EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Search for the 0_2^+ state in ^{80}Ge from isomerically purified ^{80}Ga states

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L.M. Fraile[1], J. Benito[1], J.A. Briz[1], M. Llanos[1], J.R. Murias[1], V. Sánchez-Tembleque[1], J.M. Udías[1], K. Chrysalidis[2], V. Fedosseev[2], R. Heinke[2], R. Lică[2], B. Marsh[2], B. Olaizola[2], S. Pascu[2], B. Reich[2], S. Rothe[2], K. Wendt[3], F. Weber[3], S. Sekal[4], J. Jolie[5], U. Köster[6], K.Y. Hee[6], M.J.G. Borge[7], O. Tengblad[7], W.B. Walters[8], A. Briscoe[9,10], A. Illana-Sison[9,10], A. Montes Plaza[9,10], J. Ojala[9,10], J. Pakarinen[9,10], A. Algora[11], E. Nácher[11], J. Carroll[12], C.J. Chiara[12] (for the IDS Collaboration)

[1] *Grupo de Física Nuclear & IPARCOS, Universidad Complutense de Madrid, E-28040, Spain*
[2] *CERN, CH-1211 Geneva 23, Switzerland*
[3] *Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[4] *LSNIRM, USTHB, BP 32 El-Alia, 16011 Bab Ezzouar Alger, Algeria*
[5] *Institut für Kernphysik, Köln, Germany*
[6] *Institut Laue-Langevin, Grenoble, France*
[7] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[8] *Department of Chemistry and Biochemistry, University of Maryland, Maryland 20742, USA*
[9] *University of Jyväskylä, Department of Physics, PO Box 35, FI-40014, Jyväskylä, Finland*
[10] *Helsinki Institute of Physics, University of Helsinki, PO Box 64, FI-00014, Helsinki, Finland*
[11] *Instituto de Física Corpuscular, CSIC - Universidad de Valencia, E-46071 Valencia, Spain*
[12] *U.S. Army Research Laboratory, Adelphi, Maryland 20783, USA*

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Spokesperson: Luis Mario Fraile [lmfraile@ucm.es]
Contact person: Razvan Lică [Razvan.Lica@cern.ch]

Abstract: We propose to investigate the structure of ^{80}Ge populated separately in the β decay of the isomerically purified ^{80}Ga 6^- ground state and the ^{80}Ga 3^- long-lived isomer. The isomer separation will be achieved using the PI-LIST ion source. The experiment will allow to study independently the β decay of both isomers, measure their β-decay halflives and search for the 0_2^+ state in ^{80}Ge. The presence of such state is a signature of shape coexistence, but it has not been located to date.

Requested shifts: 12 shifts (split into 1 run over 1 year)

1 Introduction

The structure of ^{80}Ge has been subject of recent controversy due to the presence of a very low-lying 0_2^+ intruder state, initially reported at 639 keV [Got16], but later dismissed in experiments at ISOLDE [Sek21] and TRIUMF [Gar20]. The 0_2^+ state was argued as a signature of shape coexistence at low energy for this nucleus ^{80}Ge, in contradiction with the systematics of the Ge isotopes and $N = 48$ isotones. Large-scale shell-model calculations predict the 0_2^+ well above 1 MeV [Sek21, Gar20], while recent IBM calculations [Zha18] place it at low energies. The 0_2^+ is yet to be found experimentally.
Here we propose to profit from the new development of the PI-LIST to separately ionize ^{80}Ga 6^- ground state and the ^{80}Ga 3^- isomer to study their β decay. The selective β decay will serve to disentangle the ^{80}Ge structure populated in each of the decays, measure the β-decay lifetimes of the 3^- and 6^- states in ^{80}Ga and search for the 0_2^+ state.

2 Physics outline

The region of the nuclear chart around ^{78}Ni, with $Z = 28$ and $N = 50$, is subject of interest not only for nuclear structure reasons, but also due to the impact of nuclear properties in astrophysical scenarios. Being located far from stability, the expected doubly-magic nature of ^{78}Ni, arising from robust $Z = 28$ and $N = 50$ shell gaps, could only be confirmed recently by experiment [Tan19]. In contrast, in the same work, deformed states at low excitation energy were found, highlighting the appearance of collective effects even at the double shell closure.
The competition and coexistence at low energy of the configurations arising from the standard shell-model orbitals and those originating from excitations across shell gaps is a common feature across the nuclide chart, but seems to be enhanced around shell and sub-shell closures. In even-even nuclei one of the signatures of shape coexistence is the occurrence of 0^+ states at a low excitation energy from the 0^+ ground states. The energy required to promote a pair of nucleons across the shell gap is balanced by correlations among nucleons, which makes the appearance of such low-lying states possible. The intruder configurations may exhibit different collective properties than the standard ones, which then lead to different intrinsic shapes. Depending on the degree of mixing the 0^+ states may be connected by intense monopole E0 transitions, which can be measured experimentally.
Germanium isotopes ($Z = 32$) have four protons in the pf shell above the $Z = 28$ shell closure and can be treated rather precisely within the shell model. They may reveal simple excitation modes that illustrate the competition of single-particle and collective behaviours. The structural changes along the Ge isotopic chain above $N = 40$ are underlined by the existence of low-lying excited 0^+ states [Has07]. A peculiar case is ^{72}Ge with N = 40, where the 0_2^+ is the first-excited state, located below the first 2^+ level, the latter being interpreted as a member of a rotational band built on the low-lying 0^+ state [Pie79]. While a spherical shape for the 0_2^+ state in ^{72}Ge is proposed in [For16], triaxially-deformed configurations for both the 0_1^+ and 0_2^+ states have also been suggested [Aya16]. The excitation energy of the second 0^+ is much higher in other Ge isotopes (see Fig. 1),

both above and below N = 40, and including the N = 50 nucleus ^{82}Ge. For heavier Ge isotopes the investigation of the magicity of the N = 50 neutron number far from stability has revealed the persistence of this gap towards Ni ($Z = 28$) with an observed minimum at $Z = 32$ that can be associated with a maximum of collectivity [Hak08]. For $N = 48$ 0_2^+ states have been found experimentally for $Z \geq 32$, and they are systematically located above 1.5 MeV excitation. The systematics of low lying states in Ge isotopes and $N = 48$ isotones is shown in Fig. 1, taken from [Sek21]. A very low-lying 0_2^+ state in ^{80}Ge cannot be expected based on the systematics.

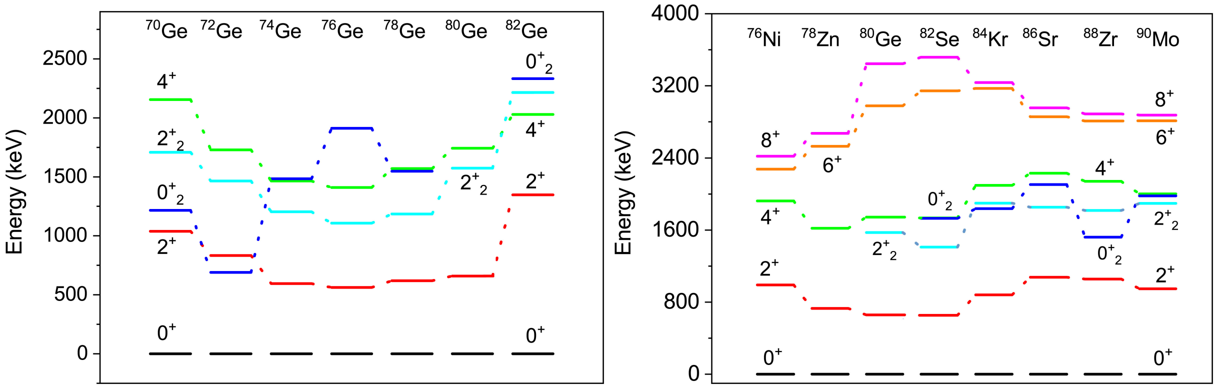

Figure 1: Level systematics for Ge $Z = 32$ isotopes and $N = 48$ isotones using published energy values [ENSDF]. The 0_2^+ in ^{80}Ge has not been experimentally found yet. Taken from [Sek21].

3 Goals and proposed measurement

We propose to investigate the structure of ^{80}Ge populated independently in the β decay of the isomerically purified ^{80}Ga 6^- ground state and the ^{80}Ga 3^- long-lived isomer. The low-lying ^{80}Ge states were first observed in the β-n decay of ^{81}Ga and β-decay of ^{80}Ga [Hof81], where the existence of two β-decaying states in ^{80}Ga based on the quasi-degeneracy of the $p_{1/2}$ and $g_{9/2}$ configurations was already suggested. This was later confirmed by colinear laser spectroscopy [Che10]. Another experiment [Ver13, Tas11] tried to assign γ-rays to the decay of the two isomers, with 1.9(1) and 1.3(2) s half-lives, on the basis of the time dependence of the γ-rays from the decay of ^{80}Ga source with an admixture of both isomers. These β-decay studies suffered from the ambiguity of the β-decaying states in ^{80}Ga, which was later clarified as a 6^- ground state and a 3^- β-decaying isomer at only 22.4 keV [Lic11]. Deep-inelastic reactions have been performed as well [Mak99, Pod04, Fau07, For18], extending the yrast band up to 10^+ and identifying many previously unobserved transitions.
The overall consistent picture of ^{80}Ge was disrupted by the report of the experimental finding of a low-lying 639(1) keV 0_2^+ state in ^{80}Ge, below the previously-measured 2^+ state [Got16]. The measurement used γ and conversion electron spectroscopy to study ^{80}Ge, which was populated in the β decay of a ^{80}Ga mixed source at the ALTO facility. The placement of the 0_2^+ state in ^{80}Ge at 639-keV was based on the observation of a

new electron conversion line at 628(1) keV in coincidence with a new weak γ transition at 1764(1) keV. The low-lying level was interpreted as a two neutron excitation across N = 50 and as evidence for low-lying shape coexistence in ^{80}Ge.
Two recent experimental reports contradict this finding. García *et al.* [Gar20] conducted an experiment with enhanced statistics using a mixed ^{80}Ga source at TRIUMF and no evidence was found in the conversion-electron spectroscopy for the 639-keV 0_2^+ to 0_1^+ transition. Moreover, several peaks in the 1764-keV energy region were identified in the coincidence gates set on the γ rays that depopulate the 5^-, 6^+, and 8^+ levels. A similar conclusion is reached in [Sek21], where the β-decay of a purified ^{80}Ga 3^- source was used to enhance the population of low-spin states in ^{80}Ge, including any excited 0^+ level, and $\gamma\gamma$ coincidences used to investigate it. In [Sek21] the 1764-keV γ ray is found in coincidence with strong transitions in ^{80}Ge, thus not feeding the proposed 639-keV 0_2^+. No connecting transitions from previously-known levels to the 639-keV and 2403-keV 2_3^+ states could be identified either. No conversion electron measurement could be performed in this case.
While shell model calculations for Ge isotopes discussed in both works [Gar20, Sek21] succeed to explain most of the experimental levels, they fail to reproduce the presence of a 0_2^+ state below ~1200 keV in ^{80}Ge. IBM calculations also place the second 0^+ level at high energy, with the exception of recent calculations [Zha18], which report the state at very low energy of the order of 650 keV, close to the 2_1^+ state.
The location 0_2^+ state remains an open experimental question.
With the present proposal we aim at understanding the β-decay of ^{80}Ga to excited states in ^{80}Ge by starting from pure, isomerically separated, states in ^{80}Ga. The independent decay of the 6^- ground state and 3^- 22.4-keV isomer will reveal the decay pattern to excited states in ^{80}Ge and will allow to unambigously obtain the apparent beta feeding and $\log ft$ values. We will be able to measure independently the β-decay halflives for both states. We will also search for the elusive 0_2^+ state, which will be preferentially fed in the β decay of the ^{80}Ga 3^- isomer. We will use γ spectroscopy and $\gamma\gamma$ coincidences to search for feeding and de-excting transitions from the 0_2^+ and conversion-electron spectroscopy to look for the internal conversion from the E0 transition to the ground state. Depending on the actual excitation energy and the $\rho^2(E0; 0_2^+ \to 0_1^+)$ transition strength, γ transitions to other excited states may be dominant.

4 Experimental details

The resonance ionization laser ion source is one of the ISOLDE flagships and has been extensively used in the last decades [Fed17]. It provides enhanced ionization selectivity, which is key in many precision experiments. Isomer selectivity has been succesfully applied with RILIS, and in-source spectroscopy in combination with decay spectroscopy setups, such as the IDS, is used in several regions of the nuclide chart. The main limitation for in-source isomer separation and spectroscopy arises from the Doppler broadening in the ion source hot cavity, which limits the available resolution. The resolution required in the case of ^{80}Ga can be estimated from Fig. 2, taken from [Che10].
To overcome the limitation, a Perpendicularly Illuminated Laser Ion Source and Trap,

PI-LIST has been proposed [Hei19], based on the ISOLDE LIST, with the novelty of enabling perpendicular laser irradiation inside the LIST RFQ structure, overcoming the Doppler broadening limitations in the hot atomic vapor [Hei17]. The price to pay for the increased resolution is a severe decrease in the ionization efficiency in the range of 100 to 1000, depending on the actual conditions. The PI-LIST has not been used online at ISOLDE and its feasibility still requires full evaluation [Hei19].

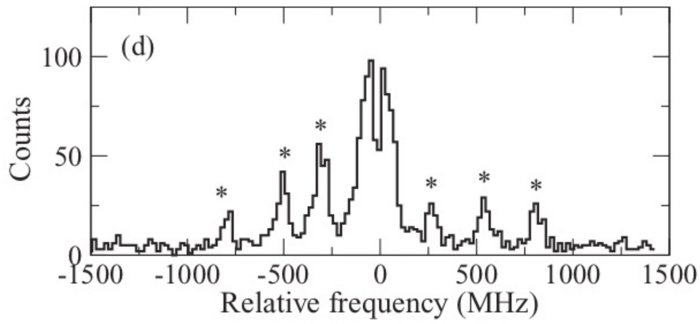

Figure 2: Optical scan taken from [Che10] where the resolved hyperfine structure of ^{80}Ga is revealed, with six peaks marked with an asterisk. One of the structures was assigned total spin 3 from the analysis, while the other was expected to have spin 6 based on shell-model calculations. The clarification of the ordering and spin of the states came from decay spectroscopy [Lic11].

We will use the ISOLDE Decay Station, equipped with 4 HPGe clover detectors, with 3.5% photopeak efficiency at 1.3 MeV, a conversion electron spectroscopy setup based on a thick annularly-segmented SPEDE Si detector and a forward beta detector. A thickness 1 mm of the SPEDE detector translates into an efficiency of about 12% for electrons up to 800 keV, but then the efficiency decreases significantly to about 2% at 1.5 MeV. For higher energies a thicker detector or an absorber needs to be used. The Ga ions will be implanted onto a mylar tape inside the IDS chamber, and the daughter activity will be removed in cycles optimized for the decay half-lives. There is the possibility of a second measurement station below the implantation one, which could be employed for parallel excited-state lifetime measurements using fast scintillators. These will be relevant for higher-spin states populated in the β decay of the 6^- level.

5 Yields and beam time request

We request the use of a UC_2/graphite target and the PI-LIST. Table 1 compiles the basic information. Starting from a yield of 3.0E5 ions/μC with surface ionization for a combination of both isomers, and an enhancement factor of 30 according to [Koe02], the estimated yield with RILIS per isomer is 4.5E6 ions/μC. According to the existing data it will not be needed to strecth the PI-LIST to its maximum resolution (about 100MHz), but rather a broader linewidth would be sufficient for isomer separation, but in any case a conservative efficiency of 1 per mille has been considered for the PI-LIST. Under these conditions, once corrected for the duty cycle due to the available proton pulses and tape movement and the ^{80}Ga 3^- or 6^- state lifetimes, it will be possible to accumulate a billion ^{80}Ga ions in the 3^- state in 7 shifts, to enhance the search for the 0_2^+ state via weak gamma coincidences and conversion electrons. For the 6^- state in ^{80}Ga, 3 shifts will be sufficient to gather just below 400 million ions. One additional shift is requested to measure the β-decay halflives. Addionally one shift will be required to tune the PI-LIST.

Table 1: Summary of estimated implanted ions.

^{80}Ga state	$T_{1/2}$ (s)	Yield (ions/μC)	p current (μA)	trans. (%)	PI-LIST eff. (%)	ions /s	duty cycle (%)	ions /hour	ions /shift
3^-	1.3	4.5E6	1.7	90	0.1	6.9E3	74	1.8E7	1.5E8
6^-	1.9	4.5E6					65	1.6E7	1.3E8

Summary of requested shifts: We request a total of 12 shifts, 1 for optimization of the PI-LIST, 7 shifts for the ^{80}Ga in its 3^- state, 3 shifts for the ^{80}Ga in its 6^- state and 1 shift specifically tailored to measure β-decay half-lives.

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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
IDS	☒ Existing	☒ To be used without any modification ☐ To be modified by update of the tape station
[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	high vacuum 10^{-6} mbar		
Temperature	LN_2 77 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]			
Beam particle type (e, p, ions, etc)	Ga		
Beam intensity	1100 s^{-1}		

Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity	10 kBq		
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]