EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Resolving the low-lying structure of ^{81}Ga using the Coulomb excitation technique

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Abstract:

We aim to study of the collective properties of the low-lying states in ^{81}Ga using Coulomb excitation. ^{81}Ga is the most exotic $N = 50$ isotone towards $Z = 28$ whose spectroscopy is presently accessible up to particle-hole states across $N = 50$. The identification of the first excited $9/2^-$ and $7/2^-$ states, dominated by the $\pi 1f_{5/2} \otimes 2_1^+(^{80}\mathrm{Zn})$ particle-core configuration will clarify the level sequences up to spin $15/2^-$ which shows inconsistency from the past spectroscopic studies. Such a characterization of the particle-hole states, sensitive to the size of the current $N = 50$ gap, is crucial to provide significant information on the $N = 50$ shell evolution towards $Z = 28$, i.e. ^{78}Ni.

Requested shifts: 12 shifts for ^{81}Ga beam plus 3 shifts to optimize the production and purification of the beam.

1 Motivation

Determination of the shell gaps requires different measurements to constrain the effective single particle energies (ESPE) originating the gap. The case of the $N = 50$ shell closure is emblematic: there has been a long debate on the reduction of the $\nu 1g_{9/2}^{-1}$ - $\nu 2{d_{5/2}}^1$ gap going from $Z = 40$ (^{90}Zr) to $Z = 28$ (^{78}Ni) [1]. Along the isotonic chain, proton $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ orbits from $Z = 28$ towards $Z = 40$ are involved while neutron $1g_{9/2}$ and $2d_{5/2}$ have to be considered greatly in the discussion of the $N = 50$ shell evolution stemming to a large degree from the tensor force component in the nuclear Hamiltonians, between protons in pf shell and neutrons in $1g_{9/2}$ and $2d_{5/2}$ orbits. Mass measurements in $N = 50, 51$ nuclei [2, 3] have shown a reduction in the mass gap of about 1 MeV from $Z = 40$ to $Z = 32 - 31$ and then its re-increasing of 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 [4]. Three-body forces, which are quadratic as a function of the number of nucleons, may be at play, or other phenomena, possibly linked to the correlations induced by the rapid lowering of the $s_{1/2}$ shell when approaching Z=30 [5]. It is expected that in $N = 50$ nuclei, states with spin higher than $4\hbar$ are dominated by the particle-hole (np-nh, n=1,2,3 at most) excitations above the $N = 50$ shell gap, thus sensitive to the size of the neutron gap. The calculated wave functions for such states show the presence of a significant component of $(\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1})$ configuration. More specifically, the energy of the first excited 6^+ state in even $N = 50$ nuclei lowers from $Z = 38$ to $Z = 32$ due to the neutron 1p-1h excitation above the $N = 50$ shell gap via $(\nu 1g_{9/2}^{-1} \otimes \nu 2d_{5/2}^{1})$ configuration [6, 7, 8] while 2p-2h excitations could be explained by including the neutron $3s_{1/2}$ and $2d_{3/2}$ orbitals in addition to the 1p-1h excitations involving $2d_{5/2}$ and/or $1g_{7/2}$ neutron orbitals [5].

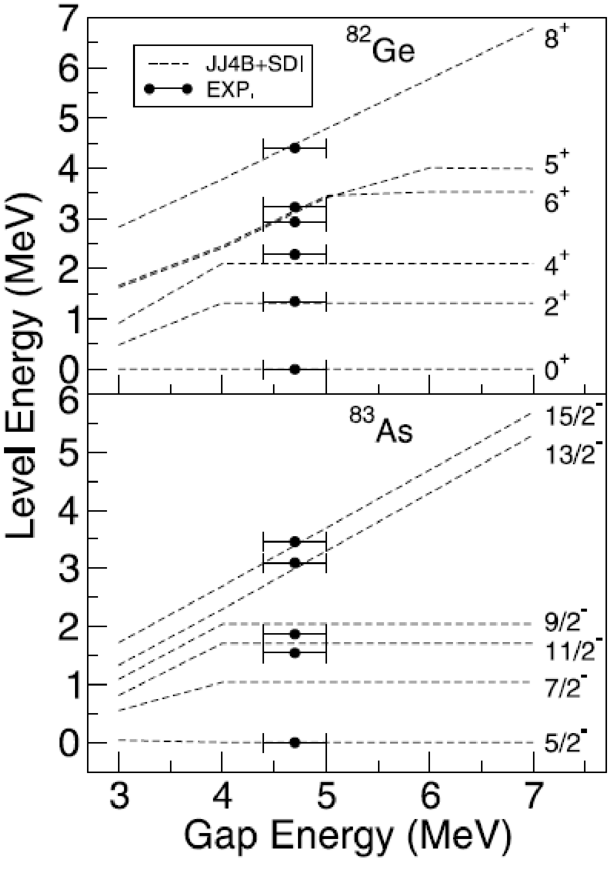

Figure 1: Level energies of ^{82}Ge and ^{83}As as a function of the $N = 50$ shell gap energy.The best agreement with the experimental energies (indicated by full dots) is obtained for a gap value of 4.7(3) MeV [8].

In $N = 50$ odd isotones, a similar trend is observed in the analogous neutron p-h excitations with spins $13/2^-$ and $15/2^-$. Identification of the p-h excitation states in ^{83}As (Z=33) and ^{81}Ga ($Z = 31$) based on spin assignments, where possible, and on SM calculations, allowed a determination of the $N = 50$ energy gap of 4.7 (3) MeV at $Z = 28$ in Ref. [8]. The SM calculations in the work used a combination of the JJ4B residual interaction for the pfg configuration space for both proton and neutrons and the two-body cross-shell matrix elements of the Surface Delta Interaction (SDI) for neutrons built on the $2d_{5/2}$, $3s_{1/2}$ and $1g_{7/2}$ orbits, assuming ^{56}Ni as an inert core. Figure 1 shows the level energies of the ^{81}Ga, ^{82}Ge, and ^{83}As nuclei calculated as a function of the $E_{\nu 2d_{5/2}} - E_{\nu 1g_{9/2}}$ energy difference, i.e. the $N = 50$ shell gap. The gap value of 4.7 (3) MeV, largely sensitive to the p-h excitations described above, was obtained through the best fit between observed and calculated states of all three isotones.
The two shell gaps, from mass and from spectroscopy measurements, 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 [9]. In the recent work of Ref. [10], the evolution of the $Z = 28$ proton gap has been investigated by including correlation effects due to multipole interaction in the total Hamiltonian. In this regard, $N = 50$ isotones going from $Z = 40$ to $Z = 28$ are particularly interesting since, when comparing with the shell model predictions, they are good candidates to pin down the changes into the shell structure hence on the fundamental properties of the nuclear many-body system.

The aim of this proposal is to determine the energy of the 13/2$^-$ state in the odd isotone ^{81}Ga via the identification of the first excited 9/2$^-$ state and thus to investigate the shell gap at $N = 50$. *The 13/2$^-$ state (as well as states of higher spin) cannot be based on configurations that include valence particles only and imply particle-hole excitations through the* $N = 50$ *shell gap. As a consequence the excitation energy of such state (and of states of higher spin) is strongly sensitive to the shell gap value.*

^{81}Ga is the most exotic $N = 50$ isotone whose spectroscopy is presently accessible up to particle-hole states across $N = 50$. However, spectroscopic data for this nucleus are greatly inconsistent. A first study with multi-nucleon transfer reactions performed at LNL suggested that the $13/2^-$ and $15/2^-$ states are at around 2.5 MeV, significantly lower than in ^{83}As [8]. Such result allowed a determination of the $N = 50$ energy gap of 4.7 (3) MeV at $Z = 28$. A more recent study performed with fusion-fission reactions at AGATA-VAMOS at GANIL [11] could not identify the transitions reported in Ref. [8], but observed other γ rays, interpreted as an yrast cascade, placing the $13/2^-$ and $15/2^-$ states at around 3 MeV of excitation energy. Such value is sensibly larger and would indicate a sort of stabilization of the spectroscopic $N = 50$ gap, more in line with mass measurements. However, ^{81}Ga was also populated from ^{81}Zn β decay in a recent experiment at ISOLDE [12]. While two of the γ transitions observed are in common with the fusion-fission studies, 1340 and 611 keV, their low $\log(ft)$ (6-7) is at odd with the tentative low-spin assignments proposed in Ref. [11]. In fact, the $5/2^+$ (or even $1/2^+$) decaying ground state of the parent ^{81}Zn, can populate spins up to $7/2^-$ only by first-forbidden transitions. A population of a $9/2^-$ level requires a unique first-forbidden transition ($\log(ft)$ 8-9 in this region), incompatible with the measured direct β feeding. A $11/2^-$ state also is ruled out for the same reason. Therefore p-h states cannot be clearly identified based on the GANIL data.

In summary, these recent data are in contrast with each other. Consequently, information on the location of the $13/2^-$ and $15/2^-$ states, and so on the spectroscopic gap below Z=32, is still missing. To clarify this situation we propose here to perform a Coulomb excitation measurement on ^{81}Ga at HIE-ISOLDE. The high intensity of the secondary beam (see the experimental description for details) will allow to unambiguously assign spin and parity to the first excited states, and to measure their B(E2) value, confirming or not their nature as core-coupled levels. As a result of such Coulomb excitation experiment, two scenarios are possible:

1. The Coulomb excitation results will confirm the spin assignments from [11] for the low-lying (at least for the $7/2^-$, $9/2^-$), thus also corroborating the energy measurement of the particle hole state. This will point to a smaller reduction of the $N = 50$ gap from ^{83}As to ^{81}Ga the previously thought, in line with mass measurement showing a re-increase of the gap towards the Z=30 ^{80}Zn nucleus. This will also mean that the decay experiment at ISOLDE measured β feeding wrong by orders of magnitude, mistaking unique first-forbidden transitions by first-forbidden ones. Considering the high statistics of the decay experiment, such an error could mean that a long-living isomeric state exists in ^{81}Zn or in ^{81}Ga, altering the observed β feedings and hence $\log(ft)$ values.
2. The Coulomb excitation results will not confirm the spin assignments from [11]: if the previous assignments from the work in Ref. [8] are confirmed, the spectroscopic $N = 50$ gap in ^{81}Ga should be around 400-500 keV lower, somehow at variance with the re-increase in ^{80}Zn shown by mass measurements. It would be also surprising that the fusion-fission mechanism used at GANIL does not prominently populate yrast states, signaling a change in the reaction mechanism when approaching ^{78}Ni.

2 Experiment

We ask for ^{81}Ga beam of 380 MeV energy (4.6 MeV/A) and 1.9×10^5 pps intensity from the CERN-ISOLDE facility. 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 7.5×10^3 pps. The beam energy is chosen to fulfill Cline's safe distance criterion [13]. The projectile nuclei will be scattered on a 4 mg/cm2 thick ^{206}Pb target. The γ-rays depopulating Coulomb excited states in the ^{81}Ga and ^{206}Pb isotopes will be detected in coincidence with scattered projectile and recoil nuclei, by the MINIBALL spectrometer [14], which consists of 8 clusters of HPGe detectors. For the detection of the scattered projectiles, we propose to use an annular double-sided silicon strip detector (DSSSD) placed at forward angles and covering an angular range from 16° to 53° in the Laboratory System. This allows for large angular coverage in the Centre of Mass system ($22^\circ \leq \theta_{CM} \leq 78^\circ$) by detecting either the scattered projectiles or the recoiling target nuclei. $9/2^-$ state in ^{81}Ga is expected to be a coupling of the unpaired proton in $1f_{5/2}$ to the 2^+ state of the even-even ^{80}Zn core [15]. Therefore, the rate estimation for the transition $9/2^-\rightarrow5/2^-$ in ^{81}Ga is based on the measured quadrupole transition probability of ^{80}Zn nucleus, B(E2:$2^+\rightarrow0^+$)= 730 e^{2}fm^4 [16]. For the transition $7/2^-\rightarrow5/2^-$ the B(E2) value is considered to be a factor of 4 less compared to the one of the transition $9/2^-\rightarrow5/2^-$. The expected γ-ray yields following the Coulomb excitation of ^{81}Ga have been calculated using the GOSIA code [17]. We expect to collect approximately 200 counts / shift in ($9/2^-$, E=1235 keV) → ($5/2^-$, E = 0 keV) and 30 counts/shift in ($7/2^-$, E=1464 keV) → ($5/2^-$, E = 0 keV), assuming the spin and parity assignments proposed in [8].

Summary of requested shifts: 12 shifts for ^{81}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 + only CD	☒ 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 MINIBALL + only CD 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]	^{206}Pb		
Beam particle type (e, p, ions, etc)	ions		
Beam intensity	1.9×10^5 pps		
Beam energy	380 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]