of fusion events will result in a much improved signal to background ratio. A suppression of the fusion channel will be done using the fusion veto device which we successfully tested at ISOLDE. For a charge breeding and cooling time of about 20ms the instantaneous beam rate at the MINIBALL target for the slow extraction mode (1ms) is up to $1*10^7$pps. At these rates the efficiency of the fusion veto, based on an anti-coincidence method, was found to be decreased. We are thus working on an upgraded design of the fusion veto for intense and long-lived beams at MINIBALL, replacing two foils of the fusion veto with a fast plastic scintillator counter at zero degree. Beam particles and fusion residues will produce a largely different light output after passing a degrader foil, and can thus be discriminated. A multihit TDC will be used to veto fusion-events offline. The setup will be fully tested and tuned using stable ^{26}Mg beam at the Munich MLL tandem laboratory. Note that the upgraded fusion veto will improve the sensitivity for this experiment, but is not mandatory for a successful run. The experience from this experiment will be important for any transfer experiment at HIE-ISOLDE beam energies.

For the count rate estimate we assume an integrated beam intensity of $4x10^5$ pps at the tritium target, based on values achieved for ^{32}Mg at MINIBALL. We assume $\sigma(0^+_1)+\sigma(0^+_2)$= 17 mb for the population of the 0^+ states after two-neutron transfer into ^{30}Mg, as was found experimentally for the case of ^{32}Mg. We furthermore assume $\sigma(0^+_2)/\sigma(0^+_1)$=1. Using FRESCO DWBA calculations we calculate cross sections for the population of the $2^+_{1,2}$ and $4^+_{1,2}$ states in ^{30}Mg. In case of the 0^+_2 state the MINIBALL efficiency for the 306 keV depopulating gamma ray is 13 %, whereas 6% MINIBALL efficiency is assumed for the higher lying states which mostly decay via ≈ 1 MeV gamma rays. Within 9 shifts (8 hours each) of beamtime at each energy setting, a few hundred gamma-gated protons can be detected for all states of interest, allowing the determination of transferred angular momenta and cross sections at sufficient precision.

The data of this experiment will be analyzed at the University of Guelph, TU Munich and TU Darmstadt and are an essential part for the Ph.D. thesis for C. Burbage (Univ. of Guelph) and C. Berner (TU Munich).

Summary of requested shifts:

In total, 20 shifts of ^{28}Mg beam at MINIBALL are requested. 1 shift is requested for the setup of the ^{28}Mg beam at 1.8 MeV/u, 9 shifts data taking at 1.8 MeV/u, 1 shift for changing the beam energy to 5.5 MeV/u and tuning the fusion veto and 9 shifts for data taking at 5.5 MeV/u.

References:

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX]	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*

Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN2, [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	152Eu(4205RP)/133Ba(4206RP)		
• Activity	23.64 kBq/22.32 kBq		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	RILIS		
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		

Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above):
(make a rough estimate of the total power consumption of the additional equipment used in the experiment)

… *kW*