Shape and structure of \(N=Z\) \(^{64}\)Ge; Electromagnetic transition rates from the application of the Recoil Distance Method to knock-out reaction.

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Transition rate measurements are reported for the \(2^+_1\) and \(2^+_2\) states in \(N=Z\) \(^{64}\)Ge. The experimental results are in excellent agreement with large-scale Shell Model calculations applying the recently developed GXPF1A interactions. Theoretical analysis suggests that \(^{64}\)Ge is a collective \(\gamma\)-soft anharmonic vibrator. The measurement was done using the Recoil Distance Method (RDM) and a unique combination of state-of-the-art instruments at the National Superconducting Cyclotron Laboratory (NSCL). States of interest were populated via an intermediate-energy single-neutron knock-out reaction. RDM studies of knock-out and fragmentation reaction products hold the promise of reaching far from stability and providing lifetime information for excited states in a wide range of nuclei.

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Experiments involving \(N=Z\) nuclei play a vital role in the understanding of nuclear structure. Along the \(N=Z\) line, protons and neutrons occupy the same Shell-Model orbitals. The resulting overlap of nucleon wave functions leads to an amplification of the residual proton-neutron interactions. In nuclei with \(28 < N = Z < 50\), large shell gaps open simultaneously for prolate and oblate quadrupole deformations. Atomic nuclei in this region are a subject of vigorous experimental studies due to a remarkable diversity of shapes. Variations in the excitation energy of low-lying states in this region are often used to analyze the evolution of structure away from the doubly-magic \(^{58}\)Ni core. However, electromagnetic transition rates are recognized as providing a more sensitive probe of collectivity and deformation. The current letter reports on the application of the Recoil Distance Method (RDM) \([\text{1}]\) to lifetime studies of \(N=Z=32 \) \(^{64}\)Ge.

Successful application of the RDM opens up new possibilities for lifetime measurements of excited nuclear states at fragmentation facilities. In the experiment reported here, states of interest were populated via an intermediate-energy single-neutron knock-out from rare isotope beams of \(^{60}\)Ge and \(^{62}\)Zn. The measurement took advantage of state-of-the-art instruments available at the NSCL; it brought together the Coupled Cyclotron Facility \([\text{2}]\) for acceleration of the primary beams, the A1900 mass separator for rare isotope selection \([\text{3}]\), the diamond timing detector for particle identification of the incoming beam \([\text{4}]\), the Segmented Germanium Array (SeGA) for \(\gamma\)-ray detection \([\text{5}]\), the Köln/NSCL plunger device for the RDM \([\text{6}]\), and the high-resolution S800 spectrograph for identification of the reaction products \([\text{7}]\). This unique combination offers access to a wide range of exotic nuclei which can be investigated via the RDM for lifetime information. Such studies can provide information on transition rates far from the line of stability.

Ground-state shapes in \(28 < N = Z < 50\) nuclei are predicted to evolve from spherical to triaxial, oblate, prolate and back to spherical as mass increases \([\text{8}]\) due to occupation of identical deformation-driving orbitals. Moreover, excited levels can have significantly different structure than the ground state. For example, in \(^{48}\)Se the oblate-deformed ground state band is reported to coexist with a prolate-deformed excited band \([\text{9}]\). Currently, the \(B(E2,2^+_1 \rightarrow 0^+_1)\) in even-even \(N=Z\) nuclei beyond doubly-magic \(^{56}\)Ni are known only in \(^{72}\)Kr from a recent Coulomb excitation experiment \([\text{10}]\). While the single-step Coulomb excitation process is used very effectively to investigate transition rates to the first excited state \([\text{11}]\), the RDM combined with knock-out or fragmentation reactions provides an opportunity to access states beyond the \(2^+_1\). In particular, the lifetime of the \(2^+_1\) and \(2^+_2\) states in \(^{64}\)Ge are reported in the current study.

The reduced \(E2\) transition rates measured here for the \(2^+_1\) and \(2^+_2\) states in \(^{64}\)Ge are in excellent agreement with the large-scale Shell Model calculations which use the recently developed GXPF1A effective Hamiltonian \([\text{12}]\). GXPF1A was first exploited in a comprehensive study of energy levels in \(^{56}\)Ni \([\text{13}]\). GXPF1A was derived from a microscopic calculation by Hjorth-Jensen based on renormalized \(G\)-matrix theory with the Bonn-C interaction \([\text{14}]\), and was refined by a systematic fitting of the important linear combinations of two-body matrix elements to low-lying states in nuclei from \(A = 47\) to \(A = 66\), including some states of \(^{56}\)Ni \([\text{12, 15}]\). The GXPF1A results yield spectroscopic quadrupole moments of nearly equal magnitude but opposite sign for the \(2^+_1\) and \(2^+_2\) states in \(^{64}\)Ge which can be understood from an anharmonicity in collective vibrations.

In the current experiment the RDM developed for
intermediate-energy Coulomb excitation was successfully applied in a measurement of nuclear states populated in single neutron knock-out reactions. A cocktail beam of rare isotopes comprised of 5% $^{65}$Ge, 35% $^{64}$Ga, 52% $^{63}$Zn and 8% $^{62}$Cu was produced via in-flight projectile fragmentation of $^{78}$Kr at 150 MeV/u as described in [18]. The constituents of the incoming beam were identified on an event-by-event basis from the RF time of flight between the K1200 cyclotron and the timing diamond detector in the object of the S800 spectrograph. The use of the radiation hard diamond for particle identification was crucial to handle the $\sim 10^6$ particle-per-second rate of the incoming beam. The quality of the identification was sufficient to completely separate incoming beam components in the off-line analysis.

The nuclei of interest for the current study were produced in nuclear reactions at the target/degrader position of the Köln/NNSCL plunger device [6]. The plunger device was mounted at the target position of the S800 spectrograph [2]. The mass and charge of the reaction products were extracted on an event-by-event basis from the time-of-flight and energy-loss information. The time of flight was measured between the diamond detector in the object of the S800 and the E1 plastic scintillator in the S800 focal plane. The energy loss measurement was performed in the ionization chamber at the S800 focal plane [19]. In the off-line analysis the outgoing reaction products were identified separately for each component of the incoming cocktail beam. Below, two channels are discussed; the single neutron knock-out from $^{63}$Zn leading to $^{62}$Zn and from $^{65}$Ga leading to $^{64}$Ge. The transition rates in $^{62}$Zn are known from measurements in stable beam facilities [20] and serve here as a consistency check.

The reaction products emerged from the 500 $\mu$m thick natC plunger target with a velocity of $\beta_H \sim 0.39$. Nuclei in excited states decayed in flight by $\gamma$-ray emission after a distance governed by the lifetime of the state. A stationary 250 $\mu$m thick $^{93}$Nb degrader positioned downstream of the target further reduced the velocity to $\beta_L \sim 0.35$. Depending on whether the decay occurred in-flight between the target and the degrader or after slowing down in the degrader, the $\gamma$-rays exhibit different Doppler shifts. Consequently, the $\gamma$-ray spectra contain two peaks for each transition. The lifetime of the state can be inferred from relative intensities of the peaks as a function of target/degrader separation using the information on the ion velocity contained in the Doppler shift.

In the current studies the Doppler-shifted $\gamma$-rays were recorded by the Segmented Germanium Array [5] with two rings of 7 and 8 detectors at a laboratory angle of 30$^\circ$ and 140$^\circ$, respectively. The data were recorded for target/degrader separations of 0-, 200-, and 500-$\mu$m. In addition, a run without the degrader was performed to measure the velocity of the reaction products downstream from the target. This run also provided information on the relative population of excited states from the reaction of interest.

A novel procedure of data analysis was developed specifically to address experimental RDM information for states with lifetimes on the order of a few ps; comparable to the time needed to cross the target and/or degrader thickness. For such short lifetimes, procedures discussed in Ref. [1] for states with $\tau \sim 50$ ps may lead to systematic errors since the contribution of decays in the target or degrader are significant and need to be accounted for. Thus in the current studies lineshapes for transitions of interest were first calculated as a function of the transition lifetime. Next the lifetime was extracted from the comparison of these calculated lineshapes to the experimental data using the least square fitting method. The quality of calculated lineshapes for lifetimes yielding the best agreement with the data is illustrated in Fig. [1].

While the details of the above analysis will be presented in a separate paper it is worthwhile to stress a few aspects of the procedure here. The parameters which define the line-shape for a given target/degrader separation,
 Besides the level lifetimes, are the velocities of the nuclei of interest at the moment of the gamma emission and the geometrical dimension and energy resolution of the Ge detectors in use. In the current experiment the information on the velocities of the incoming beam ions and the corresponding outgoing reaction products is defined within 2% and 6% by the settings of the A1900 and the S800 separators, respectively. The actual stopping powers, which impact the line-shape calculations, are defined at the intermediate energies by atomic processes and can be modeled quite accurately. Only very small modifications were needed to reproduce the measured velocities of the recoiling ions after they have passed the target and the degrader. The response of the SeGA array is understood from the off-line source calibrations and Lorentz transformation from the source to the laboratory reference frame. The energy and angular straggling of the reaction products as well as the energy resolution of the gamma detectors are described by a single parameter which enters as a width-parameter into Gaussian functions out of which the line-shape is composed. In the present analysis four different width-parameter values were used corresponding to decays occurring in or after the target and for the observation of the gamma transitions in the 30° or 140° Ge ring of the SeGA array. These values were selected to give a good representation of the width of the two components of gamma-ray transitions observed in the spectra including these measured with the plunger target only. Thus having fixed the parameters for the line-shape calculations the level lifetimes were deduced from a fit of the calculated line-shapes to the measured spectra; the only free parameters of the fit were the lifetimes of interest and normalization factors to account for different statistics accumulated at different target-degrader distances and observation angles.

In the plunger experiments at intermediate energies the beam crossing the target has enough energy to react in the degrader. It was measured that in the current experiment 40% of the observed excitations come from the reaction on the degrader. This value of 40% was used in all fits for 64Ge and also for 62Zn.

In case of 62Zn the 2+ 1 lifetime was determined by taking into account the 10% feeding from the 2+ 1 state with the 3.8(6) ps lifetime given in the literature [20]. The extracted lifetime of 4.2(7) ps is in excellent agreement with the 4.2(3) ps lifetime of Ref. [20]. Moreover, separate studies of the impact of the unobserved feeding on the measured value indicate that ~90% of the intensity of the 2+ 1 decay in 62Zn comes from fast feeding. This observation makes the knock-out reaction an excellent tool for lifetime measurements.

In 64Ge a significant feeding of ~30% via the 677-keV transition from the 2+ 2 to the 2+ 1 level was observed, see Fig. 1. Thus, the lifetime of the 2+ 2 state was fitted to the data shown in Fig. 1 utilizing a single exponential decay, while the corresponding fit for the 2+ 1 state was done taking into account the observed feeding. The results for the first measurements of the 2+ 1 and 2+ 2 state lifetimes of the N=Z 64Ge are 3.3(5) and 8.4+2 ps, respectively. From the measured lifetimes and data in Refs. 14 and 20, experimental observables were extracted and compared to the Shell Model GXPF1A calculations as summarized in Tab. 1. The GXPF1A interaction was recently compared to the Shell Model GXPF1A calculations as summarized in Tab. 1. The GXPF1A interaction was recently improved on the velocities of the incoming beam ions and to account for different statistics accumulated at different target-degrader distances and observation angles.

The opposite quadrupole moments can be qualitatively explained by large-amplitude collective dynamics. In the case of an anharmonic vibrator Hamiltonian, which seems applicable based on the observed excitation energy pattern and from microscopic calculations of Ref. 8, the most important anharmonicity is quartic ( α4) in the quadrupole coordinate (α). The semi-microscopic estimates of various types of anharmonicity were given in [23] based on the soft quadrupole mode with low quadrupole frequency, relatively close to the RPA instability. Here the quadrupole frequency is ~1/2 of the

| nucleus | observable | exp. | th. | unit |
|---------|------------|-----|-----|------|
| 64Ge    | E(2+ 1)    | 0.902 | 0.938 | MeV |
| 64Ge    | E(0+ 0)    | 1.353 | 1.353 | MeV |
| 64Ge    | E(2+ 2)    | 1.579 | 1.559 | MeV |
| 64Ge    | E(4+ 4)    | 2.053 | 1.995 | MeV |
| 64Ge    | B(E2, 2+ 1 → 0+ 0) | 410(60) | 406 | e² fm⁻² |
| 64Ge    | B(E2, 2+ 2 → 2+ 0) | 620(210) | 610 | e² fm⁻² |
| 64Ge    | B(E2, 2+ 0 → 0+ 0) | 1.5(5) | 14 | e² fm⁻² |
| 64Ge    | B(E2, 0+ 2 → 2+ 0) | 483 | e² fm⁻² |
| 64Ge    | B(E2, 4+ 2 → 2+ 0) | 12 | e² fm⁻² |
| 64Ge    | B(E2, 4+ 0 → 2+ 0) | 674 | e² fm⁻² |
| 64Ge    | B(E2, 4+ 2 → 2+ 2) | 9 | e² fm⁻² |
| 64Ge    | Q(2+ 1)    | -18.6 | efm² |
| 64Ge    | Q(2+ 2)    | +18.5 | efm² |
| 62Zn    | E(2+ 1)    | 0.954 | 1.012 | MeV |
| 62Zn    | E(2+ 2)    | 1.805 | 1.908 | MeV |
| 62Zn    | B(E2, 2+ 1 → 0+ 0) | 250(18) | 295 | e² fm⁻² |
| 62Zn    | B(E2, 4+ 1 → 2+ 0) | 290(30) | 231 | e² fm⁻² |
| 62Zn    | B(E2, 2+ 0 → 0+ 0) | 4.5(7) | 11 | e² fm⁻² |
| 62Zn    | Q(2+ 1)    | -22.3 | efm² |
| 62Zn    | Q(2+ 2)    | +13.8 | efm² |
pairing gap, i.e. not very low. In the limiting case of strong quartic anharmonicity, the prediction \( R = E(4_1)/E(2_1) = 2.09 \). The perfect case is \(^{100}\text{Pd}\), where all states of the yrast band practically coincide with predictions of strong quartic anharmonicity that is characterized by O(5) symmetry. In the case of \(^{64}\text{Ge}\) \( R = 2.13 \), close to this limit are \(^{70,72}\text{Ge}\) with \( R = 2.07 \).

The cubic anharmonicity, discussed first in Ref. [20], is related to single-particle levels changing with deformation; this can give a first order phase transition to static deformation. In the limiting case of strong quartic anharmonicity, the cubic term is typically small. This is analogous to the three-phonon vertex in quantum electrodynamics that is strictly forbidden by the Furry theorem (virtual contributions of electrons and positrons cancel exactly). For \( N = Z \) nuclei this would be the case for exact particle-hole symmetry; in the BCS theory the effect is proportional to the sum of contributions \( (q^2 - t^2) \) which almost cancel, but not exactly. It can be observed from a Nilsson diagram that for \(^{64}\text{Ge}\) the lowest energy states which originate from the \( g_{9/2} \) orbital go down for both signs of deformation, while the hole level originating from the \( f_{7/2} \) orbital goes up on the prolate side [27]. With a large amplitude of zero point quadrupole motion, the nucleons probe all these shapes, and the cubic anharmonicity is relatively important. Moreover, it should be stressed that the effect is enhanced by the coherent action of protons and neutrons occupying the same shells. The cubic anharmonic term mixes the states with phonon numbers differing by one unit (its contribution to energy comes only in the second order and therefore is not large). For the \( 2^+_1 \) and the \( 2^+_2 \) states this mixing results in quadrupole moments equal in magnitude and opposite in sign as given in Tab. [11].

If the amplitude of zero point vibration is large and various deformations are probed, there appears “virtual rotation” [25] based on slowly evolving dynamic deformation. This splits the two-phonon states by \( \frac{1}{2\pi} \) \( \times I(I + 1) \), for \(^{64}\text{Ge}\) \( R = 31 \text{ MeV} \). For good rotors the “Alaga ratio” of the absolute value of the quadrupole moment in the lowest \( 2^+ \) state to the \( \sqrt{B(E2)} \) from this state to the ground state is \( 2/7 \). Here we have instead 0.9, which means that the transition probabilities are much weaker than it would be for a good rotor.

In summary, picosecond RDM lifetime measurements were performed using a unique combination of state-of-the-art instruments and knock-out reactions with rare isotope beams at the NSCL. Studies of this type hold the promise of reaching far from stability and providing lifetime information for intermediate-spin excited states in a wide range of nuclei. The absolute \( E2 \) transition rates measured here for the \( 2^+_1 \) and \( 2^+_2 \) states in \( N = Z \) \(^{64}\text{Ge}\) are in excellent agreement with state-of-the-art large-scale Shell Model calculations. Theoretical analysis suggests that \(^{64}\text{Ge}\) is a \( \gamma \)-soft anharmonic vibrator.

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