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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Neutron single-particle states towards ^{78}Ni: ^{80}Ga$(d,p)^{81}$Ga

January 10, 2018

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Abstract:
The aim of the presented proposal is to study the neutron single-particle states of ^{81}Ga via one-neutron pickup reaction in inverse kinematics, ^{80}Ga (d,p) ^{81}Ga. ^{81}Ga is the most exotic $N = 50$ isotone towards $Z = 28$ where high-lying neutron core excited states will be populated and be identified by spin and parity for the first time through the proposed one-step direct reaction process. Characterization of the states originating from $1p-1h$ excitations is sensitive to the size of the current $N = 50$ gap and will provide the necessary information on the $N = 50$ shell evolution towards $Z = 28$, i.e. ^{78}Ni. The excited states of ^{81}Ga will be populated through the reaction with a ^{80}Ga beam at an energy of 6.25 MeV/A impinging on a deuterated-polyethylene target. Emitted protons as well as γ rays de-exciting the states in residual nuclei will be detected using the MINIBALL + T-REX setup.

Requested shifts: 18 shifts for ^{80}Ga beam plus 3 shifts to optimize the production and purification of the beam.

1 Motivation

Exploring nuclear structure and the so-called shell evolution experimentally becomes rather challenging when more and more neutrons are added to the atomic nucleus [1]. In this respect, the ^{78}Ni region where $Z = 28$ and $N = 50$ shell gaps are formed and where there is significantly less known compared to the other doubly-magic regions, attracted much attention lately both experimental and theoretical groups. The main question is to understand how the $Z = 28$ and $N = 50$ gaps evolve from stable borders to the unstable ones and the underlying forces behind it. The evolution of the $Z = 28$ shell gap from $N = 28$ (^{56}Ni) to $N = 50$ (^{78}Ni) is nowadays better known from the large number of experimental studies accompanied by the state-of-the-art shell model calculations [2, 3, 4, 5, 6, 7] while the $N = 50$ shell closure seems to require more experimental inputs towards $Z = 28$ (^{78}Ni).

The evolution of the $N = 50$ shell closure comprises the nuclei from $Z = 40$ (^{90}Zr) to $Z = 28$ (^{78}Ni) along the $N = 50$ isotonic chain. Mass measurements in $N = 50, 51$ nuclei [8, 9] have shown a reduction in the mass gap of about 1 MeV from $Z = 40$ to $Z = 32 - 31$ and then its re-increasing by few hundreds keV at $Z = 30$. This behaviour is not compatible with a two-body standard monopole drift, which should be linear as a function of the number of nucleons and underlines that the effects of correlations have to be taken into account in the nuclear Hamiltonians. The $N = 50$ gap values extracted from mass and from spectroscopy, are both the results of the interplay between the monopole variations the ESPE of $1g_{9/2}$ and $2d_{5/2}$ shells and of quadrupole and pairing correlations as explained in Ref. [10]. In this respect it is not difficult to see that $1p - 1h$ excitations along the $N = 50$ isotonic chain are essential ingredients not only in the discussion of the $N = 50$ shell gap evolution on the neutron drip line but also as inputs to the theory to pin down correlation effects from $np - nh$ excitations. Recent mass measurements of the neutron-rich copper isotopes $^{75-79}$Cu at ISOLDE [11] and their comparison to large-scale shell-model calculations using PFSDG-U interaction [7] point out the same fact that excitations across the both $Z = 28$ and $N = 50$ shell gaps are necessary in order to reproduce the experimental findings, in which one of them can be a possible island of inversion phenomena in the $N = 50$ shell number at Z=28. In order to investigate the proposed shape coexistence in the doubly-magic ^{78}Ni nucleus and the region nearby, experimental information on number of $1p-1h$ excitations and occupancies of the neutron orbits are among the necessary inputs along the $N = 50$ chain and known so far up to $Z = 32$ (^{82}Ge).

$1p - 1h$ states above the $N = 50$ gap:

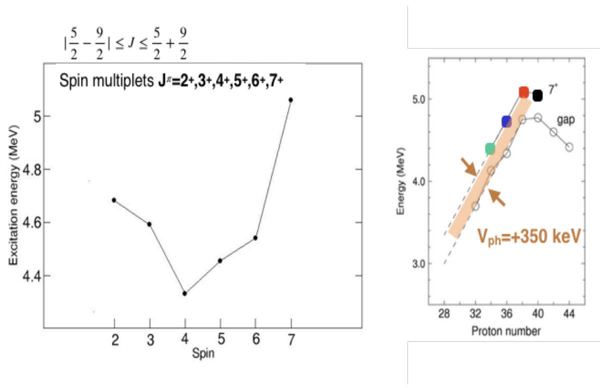

Figure 1: Left: Excitation energies of the six multiplets in ^{90}Zr as a function of their spin. Right: Systematics of the 7^+ states from the $\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$ configuration in the even-even N = 50 isotones and of the gap N=50. The figures are taken from Ref. [1]

It is expected that in $N = 50$ nuclei, higher-lying states above 2 -3 MeV are dominated by the particle-hole ($np-nh$, n =1,2,3,4 at most) excitations above the $N = 50$ shell gap, i.e. between the $1g_{9/2}$ and $2d_{5/2}$ orbits. The calculated wave functions for such states show a presence of a significant component of $1p-1h$ excitation with the ($\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$) configuration. The resulting states arising from the ($\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$) configuration are nothing but the multiplets J^{π}=2^+, 3^+, 4^+, 5^+, 6^+, 7^+. A complete identification of these multiplets along the $N = 50$ isotonic chain has been done for $^{90}_{40}$Zr [12] and $^{88}_{38}$Sr [13] so far via one-neutron pickup reactions, ^{91}Zr(^{3}He,α)^{90}Zr and ^{87}Sr$(d,p)^{88}$Sr, respectively. When it comes to the more exotic members of the isotonic chain, this complete identification of the $1p-1h$ multiplets could not be performed anymore but only the 7^+ state was identified via the γ-ray spectroscopy following the fusion-fission reaction in $^{86}_{36}$Kr and $^{84}_{34}$Se. Finally $^{82}_{32}$Ge is the the last member whose 6^+ and 5^+ states sensitive to the size of the gap were identified via multi-nucleon transfer reactions [14]. Systematics of these spin multiplets arising from the $\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$ configuration is essential as it will provide the exact determination of the shell gap value and the effect of the correlations along the chain. Figure 1 shows this case for the $N = 50$ shell from $Z = 40$ to $Z = 34$. In the figure on the left, the complete identification of all the multiplets in ^{90}Zr shows a parabola ending with the 7^+ and 2^+ values. Instead the figure on the right hand side, accordingly how the experimental 7^+ states are following the gap value with a difference of +350 keV which is attributed to the repulsive p-h interaction, $V_{ph}=V_{g^{-1}_{9/2}d^{1}_{5/2}}$.

Figure 2 shows these experimentally identified $1p-1h$ states in $N = 50$ isotones up to Z=32. Starting from the $^{81}_{31}$Ga nucleus there is no information on any member of the $1p - 1h$ multiplets. Presently, ^{81}Ga is the most exotic $N = 50$ isotone and its spectroscopy is now accessible at ISOLDE up to the particle-hole states across $N = 50$. *The present proposal, therefore, aims at studying neutron single-particle energies of* ^{81}*Ga via the* (d, p) *reaction in inverse kinematics. The states from the p-h excitations above the neutron gap and thus its evolution up to* $Z = 31$ *will be determined in a very selective way. This study will help us to understand the role of the correlations and greatly contribute to increase our knowledge on the p-n interactions, in particular the contribution of the tensor interaction between the involved shells in the* ^{78}*Ni mass region. Furthermore, It will be the first time that* (d, p) *transfer reaction in inverse kinematics will be applied to a member along the* $N = 50$ *chain and a successful analysis of the data set will make us apply the same method to the next neighbouring* ^{80}*Zn (Z=30) nucleus in the future at ISOLDE.*

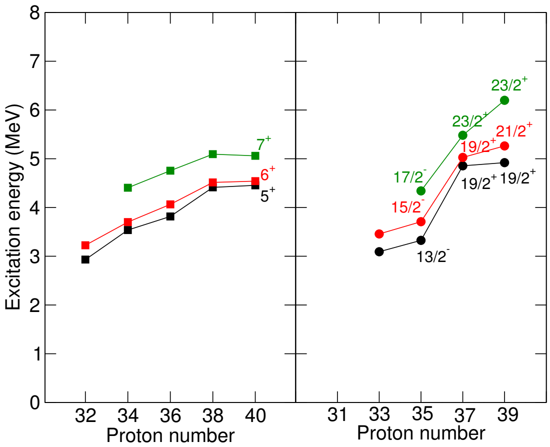

Figure 2: Evolution of the $1p-1h$ excited states, in the even-even and odd-even $N = 50$ isotones.

There is limited information about the excited states in ^{81}Ga. Its low-lying states were populated for the first time via beta-decay of ^{81}Zn at ISOLDE [15] and its level scheme up to 2.3 MeV was built in Ref [14] via multi-nucleon transfer reaction of an ^{82}Se beam at 515 MeV on a thin ^{238}U target. In the same work, the excited states of the odd-A member $^{83}_{33}$As were also populated. The analogous neutron $1p - 1h$ excitations with spins $13/2^-$ and $15/2^-$ were identified for $^{83}_{33}$As. Characterization of the $1p - 1h$ states in ^{83}As based on spin assignments and on SM calculations allowed a determination of the $N = 50$ energy gap of 4.7 (3) MeV at $Z = 28$. However, due to insufficient statistics, firm spin and parity assignments were not performed for $^{81}_{31}$Ga. Figure 3 shows the level scheme of ^{81}Ga obtained together with the

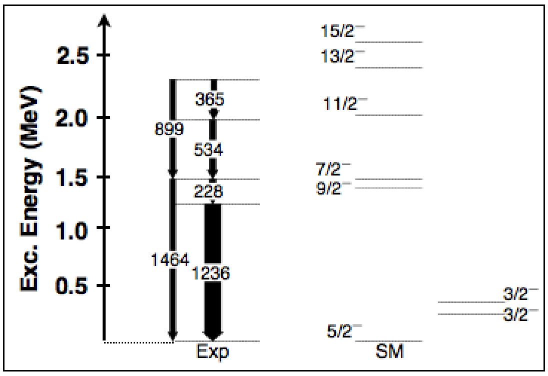

Figure 3: Level scheme of ^{81}Ga obtained in the work of [14]. Shell model calculations include $1p-1h$ excitations above the $N = 50$ shell.

comparison to the shell model calculations [14]. Interestingly if the excitation energy at 2.3 MeV from the experimental level scheme were included as a data point in Figure 2, the gap value would become quite lower respect to the systematics of the even-even isotones.

2 Experiment

We propose to measure the neutron particle-hole states of ^{81}Ga via single neutron transfer reaction ^{80}Ga (d, p) ^{81}Ga in inverse kinematics. The ^{80}Ga beam will be post-accelerated to an energy of 500 MeV (6.25 MeV/A), impinging on a 1 mg/cm^2 deuterated polyethylene CD_2 target. The given beam energy is chosen to optimize the reaction cross sections shown in Figure 4. A production yield of 3.5×10^5 at/μC for ^{80}Ga has been achieved using a UC_x target and laser ionized using RILIS [17]. Assuming 2μA of proton beam current and 2% transmission efficiency to the MINIBALL beam line, the beam intensity on the target should be of the order of 1.4×10^4 pps. The experimental setup will consists of the T-REX silicon-detector array [18] coupled to the MINIBALL γ-ray spectrometer [19]. This setup permits to detect the emitted protons in coincidence with the γ rays de-excited from the residual nucleus. The coincidence technique is necessary in the present case where the resolution of the proton spectra are worsens for the choice of the target thickness (1 mg/cm^2) and will allow us to resolve the states of interest. It has been already employed successfully by the previous studies at REX-ISOLDE. The main focus of the proposed experiment is to populate the neutron particle-hole states arising from the $\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$ configuration. The states of the multiplets $\nu 1g^{-1}_{9/2} \otimes \nu 2d^{1}_{5/2}$ will be selectively populated by requiring an angular momentum transfer of $l = 2$. At present, only the first two members of the multiplet with spins $13/2^-$ and $15/2^-$ are predicted by the SM calculations and their energies are 2500 and 2700 keV, respectively (See Figure 3). In addition, there will be other spin multiplets from the transfer of a ($l = 0$) neutron into the $3s_{1/2}$ orbit. Previous (d, p) reaction of the other $N = 50$ isotone ^{88}Sr [13], showed that the population of these states are similar to the states of the $2d_{5/2}$ multiplets and lying above these multiplets. However, SM predictions would be helpful to guess the position of these states and at present there are no these calculations for us to consider their population rates in the presented proposal.

Figure 4 shows DWBA calculations performed for $l = 2$ transfer and for each state using the code FRESCO [20]. Angular distribution of protons emitted in the reaction are calculated using the deuteron optical model parametrization in Ref. [21], labeled in L, and three different sets of proton parameters from [22, 23, 24], labeled in B, M, and V, respectively. The estimated cross sections are taken from the average of these three different sets of calculations. For the the $2d_{5/2}$ state at 2500 and 2700 keV the calculated cross sections are 3.5 mb and 2.5 mb, respectively (for a spectroscopic factor of 1).

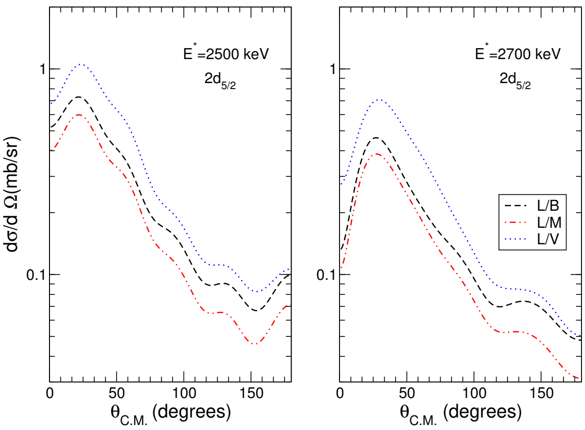

Figure 4: Angular distribution of protons emitted in the reaction ^{80}Ga (d, p) ^{81}Ga populating the $2d_{5/2}$ state at 2500 keV (left) and for the state at 2700 keV (right)

For a beam intensity of 1.4×10^4 pps at the target position, and a target thickness of 1.0 mg/cm^2 the rates of about 0.015 and 0.011 events/sec are estimated. Proton detection efficiency in the barrel detector for both $2d_{5/2}$-character states is taken as 50% in a good approximation.

The γ rays showing successive decays from $2d_{5/2}$ multiplets range from 250 keV to over 1.3 MeV for the other odd-A members of the isotonic chain, mainly ^{87}Rb, ^{85}Br, and^{83}As. The absolute photo-peak efficiency of MINIBALL varies from 13% at 250 keV to 5% at 1.3 MeV. Assuming an average photopeak efficiency of 8%, final rates of 50 and 40 events/day are expected in the proposed experiment. For the clear identification of the states of interest, which requires, both, proton and γ-ray gates, we foresee a 6 days of data taking.

Summary of requested shifts: 18 shifts for ^{80}Ga beam plus 3 shifts to optimize the production and purification of the beam.

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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	Availability	Design and manufacturing
(MINIBALL + T-REX)	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ 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
[Part 2 of experiment/ equipment]	☐ 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
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [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]	CD2		
Beam particle type (e, p, ions, etc)	ions		
Beam intensity	3.5×10^5 pps		
Beam energy	500 MeV		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	^{152}Eu, ^{133}Ba		
• 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 (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		

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]		

Hazard identification:

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]