EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Ground and isomeric state spins, moments and radii of Ge isotopes across the $N = 40$ subshell closure via laser spectroscopy at COLLAPS

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Abstract

We propose the application of high resolution collinear laser spectroscopy to the study of $^{65-76}$Ge ($N = 33$ to $N = 44$) isotopes, crossing the $N = 40$ subshell closure. The magnetic moments, electrostatic quadrupole moments and changes in mean square charge radii that will be obtained from these measurements will address a number of physics questions. The origins of shape coexistence, the extent and evolution of the $N = 40$ neutron subshell closure and the rare onset of inverted odd-even staggering in nuclear charge radii are simultaneously found to play a significant role in this region. The beam request in this proposal is only for a limited number of isotopes close to stability, which have their own physics interest but also serve as the basis for the studies of the very neutron rich isotopes addressed in the Letter of Intent for beam testing and development, submitted with this proposal. It is our aim to study a new region of shape coexistence that has just been identified in the $N = 48$ and 49 isotones.

Requested shifts: 11 shifts in one run.

1 Introduction

A long running programme of measurements at COLLAPS has addressed Ni isotopes and nuclei above it [1, 2, 3, 4]. This work has answered many questions on the strength and influence of the $N = 40$ subshell closure [5], the inversion of the proton $f_{5/2}$ and $p_{3/2}$ effective single particle orbitals [6, 7] and has additionally provided a wealth of magnetic moments and quadrupole moments as input for the ongoing development of state of the art large scale shell model calculations [8, 9]. Although much has been learned along the way, a number of new and intriguing questions have appeared in the course of this work. The charge radii of Zn and Ga have revealed an uncommon departure from the ubiquitous normal odd-even staggering in the region of $N = 40$. Such a departure has previously been observed in the neutron deficient isotopes of Kr, Sr and Rb also around $N = 40$ and was associated with the odd neutron driving the soft proton core into ridged deformation [10]. The absence of charge radii measurements of radioactive isotopes of Ge leaves open the question of whether this entire region is subject to this uncommon phenomenon or whether these occurrences are unconnected. It is perhaps an intriguing but as yet unexplained coincidence that this anomalous behaviour of the nuclear charge radii happens to coincide with a well know region of shape coexistence.

Additionally, the large isomer shift observed in ^{79}Zn has given strong indications for shape coexistence at rather low excitation energy (1 MeV) in this nucleus [11]. When taken in combination with the recent results from conversion electron spectroscopy on ^{80}Ge [12] this could be viewed as a previously unidentified region of shape coexistence in the vicinity of the supposedly doubly magic isotope ^{78}Ni ($N = 50$) , which is rather unexpected. Questions on the magicity of these exotic isotopes are raides by these findings. In addition we cannot yet tell if the regions around $N \approx 40$ and $N \approx 50$ are truly distinct or whether shape coexistence is present across this entire region of the nuclear landscape.

2 Physics Motivation

2.1 On the origins of the shape coexistence in the $Z \approx 34$, $N \approx 40$ mass region.

For the even N $^{70-76}$Ge isotopes the mean square quadrupole moment $\langle Q^2 \rangle$ of the first excited $I^\pi = 0^+$ state has been shown to systematically differ from that of the ground state (see Fig. 35 of Ref. [13]). This clear signature of shape coexistence has attracted two competing interpretations. Van den Berg et al. [14] concluded that the evolution of shapes for these states could be related to and described by the degree of mixing of the proton $(2p_{3/2})^4$ configuration with $(2p_{3/2})^2(1f_{5/2})^2$ in the respective states. In this analysis it was assumed that the neutron configuration was the same for both the ground state and the first excited $I^\pi = 0^+$ and deformation was generated by the pairwise excitation to the $1f_{5/2}$ proton. Conversely Becker et al. [15] concluded that it is in fact the relative population of the neutron $p_{1/2}$ and $g_{9/2}$ orbitals that is responsible for differences in deformation observed in this region. Although laser spectroscopy can not directly probe the excited $I^\pi = 0^+$ states referred to here, it can bring significant new information to the story of shape coexistence in this region. It is well known that a change in deformation must result in a change in charge radius via the expression

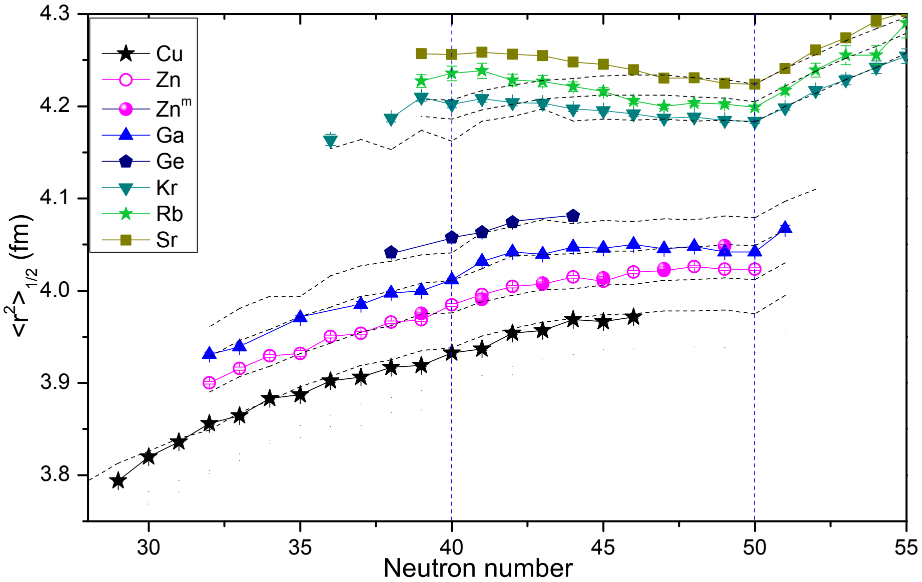


Figure 1: Root means square charge radii in the Ni region, including preliminary results of Zn isotopes [16], and published results [5, 17, 18].

for axially symmetric nuclei $\langle r_c^2\rangle = \langle r_c^2\rangle_0(1+\frac{5}{4\pi}\sum\langle\beta_i^2\rangle)$. In which $\langle r_c^2\rangle_0$ is the radius of the spherical nucleus of equal volume and β_i is the deformation parameter of order i. As can be seen from this expression the observable from laser spectroscopy $\langle r_c^2\rangle$ is directly related to $\langle\beta_i^2\rangle$ which in turn is connected to $\langle Q^2\rangle$. In combination with the spectroscopic quadrupole moments we will obtain from the hyperfine structure of the odd N Ge isotopes, the charge radii will allow the evaluation of $\langle Q^2\rangle - \langle Q\rangle^2$. For a “pure” single particle state this difference would be 0 and must be positive and increasing as the mixing between the two low lying shape coexistent states increases. As identified in Heyde and Wood [13] the even N $^{70-76}$Ge ground states should progress from weakly deformed to strongly mixed to strongly deformed with increasing neutron number. It is envisaged that the combinations of observables, including both moments and radii, available by collinear laser spectroscopy, will be able to provide a critical test of this picture.

In addition, a measurement of the isomer shift between the $I^\pi = 1/2^-$ and $I^\pi = 9/2^+$ states in ^{73}Ge will test the validity of the assumption that the changes in deformation are related to the relative occupancy of the neutron $p_{1/2}$ and $g_{9/2}$ orbits. Measurements of the spectroscopic quadrupole moments of the ^{65,75}Ge isotopes in combination with the observed isotope shifts in $^{65-76}$Ge will provide a firm and detailed basis for the evolution of deformation in the ground states and long lived isomers across this region of shape coexistence.

2.2 Evolution of $N = 40$ from a week subshell closure to a region of anomalously inverted odd-even staggering

Across the nuclear landscape one feature of all known charge radii measurements appears to persist with only a few special notable exceptions [10, 19, 20, 21]. This feature, the normal odd-even staggering (OES) of charge radii in which the odd-N isotope is found to have a smaller charge radius than the average of its two even neighbors was observed to be strongly inverted in the charge radii of Ga at $N = 41$ and significantly diminished at $N = 39$. A preliminary analysis of recent measurements of the Zn isotopic chain has indicated a weaker inversion of OES at $N = 41$ and a relatively normal OES at $N = 39$. Taken together with the charge radii of Cu [5] and the preliminary analysis of the first Ni data, this would suggest a progressively increasing departure from normal OES as one moves away from $Z = 28$.

When comparing to the charge radii of Kr, Rb and Sr it would appear that a region of significantly enhanced inverted OES may be located between these 2 regions. However the charge radii of the stable Ge isotopes [22] suggest that this effect diminishes between the above regions. It should be noted that the $N = 41$ isotope ^{73}Ge was only measured using muonic x-ray spectroscopy, which can be subject to large untreated model uncertainties. In the specific case of ^{73}Ge the uncertainty was simply assumed based on the uncertainties in the other isotopes and higher order moments were not considered as electron scattering data was not available. This treatment substantially differs from that of the even isotopes. Thus a consistent set of optical measurements across $N = 40$ is necessary to determine if the inverted OES continues or is limited to Zn and Ga. Once again the existence of data on $\langle Q^2 \rangle$ and the measurement of $\langle Q \rangle$ proposed here may well give significant new information on the origin of this atypical phenomenon.

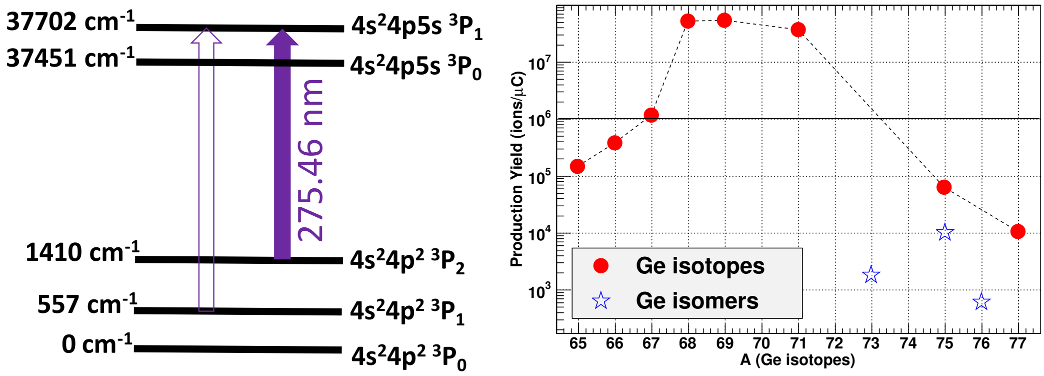
2.3 Shape coexistence in the region of $N = 50$

One of the key physics cases in this programme is measurement of the magnetic moment and isomer shift in ^{81}Ge. However, the measurement of neutron-rich Ge isotopes are suggested as a LOI as only very limited information is available on the production of Ge with a UCx target. Therefore, this physics case will be discussed in detail in the LOI, which will be submitted together with this proposal [23].

3 Experimental method

Here we propose a bunched beam, fluorescence detected collinear laser spectroscopy on atomic Ge using the COLLAPS setup. For details of the technique see early work [24]. The fast ion beam will be neutralized using a charge exchange cell filled with Potassium vapor in order to populate the atomic state, from which laser spectroscopy can be performed. The resulting fast atom beam will contain a mixture of atoms in various atomic states, and thus the full beam intensity is not available for any given atomic transition.

Simulations of the charge exchange process of Ge ions on K vapor have been performed using the model of Rapp and Francis [25, 26] and accounting for the redistribution of population during the 20 cm between the charge exchange cell and the optical detection region. It gives that the dominant contributions to the final population of states are the 557 cm^{-1} $4p^2\ ^3P_1$ metastable level with 17 % of the total population and the 1410 cm^{-1} $4p^2\ ^3P_2$ metastable level with 13 % of the total population. Based on the sensitivity to charge radii and quadrupole moments we conclude that the optimum transition for this system will be the 275.4588 nm $4p^2\ ^3P_2 \rightarrow 4p5s\ ^3P_1$, as shown in Figure 2a, which may be accessed by frequency doubling of our new Matisse cw dye laser, which has been just installed in the COLLAPS laser lab.



(a) (b)

Figure 2: (a) Transition to be used for the proposed experiment. (b) Production yield of Ge isotopes extrapolated yields based on the release systematics and in-target production calculated by the target group using a ZrO_2 target [27].

4 Beam time request

For production of the Ge isotopes relevant to this proposal we request a ZrO_2 target with a hot plasma ion source and an atomic Sulfur leak. Database yields along with extrapolated yields based on in-target production rates [27] and corresponding release systematics are presented in Table 1, and plotted in Figure 2b. Based on observed detection efficiencies for transitions of a similar strength and the calculated population of the lower state we conclude that our experimental detection efficiency will be in the region of 1 photon per 8000 ions generated by ISOLDE. Considering the ISOLDE yields presented in Table 1 and typical background rates of the order of 2000 photons/s, we request 11 shifts, as detailed in Table 1, to complete this first part of the Ge program.

For the isotopes with a high production yield larger than 10^5 ions/μC, we count 1 shift for each odd-mass isotope. The data taking rate is basically limited by the fact that the PMTs cannot accept an instantaneous rate of more than 10^7 Photons/s and by the requirement to obtain 3 independent measurements, each well calibrated to the reference isotope. For the even isotopes the scanning region required is some 5 times smaller and thus we estimate that all 6 isotopes may be measured and appropriately calibrated within a period of 3 shifts, including reference scans. It should be noted that the time does not scale directly with the scanning range due to the dominant influence of the time required

Table 1: Known information for neutron-rich $^{65-76}$Ge , as well as the extrapolated production yield from ZrO_2 target.

Isotopes	Spin	Half-life	μ (μ_N)	$Q_s(b)$	Yield/μC	Required shifts
^{65}Ge	$3/2^-$	30.9s			1.4× 10^5	1
^{67}Ge	$1/2^-$	18.9m			1.1× 10^6	1
^{69}Ge	$5/2^-$	39.1h	(+)0.735(7)	0.024(5)	5.0× 10^7	1
^{71}Ge	$1/2^-$	11.4d	+0.547(5)		3.4× 10^7	
^{71m}Ge	$9/2^+$	20.41ms	-1.0413(7)	0.34(5)		1
^{73}Ge	$9/2^+$	stable	-0.8794677(2)	-0.17(3)		
^{73m}Ge	$1/2^-$	499ms			1.8× 10^3	2.5
^{75g}Ge	$1/2^-$	82.78m	+0.510(5)		6.0× 10^4	
^{75m}Ge	$7/2^+$	47.7s			1.0× 10^4	1.5
$^{66-76}$Ge	0^+					
reference						3
Total						**11**
Stable beam						2

to change mass for calibration scans and reference scans. For ^{73}Ge, scanning time is determined by the production of the shorter half-life isomeric state. Here we have estimated the time required to observe the smallest component of this within full accumulated statistics at the 3 sigma level. As this component only gives the sign of the magnetic moment, once observed in the cumulative statistics the data can be separated to give better control of the systematics. But, for ^{73m}Ge with a 0.5 s half life, the extrapolation of release characteristics may be speculative. However the 1.5 additional shifts we estimate for the observation of this interesting isomeric state do not constitute a substantial increase in our beam time request and in the event that the yield decreases more rapidly with half life than we anticipate, we would require this additional time for the measurement of ^{65}Ge and ^{75m}Ge. In the case of ^{77}Ge, we will again be limited by the production of the isomeric state. Therefore, we plan to do this measurement in a future experiment, using the higher yields expected from the UC_x target (see LOI [23]). An additional two shifts of stable beam are requested for setup and optimization of the spectroscopic scheme.

Summary of requested shifts: 11 shifts of radioactive beam are being requested for the study of $^{65-77}$Ge (as summarized in **Table 1**).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: COLLAPS

Part of the	Availability	Design and manufacturing
(COLLAPS)	⊠ Existing	⊠ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed CRIS installation.

Additional hazards: None