EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Shell evolution in Ge isotopes with N≥50 investigated via fast-timing methods.

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Abstract: Neutron-rich nuclei around the double-magic ^{78}Ni nucleus are expected to show rapid structure changes from spherical shape to well-deformed nuclei. In particular, nuclei around N=50 and heavier than Ni, such as neutron-rich Ge isotopes, are predicted to exhibit coexistence between spherical and γ-soft shapes. Additionally, triaxial degrees of freedom may play an important role. Nevertheless, the available experimental information is still scarce. Profiting from the beam purity and high production yields achieved at ISOLDE we propose to investigate the neutron-rich $^{83-86}$Ge isotopes populated by β-decay and β-delayed neutron emission of neutron-rich Ga, in order to expand the level schemes and investigate sub-nanosecond lifetimes of excited states. In addition, we propose to explore the production of ^{87}Ga.

Requested shifts: 22 shifts, (split into 1 run over 1 year)
Installation: ISOLDE Decay station

1 Physics case

Neutron-rich nuclei in the vicinity of ^{78}Ni make it possible to investigate the evolution of single-particle states far off stability when few protons and neutrons are added to a *doubly magic* core. The study of isotopes in the region may also provide information on how collectivity develops in the valence space outside ^{78}Ni when just a bunch of nucleons are added. In this proposal we concentrate on the β decay of neutron-rich Gallium isotopes populating states in Germanium isotopes (Z=32) with neutrons above the N=50 neutron shell closure, and specifically on the odd ^{83}Ge and ^{85}Ge, and the even-even ^{84}Ge and ^{86}Ge. The β-decay of neutron-rich Ga via Gamow-Teller (GT) transitions involves the decay of neutrons with dominant configurations in the N=50 neutron shell, and thus requires cross-shell transformations that populate states at high excitation energies. The enhanced GT strength at such energies favours β-delayed one-neutron and two-neutron emission, as observed in several of these neutron-rich Ga isotopes [1, 2], the population proceeding also via competing first-forbidden transitions. The decay pattern leads to the population of selected states in Ge. The β-decay of heavy Ga isotopes has also been discussed in the context of r-process nucleosynthesis since the decay branching ratios and the population of excited states via direct β, β-delayed one-neutron and two-neutron emission branches are important to evaluate theoretical models. These may impact the description of the decay properties in the context of multi-neutron emission, which in turn could influence isotopic abundances from the r-process.

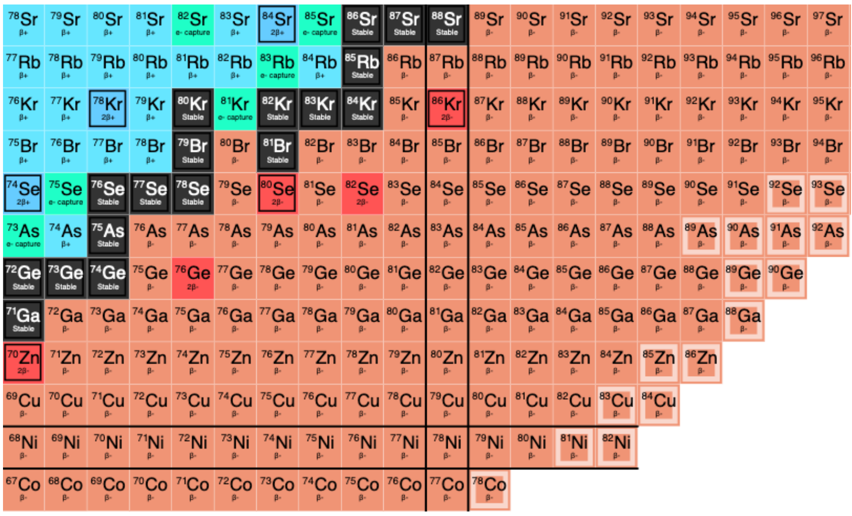

Figure 1: Chart of nuclides highlighting the region of interest.

With Z=32, the neutron-rich Germanium isotopes have a proton configuration with four particles occupying the *fp* shell. Shell-model calculations indicate that protons mostly fill the $0f_{7/2}$ orbital up to Z=28 and occupy the $0f_{5/2}$ orbital with a limited occupation of the $1p_{3/2}$ orbit [3]. Protons play hardly any role in the possible configurations and on the excitations of heavy even-even Ge isotopes, which are therefore mostly due to the neutron orbitals. Nonetheless this situation may change for heavy neutron-rich isotopes such as ^{86}Ge. Neutrons fill the N=50 shell with the *fp* and the $0g_{9/2}$ orbitals,

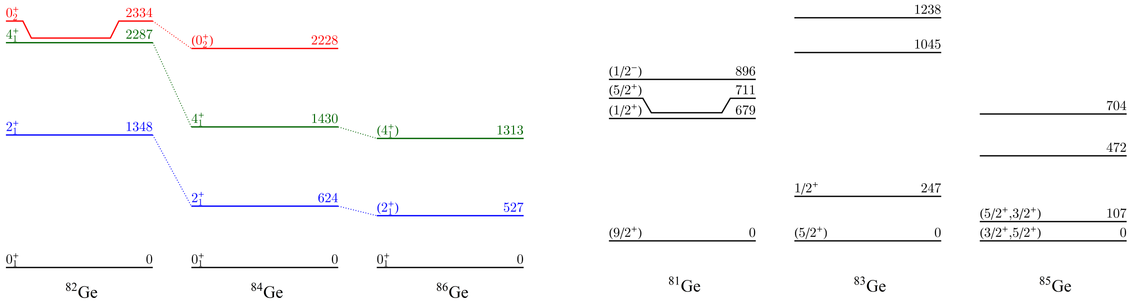

Figure 2: Low-lying states in even-even ^{82}Ge, ^{84}Ge and ^{86}Ge (left) and odd mass ^{83}Ge and ^{85}Ge (right). See text for details.

the extra neutrons having dominant $1d_{5/2}$ configuration. Thus, excitations across N=50 are relevant to understand the structure of neutron-rich nuclei. Theoretical calculations show a rapid change in the nuclear structure for the neutron-rich Ge [4]. The coexistence between prolate, oblate, and as well as between spherical and γ-soft shapes, is predicted. In particular, shell model and beyond mean-field calculations predict the development of triaxiality in the region above N=50 [3], being the ^{86}Ge where the maximum of triaxiality is expected. New information on the n-rich Germanium isotopes level schemes, as well as on lifetime measurements is required to confirm this interpretation.

The aim of the proposal is two-fold: on the one hand extending the level schemes of neutron-rich Ge isotopes populated in β-decay and β-delayed emission branches of Ga, and on the other hand providing the lifetime measurements of excited states in these exotic nuclei.

1.1 Even-even Ge isotopes

The systematics of low-lying states in even-even Ge is depicted on the left-hand side of Figure 2 for ^{82}Ge [5], ^{84}Ge [6, 7, 8, 2] and ^{86}Ge [2], illustrating the position of the first-excited 2_1^+ states, the 4_1^+ states and the potential location of the 0_2^+ level, which is expected to come down in energy when neutrons are added.

Regarding the structure of ^{84}Ge (N=52), information on excited levels exists [6, 7, 8], complemented by a recent study [2] that reports its population in the β-decay of ^{84}Ge, ^{85}Ge and ^{86}Ge via direct β, β-n and β-2n decay branches, respectively. States in ^{84}Ge are identified up to 3.5 MeV, while the Q_β is 14 MeV and the Q_{β_n} 10 MeV [9].
There is ample margin for the extension of the level scheme, as recently illustrated by a yield test of neutron rich Ga beams at ISOLDE employing the IDS setup [10], where a couple of new states could already be tentatively proposed in just about 15 minutes of beam time.
Regarding the low-lying states, the 2_1^+ lifetime has been measured to be τ = 14 ps [11], yielding a very large B(E2; $0^+ \rightarrow 2^+$) rate of 28 W.u., much higher than the measured value of 10 W.u. ^{82}Ge for [12], corresponding to a mean life of about 40 ps. The state is fed both in β and β-n (see Table 1) and populated by γ transitions, enabling fast-

timing measurements employing $\gamma\gamma$(t) and $\beta\gamma\gamma$(t) coincidences, although at the limit of the fast-timing centroid-shift method for this nucleus.
The expected excited states that will be β-fed in ^{84}Ge also include the second 0_2^+ level, which is calculated to be around 2 MeV in excitation. A branch to the 2_1^+ level is expected [2], similar to ^{82}Ge [5]. Owing to the different configuration compared to the ground state band a relatively long lifetime could be expected, which maybe within reach for fast-timing measurements.

With respect to the ^{86}Ge structure, the available information is very scarce [2], with only a couple of excited states proposed. The direct β-decay branch from ^{86}Ga amounts to 26(3)%, which should make it possible to populate the nucleus with sufficient statistics, being Q_β=15.6 MeV from systematics. A strong β-delayed one-neutron emission branch from ^{87}Ga should also exist, although the production ^{87}Ga is quite limited. The high production at ISOLDE offers a unique possibility to build the decay scheme. There is a possibility to feed the expected 0_2^+ level with sufficient statistics for a direct lifetime measurement in double $\beta\gamma$(t) coincidences, depending on the population. There is no prior experimental B(E2; $2^+ \rightarrow 0^+$) measurement for this nucleus. Using the value of 28 W.u. from ^{84}Ge mentioned above, a lifetime of 32 ps for the 2^+ is obtained, but for a measurement γ feeding to the level will be required, which has not been observed yet.
For the interpretation of the structures, in addition to the interacting shell model with state-of-the-art interactions for the region, we will rely on mean field methods. Hartree-Fock-Bogoliubov (HFB) calculations will provide the ground-state wave functions and single-particle energies in the mean field, and the projected generator coordinate method will be used to restore broken symmetries in the HFB wave function and account for correlations beyond the mean field. This methodology has been recently applied to the region using the TAURUS suite [13, 14]. The calculations were able to provide collective wave functions reflecting the configuration mixing as well as B(E2) rates and spectroscopic quadrupole moments.

1.2 Odd-even Ge isotopes

In a simplified shell-model interpretation, the low-lying levels in the odd-A Ge isotopes are identified as single-neutron quasi-particles coupled to the spherical ground state in the even-even nuclei. A plot of the systematic trends for ^{83}Ge (N=51) and ^{85}Ge (N=53) is shown in Fig. 2, together with ^{81}Ge, which is already below the neutron shell gap.
The ^{83}Ge isotope is strongly populated both in the direct β-decay of ^{83}Ga [15] and in the βn decay of ^{84}Ga [15, 2]. With the much-increased yield, the proposed experiment offers an excellent opportunity to expand the level scheme and understand the nature of the low-lying states. Fast-timing measurements will reveal the lifetime of the first-excited state, with proposed $1/2^+$ spin-parity, which should then de-excite to the $5/2^+$ ground state via an E2 transition. Using the 12 W.u. rate from the ^{82}Ga core a lifetime of 3.5 ns will be expected, while for a 28 W.u. rate as in ^{84}Ga, a shorter value will be obtained, thus providing information on the onset of deformation and the nature of the involved states. Such measurements will be feasible using double $\beta\gamma$(t) coincidences. Lifetimes of higher-lying should be also accessible with our technique.

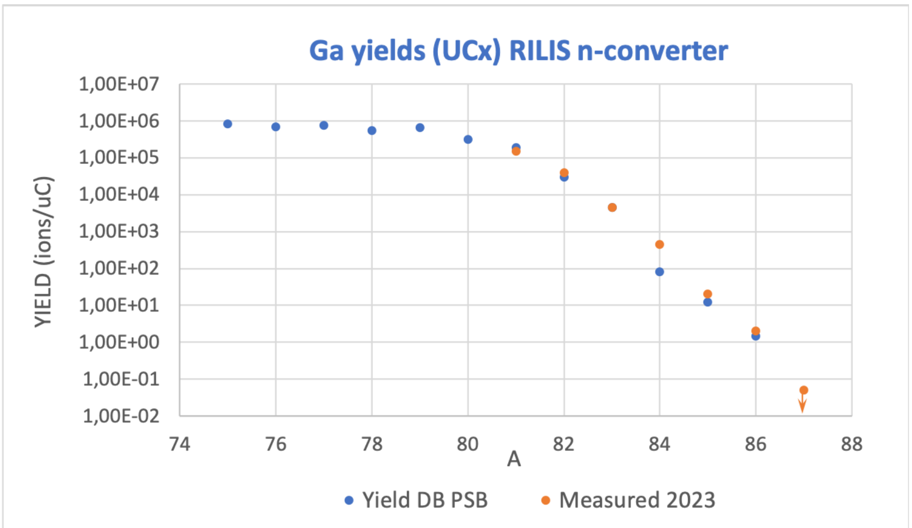

Figure 3: Experimental ISOLDE yields for Ga using PSB 1.4 GeV protons on converter

The excited structure of ^{85}Ge has been measured in [2], but the spin-parity of the low-lying states is not known. With our measurements we will be able to expand the level scheme and measure the lifetimes of the low-lying 108- and 207-keV states [2] to try to identify their nature.
A production test on the very exotic ^{87}Ga is also proposed to investigate the potential population of excited states in ^{86}Ga and ^{87}Ga.

2 Experimental details

Neutron-deficient gallium beams were produced in the past with relatively high yields [16] using UC_x targets fitted with a neutron converter and selective ionization using the ISOLDE RILIS [17], as shown in Figure 3. In a recent beam test, we were able to verify the production yields and perform test measurements at the ISOLDE Decay Station (IDS) [18]. The new yields are consistent with the previous measured ones, as shown in Fig. 3.

Hence, we propose to use the same type of primary target, UC_x, coupled to a proton-to-neutron converter and with a proton beam intensity of 2 μA. The neutron-rich gallium beams will be isomerically selected by the ISOLDE-RILIS system [17], and transported to the ISOLDE Decay Station (IDS). Isobaric contamination from surface-ionized Rb isotopes is expected for several masses. For the A=86 case, ^{86}Rb with $T_{1/2}$=18.7 days will be produced [16], leading to a main γ decay transition with an absolute intensity of 8%. The contaminant can be reduced by making use of the IDS tape station where the ions are implanted. In the A=84 mass the presence of ^{m84}Rb has been observed, but its impact can be mimimized using coincidences with the β detectors. Other observed contaminants in the test beam time were due to the internal transition of isomeric states in Sr isotopes, but those can also be gated out during the analysis. Nevertheless, we will collect data using the laser-off mode to address the impact of surface-ionized isobaric contamination for each individual case.

The proposed β-decay experiment will make use of the IDS setup consisting of the tape station equipped with a fast plastic scintillator close to the implantation point having almost 50% total efficiency for β detection, and about 25% beta efficiency for fast timing measurements. It will be coupled to a combination of a minimum of eight HPGe clover-type detectors and two $LaBr_3$(Ce) detectors to register β-delayed γ-rays. The expected total photopeak efficiency of the Clover detectors will be around 8% at 1.0 MeV, and 1% at 0.8 MeV for the $LaBr_3$(Ce) detectors. The available intensity of the Ga beams will allow us to perform γ-γ coincidence studies to define the transition sequences and establish the level schemes. As discussed above, the use of fast $LaBr_3$(Ce) detectors will give us access to lifetime information down to the tens of picoseconds range for states in the daughter nuclei, and therefore on the reduced transition probabilities.

Isotope (J^π)	$T_{1/2}$ [ms]	Yield [ions/μC]	Ions/s	Decay mode	br(%)	β_{Gated}-γ_{Ge} [Counts/shift]	β-γ_{LaBr}-γ_{Ge} [Counts/shift]	Shifts
^{83}Ga ($5/2^-$)	308(1)	4500	7700	β	37(3)	$6.3{\cdot}10^5$	525	1.5
				β-n	63(3)	-	-	
^{84}Ga (0^-)	95(2)	450	770	β	61(2)	$6.3{\cdot}10^4$	155	3.5
				β-n	37(2)	-	340	
^{85}Ga ($5/2^-$)	92(4)	20	34	β	22(3)	$2.8{\cdot}10^3$	65	6
				β-n	76(3)	-	70	
^{86}Ga (?)	43(2)	2	3.4	β	26(3)	$2.8{\cdot}10^2$	-	8
				β-n	60(3)	-	-	
^{87}Ga ($5/2^-$?)	29(4)	$\leq$0.05	$\leq$0.1	β-n	?	-	-	1

Table 1: Summary of the expected yields and count rates at the IDS. The β_{Gated}-γ_{Ge} column represents the counts rates per shift in a 1-MeV γ-ray beta-gated line assuming an absolute intensity of 10% in the decay. For the most relevant transitions, the depopulating γ-rays from the 2_1^+ for the even-even case and the fist low-lying state in the odd-even cases the estimates are used for β-γ_{LaBr}-γ_{Ge} coincidences.

The expected yields, the number of counts per shift, and the number of shifts required for each measurement are shown in Table 1. The count rates have been estimated assuming a 90% transmission efficiency to IDS and an average 1.8 μA proton intensity. For the coincidence estimates the expected feeding to the first-excited state in each of the $^{83-86}$Ge nuclei have been used as reference together with the detector efficiencies.

In summary, we aim to expand the level schemes of $^{83-86}$Ge isotopes populated in β-decay and β-delayed neutron emission branches from neutron-rich Ga and perform a systematic investigation of subnanosecond lifetimes of low-lying excited states.

Summary of requested shifts: We request 19 shifts in total for the $^{83-86}$Ga isotopes. In addition, 1 shift will be needed to explore the ^{87}Ga decay and 2 shifts are requested for fast-timing calibrations using online and offline sources of (^{138}Cs, ^{140}Ba, ^{88}Rb, and ^{24}Na), for a total of 22 shifts.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
Isolde Decay Station IDS	☒ To be used without any modification ☐ To be modified

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from <u>flexible or transported</u> equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			