EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Investigating high-energy single-particle states in ^{83}Ge via one-neutron transfer using ACTAR TPC

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Requested shifts: 7 shifts, (split into 1 run over 1 year)
Beamline: XT03 (ACTAR TPC)

Abstract: We propose to investigate the relative position of the neutron orbitals νd3/2, νg7/2 and νh11/2 in ^{83}Ge via the one-neutron transfer reactions (d,p) and (α,^{3}He) in inverse kinematics. This nucleus is only four protons and one neutron above the doubly-magic ^{78}Ni. Neutron ESPE in N=51 isotones vary as a function of proton number due to the tensor interaction, but measurements of the states with higher energy and momentum than the first excited state are needed to fit this interaction. Currently, there is clearly a very strong difference between the theoretical expectations and the experimental values. To identify the neutron configurations, we propose to measure the energy and the angular cross section using ACTAR-TPC and its ancillary detectors. Mixtures of ^{4}He and D2 gases will be used as a target to populate the different states.

Physics case

The behaviour of the nucleons in the nucleus is well described by the shell-model. Neutrons and protons occupies orbitals, which are filled such as the total energy is minimised. The energies of these single particle orbitals are called effective single-particle energies (ESPE), and from their relative position rise the so-called "magic numbers". Nuclei with these numbers of protons and/or neutrons are subject to an increase of their binding energy. However, it has been observed that magic numbers depends on the isospin of the system, and recent improvements in both theoretical models[Ots05,Ots10,Sie10,Shi12] and experimental studies[Hos05,Got16,Fla09] have been made in order to understand the evolution of these shells near the crossing of two shell gaps, Z=28 and N=50.

Odd-mass nuclei with 51 neutrons have been investigated in order to map the evolution of the neutron orbitals as a function of the charge number. The spin and parity assignment and the energy of the ground or excited states are directly related with the orbital and the ESPE occupied by the one valence neutron. Therefore, one-neutron pick-up performed with transfer reactions has been used on several N=50 cores to determine the ESPE of the low-energy ν2d5/2 and ν3s1/2 orbitals[Sha12,Tho05,Tho07]. Higher energy states, corresponding to the neutron occupying the νd3/2, νg7/2 and νh11/2 shells, were not or poorly populated due to unappropriated angular matching and low cross section. The emptying of the πf5/2 orbital act differently on these neutron shells due to the tensor component of the monopole proton-neutron interaction [Ots05]. Further measurements are needed to fit the two-body matrix elements and predict the evolution of the neutron ESPE.

Several shell-model predictions for these ESPE are presented in Figure 1. Between Z=28 and Z=38, they only agree on the general trend of the d3/2. The neutron ESPE for the νg7/2 orbital is predicted to decrease with the number of proton but the measurement of the ν7/2+ shows a quite flat tendency. Moreover, the location of its crossing with the νd3/2 is still unknown. As the νh11/2 has a higher momentum and energy, it has never been studied and its trend is totally unknown. Its evolution follows opposite trend from one model to another, and therefore needs measurement to be constrained.

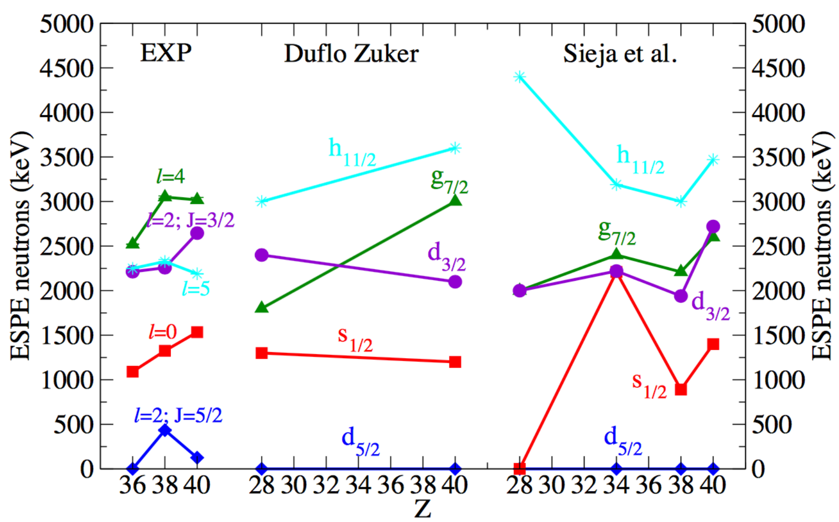

Fig. 1 - Evolution of the neutron effective single particle energy
in the N=51 isotones above the ^{78}Ni core, from shell-model calculations (from [Ver16]).

Also, based on the predictions from Duflo-Zuker[Duf99], the order of the νg7/2 and the νd3/2 reverses around Z=32, which could lead to two non-degenerated states in ^{83}Ge. We propose to disentangle the two states at this energy by using the two different one-neutron transfer reactions, (d,p) and (α,^{3}He), which will populate the two states but with different ratio because of momentum matching.

One-neutron stripping reactions have already been performed on ^{83}Ge and ^{85}Se [Tho05,Tho07] and the identified excited states are presented in Figure 2. Identification of the νd3/2 from the νg7/2 in ^{85}Se was attempted based on the angular distribution of the proton corresponding to a state at 1.115 MeV, but the spectroscopic factor does not agree with the tendency of the other N=51 isotones. Moreover, a plunger experiment [Did17] concluded that this state originates from core-coupling. Two states around 1.4 MeV were also observed but no spin could be assigned. So far, in ^{83}Ge, only the ground state (5/2+) and the first excited state (1/2+) have been unambiguously identified as mainly single-particle states[Tho05]. In ^{83}Ge, a state at about 0.85 MeV was observed and could correspond to the 7/2+ resulting from the neutron in the νg7/2. However, the spectroscopic factor calculated for this state doesn't follow the general trend of the N=51 isotones. In recent decay experiment[Als16], few 3/2+ were measured in ^{83}Ge, at 1 and 1.2 MeV, but no 7/2+ states were identified.

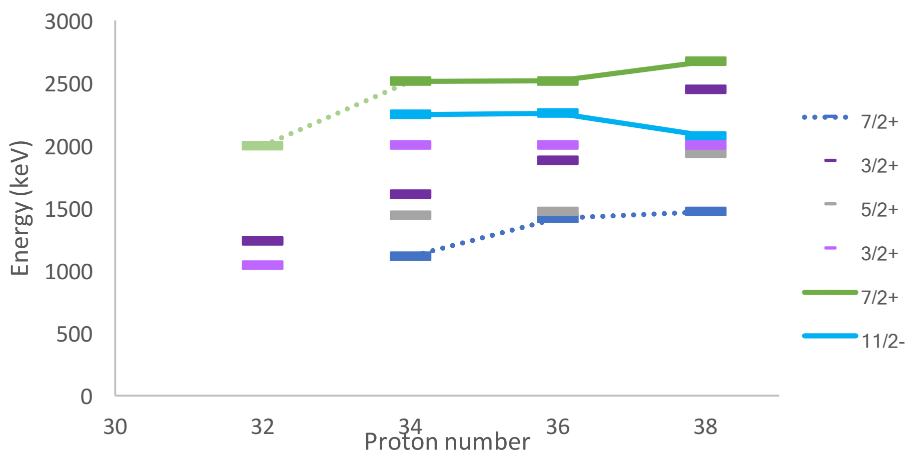

Fig. 2 - Experimental measurements of the excited states in the odd-mass N=51 nuclei. (figure adapted from [Ver16]). The 7/2+ state in ^{83}Ge was tentatively identified at about 2 MeV [Del17].

We propose to perform one-neutron transfer reactions in order to populate these states. In particular, the use of transfer reactions will allow us to disentangle the origin of the low 7/2+ states, since only the single-particle states should be populated by transfer reactions. At the energies available at the ISOLDE facility, (d,p) and (α,^{3}He) are matching respectively low-momentum transfer (l=0, l=2) or high momentum transfer (l≥4). The identification of the transferred momentum will be performed by measuring the angular distributions of the emitted protons or ^{3}He and compared with DWBA calculations.

Experimental setup

The ^{82}Ge beam will be produced using the UC_X target within the RILIS facility. The expected intensity of the beam exiting the primary target is about 10^5 pps. With a typical transmission of 5%, a beam intensity of 5×10^4 pps is expected at the entrance of the active-target volume. For now, beam energy is 7 MeV/u but could reach 10 MeV/u in the near future. This beam energies allow the excitation of high-energy 11/2+ and 7/2+.

We propose to use the active-target ACTAR-TPC [Act] that has been recently developed at GANIL (see Fig. 3). In this device, (i) the reaction between the beam and the gas takes place in the active volume, and (ii) the same gas volume is used as a detector: the reaction products ionize the gas, releasing electrons that drift to a highly pixelated pad plane. The charge collected on the pads provides the 2D projection of the tracks while the third dimension can be reconstructed using the drift time of the electrons in the chamber. This allows a full 3D reconstruction to be performed, on an event by event basis, that provides a complete measurement of the kinematics, including angular distributions over a wide range of angles.

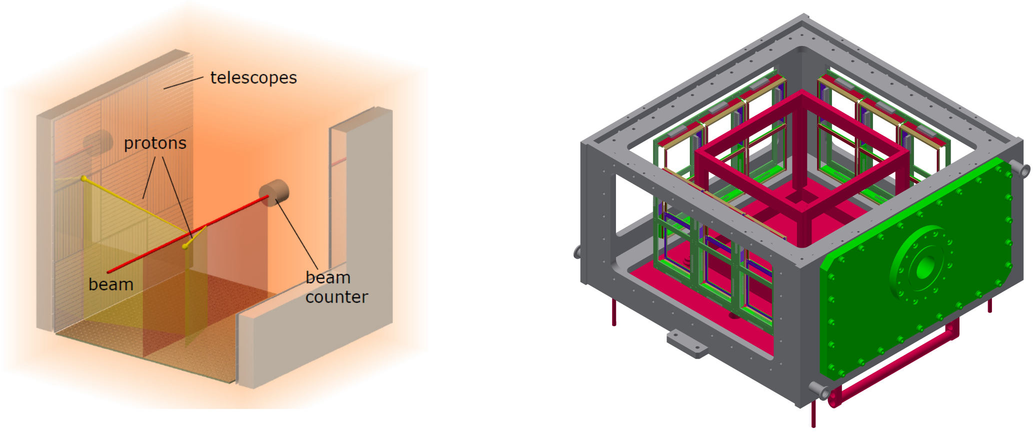

Fig. 3 - The ACTAR TPC detector consists of a gas volume that is used as a reaction target and as a detector. 3D tracks are reconstructed using the projection on the pad plane and the drift time of the electrons. Si detectors are added to the sides to record the energy of the particles that escape the gas volume.

Based on previous inelastic-scattering experiments with the ACTAR TPC demonstrator, the angular resolution is approximately 1 degree (FWHM)[Pan14], and excitation energies have been measured with a resolution better than 175 keV (FWHM)[Rog17]. This resolution, that is achievable with ACTAR TPC, is nearly two times better than the one expected (between 400 and 1000 keV) in the solid target experiment of the previous proposal and similar experiments performed in this region [Tho07]. The length of the chamber acts like a very thick target, and allows for an increased reaction rate. These two characteristics make the active target ideally suited for transfer reactions in inverse kinematics with beam intensities below 10^5 ions/s.

Ancillary detectors such as Si detectors will be placed all around the active volume. The Si detectors that will be added to ACTAR TPC have an energy resolution of approximately 75 keV. The energy measured in these detectors will be used to provide total kinetic energies and particle identification. These auxiliary detectors have already been successfully tested and used in previous experiments. In the final design of the ACTAR TPC, the expected efficiency with the two Si walls parallel to the beam, and the DSSDs positioned at forward angles, is approximately 37%.

The gases used as targets in this experiment will be D2 and ^{4}He. The pressure in the chamber will be between 500 mbar and 1 bar, depending on the gas mixture used. Mixtures with iC4H10 (about 5%) or CF4(about 5%) could be used, in order to have sufficient gain to increase the dynamical range.

Analysis principle

To populate the (3/2+) state by transferring low-l momentum (l=2), we propose to use a gas target of deuterium. Kinematic calculations of the proton emitted in the reaction process shows protons with energy higher than 7 MeV at forward angles. As a result, we intend to use the Si detectors positioned around the chamber to identify the protons going through the gas volume. This part of the experiment aims to detect protons following (d,p) reactions in inverse kinematics. For the proton following a l=2 transferred momentum (see Fig. 4), most of the protons will be emitted at forward angles in the centre of mass ($0° \leq \theta_{CM} \leq 50°$), which corresponds to backward angle in the laboratory frame ($80° \leq \theta_{lab} \leq 180°$).

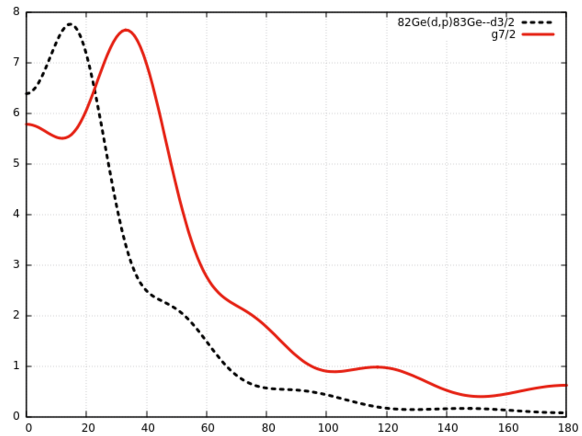

Fig. 4 - Angular cross sections of protons for either l=2 (d3/2) or l=4 (g7/2) transferred momentum (both curves have ben renormalized for comparison purpose) [Yan17].

As explained above, 3/2+ and 7/2+ states could be unresolved or degenerate. In order to distinguish and determine the energy of these two states, we propose to populate them via (d,p) reaction, but also via high-momentum transfer reaction, (α,^{3}He). The latter is feasible with the beam energy available at ISOLDE, but at the time of writing this proposal, DWBA calculations for this reaction are still ongoing. Determination of the energy of the unresolved excited states will be done by comparing the relative heights of the proton groups for these two different reactions. Also, relative spectroscopic factors will be calculated by fitting the total angular distribution with both components.

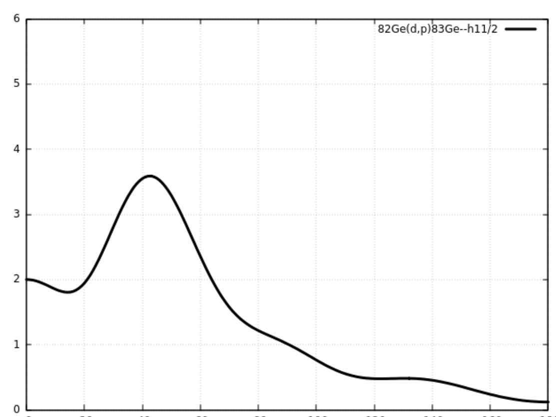

Fig. 5 - Proton angular cross section for the 11/2- state at 2.9 MeV[Yan17].

To populate the high-energy 11/2- state (l=5), we propose to perform (α,^{3}He) reaction because of a better momentum matching at the beam energy available at ISOLDE. Kinematic calculations of the ^{3}He particles, performed for the 11/2- at about 2.9 MeV, shows that the total kinetic energy will be rather low (less than 16 MeV) and that the angle in the laboratory frame should not exceed 36°. DWBA calculations have been performed for (d,p) transfer reaction to estimate the cross section, despite the imperfect momentum matching, and are presented in Fig. 5.

Beam request

As the beam goes through the gas volume, the beam energy at the interaction point varies, and is experimentally deduced from the reconstruction of the vertex. In the following section, an average beam energy of 6 MeV is taken to estimate the reaction rates. A gas pressure of 1 bar is used as the most probable setting, with the ideal gas mixture of D_2(95%) with CF_4(5%).

Since the reaction occurs in the active volume of ACTAR TPC, the angular coverage of the detector is considered to be 4π, with a detection efficiency close to 100% [Van15]. However, the heavy beam is highly ionizing the gas volume and the tracks with a low angle with respect to the trajectory of the beam will be difficult to reconstruct. Thus, we take an estimation of 90% to account for this effect in the following calculations. As described above, Si detectors surrounding the active volume will be used to identify the high-energy protons escaping the gas volume. This would reduce the angular coverage and the charged-particle detection efficiency to at least 37%, but would result in an efficiency higher than that of the available γ-ray detector arrays.

The total reaction cross sections for each orbital obtained from DWBA calculations are given in Table 1. The expected rate for the (d,p) reactions are calculated considering a spectroscopic factor of 0.6.

Transferred momentum	Total cross section (mb)	Event rate (h^{-1})	Detected events (per shift)
l=2 (νd3/2)	49.1	763	2.1 K
l=4 (νg7/2)	14.2	220	0.6 K
l=5 (νh11/2)	13.8	215	0.6 K

Table 1 – Rate estimation for the one-neutron transfer (d,p) reactions to the different orbitals, and the number of detected events after the efficiency correction.

Despite the advanced techniques developed by the TISD team (neutron converter, quartz transfer line) other nuclei such as ^{82}Se will also be produced and will contaminate the ^{82}Ge beam. Therefore, several runs with Lasers ON/OFF are required to discriminate the ^{82}Ge events from this contamination. Based on a previous (d,p) reactions experiment [Tho05], ^{82}Se would represent about 85% of the laser-ionized beam. As a result, we require 2 shifts with Lasers OFF. 1 additional shift will be dedicated to beam and detector tuning, leading to a total of 7 shifts.

Remarks

The full ACTAR TPC detection system will be constructed and prepared to perform first physics experiments starting in the Summer of 2017. This detector was funded through an ERC starting grant that included an experiment at ISOLDE as one of its three milestone experiments. This experiment is therefore proposed within the framework of the ERC grant, as the first transfer reaction using this novel apparatus.

Summary of requested shifts:

Beam	Total intensity	Target	Energy, MeV/u	Laser	Shifts
*			-	-	1*
$^{82}Ge+^{82}Se$	$4. 10^4$ pps	UCx	7	ON	4
$^{82}Ge+^{82}Se$	$4. 10^4$ pps	UCx	7	OFF	2

***1 shifts for setting up, beam and detector tuning. The yields are extracted from the ISOLDE yield database.**

References:

[Ots05] T. Otsuka *et al*., Phys. Rev. Lett. 95 (2005) 232502

[Ots10] T. Otsuka *et al*., Phys. Rev. Lett., 104, (2010) 012501

[Sie10] K. Sieja, F. Nowacki, Phys. Rev. C, 81, (2010) 061303(R)

[Shi12] N. Shimizu, *et al.,* Prog. Theor. Exp. Phys., (2012) 01A205

[Hos05] P.T. Hosmer, *et al.,* Phys. Rev. Lett. 94, (2005) 112501

[Got16] A. Gottardo, *et al*., Phys. Rev. Lett. 116, (2016) 182501

[Fla09] K. T. Flanagan, Phys. Rev. Lett. 103, (2009) 142501

[Fla10] K.T. Flanagan, *et al.,* Phys. Rev. C 82, (2010) 041302(R)

[Sha12] D. K. Sharp, Phys. Rev. C 87, (2013) 014312

[Tho07] J. S. Thomas *et al*., Phys. Rev. C 76, (2007) 044302

[Tho05] J. S. Thomas *et al*., Phys. Rev. C 71, (2005) 021302

[Ver16] D. Verney, Habilitation à diriger des recherches – tel-01376570 (2016)

[Duf99] J. Duflo, *et al*., Phys. Rev. C 59, (1999) 2347 (R)

[Did17] F. Didierjean, to be published

[Del17] C. Delafosse, private communication

[Als16] M. F. Alshuidfat, Phys. Rev. C 93, (2016) 044325

[Ver07] D. Verney *et al*., Phys. Rev. C 76, (2007) 054312

[Act] see http://pro.ganil-spiral2.eu/laboratory/detectors/actartpc/docs/actar-tpc-conceptual-design-report/view

[Pan14] J. Pancin *et al*, NIM A 735, (2014) 532

[Rog17] T. Roger, to be published in NIMA

[Yan17] J. Yang, private communication

[Van15] M. Vandebrouck *et al*, Phys. Rev. C 92, (2015) 024316

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises ACTAR TPC, DSSD or Si detectors

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
ACTAR TPC	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing

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	ACTAR-TPC	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	1 bar; 80 L		
Vacuum			
Temperature	295 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	[V], [current][A]		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	D2 (95%) + iC4H10 (5%) or D2 (95%) + CF4 (5%) and He (100)		
Beam particle type (e, p, ions, etc)	Ions		
Beam intensity	$\leq 10^5$ pps		
Beam energy	Up to 10 MeV/U		
Cooling liquids			
Gases	D2 (95%) + iC4H10 (5%) or D2 (95%) + CF4 (5%) and He (100)		
Calibration sources:	☐		
• Open source	☐		

• Sealed source	☒ [ISO standard]		
• Isotope	^{228}Th, or standard 3α source		
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
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	D2, 80 L		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	D2, 80 L		
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*