EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Investigation of collectivity in N=Z nuclei: Coulomb excitation of ^{60}Zn

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Abstract: We will investigate shape evolution in the region of transitional nuclei lying just above the doubly-closed shell nucleus ^{56}Ni. At the lower edge, in ^{60}Zn, the interplay between the stabilizing shell effects and the correlation energy gain is very subtle. This proposal aims at measuring the transition strength B(E2↑) in the ground-state band to extract the deformation parameters of the low-lying excited states of ^{60}Zn. This will be possible due to the combination of the intense ^{60}Zn available at the ISOLDE facility together with the highly-efficient MINIBALL γ spectrometer coupled to a DSSD detector.

Requested shifts: 21 shifts, (split into 1 run over 1 years)
Installation: MINIBALL + CD-only

1 Scientific motivation

Ground-state shapes in N = Z nuclei from Ni to Sn are predicted to evolve from spherical to triaxial, oblate, prolate, and back to spherical as mass increases [1] due to occupation of identical deformation-driving orbitals. Experimentally the neutron-deficient nuclei, above the doubly-closed shell ^{56}Ni nucleus, with masses between 56 and 80, are well known to change their collective properties rapidly with proton and neutron numbers. These nuclei lie in the transitional region from the spherical shape (e.g., ^{56}Ni [2]) to the prolate deformation (e.g., ^{80}Zr [3]).

In the neutron-deficient N$\simeq$Z zinc isotopes, considerable experimental information exists about both excitation energies and transition probabilities [4]. ^{58}Zn is the most exotic neutron-deficient Zn isotope, that is presently known in terms of γ-ray spectroscopy. This nucleus has been recently investigated in a proton-transfer reaction at NSCL and the first excited states are established [5].

In ^{60}Zn, neither a firm assignment for the 0_2^+ and 2_2^+ levels exists, nor the B(E2) values. In this nucleus, lifetimes are not known in the ground-state and the side band. In the 1970s, excited levels in ^{60}Zn were populated using the (^{3}He,n) reaction and their energies and spin-parity assignments were made on the basis of the neutron energy, deduced by ToF, and angular distributions [6], compared with distorted-wave calculations. Subsequently, in a following experiment, γ-rays emitted following the (^{3}He,nγ) reaction were also detected [7]. The assigned spins and parities were speculated on the basis of previously assigned values and intensity. No γ-γ coincidence data were obtained and the resulting level scheme is therefore tentative. Comparison with shell model calculations, using a inert ^{56}Ni core and trimmed matrix elements, could reproduce the excited 0_2^+ state.

An experiment to verify the existence of the second-excited band will be performed at the end of October 2015 using the GALILEO γ-ray detection array at the Legnaro National Laboratory. The information on the energy of the 2_2^+ and the existence of the 0_2^+ will be used to infer, indirectly, the structure of the nucleus.

The sign of the spectroscopic quadrupole moment of the first 2^+ is not accessible from

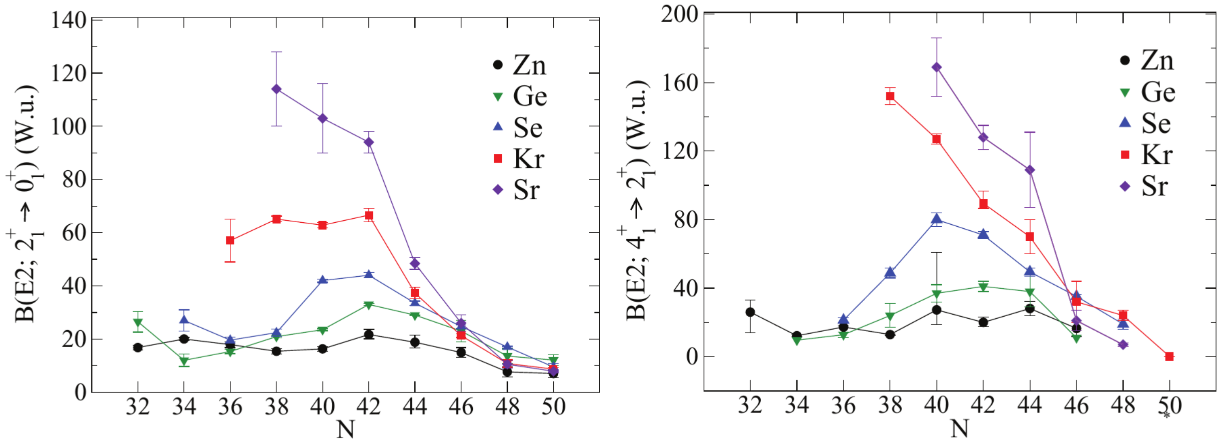

Figure 1: B(E2;$2_1^+ \rightarrow 0_1^+$), on the left-hand side, and B(E2;$4_1^+ \rightarrow 2_1^+$), on the right-hand side, plotted against the neutron number. Taken from Ref [4].

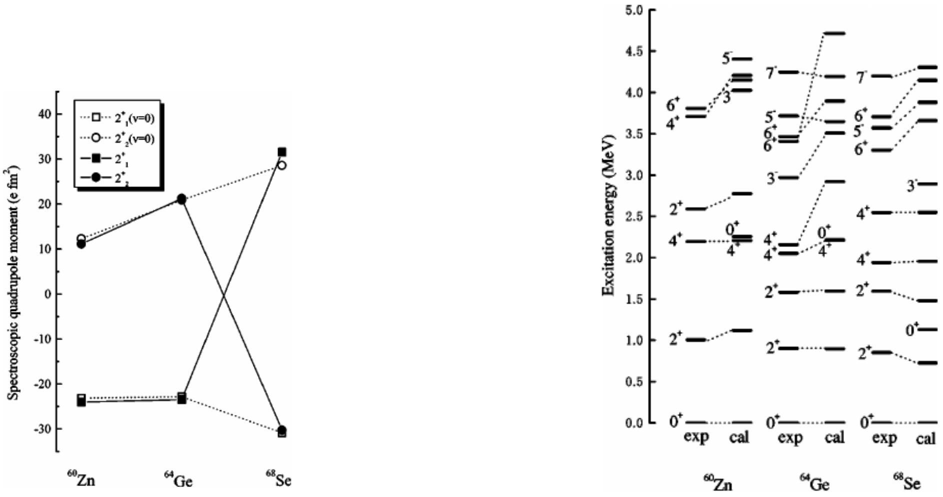

Figure 2: On the left, spectroscopic quadrupole moments in ^{60}Zn, ^{64}Ge, and ^{68}Se. The open squares and circles are those obtained by ignoring the T = 1 monopole matrix elements. On the right, experimental and calculated energy levels for the same nuclei. Taken from Ref. [11].

most of the measurements in these neutron-deficient nuclei and is experimentally known only in very few cases. Therefore the B(E2) values remains a unique piece of information in order to evaluate the collectivity at low excitation energy. The B(E2) values of the even-even $^{62-70}$Zn isotopes have been systematically determined by employing the Doppler-shift attenuation method [8]. The B(E2;$2^+_1 \rightarrow 0^+_1$) value revealed oscillating behavior, opposite with respect to the B(E2;$4^+_1 \rightarrow 2^+_1$), see Fig. 1, taken from Ref [4]. In the heavier N∼Z isotopes the progressive occupation of the $g_{9/2}$ orbital drives the nuclei towards larger collectivity and deformation. In ^{64}Ge and ^{68}Se the B(E2) values, obtained through a lifetime [9] and an intermediate Coulomb-excitation [10] measurement, respectively, revealed a triaxial nature of these isotopes. In ^{72}Kr, the 2^+_1 transition strength to the ground state is significantly larger than in the ^{64}Ge and ^{68}Se isotopes and an oblate ground state is found to be consistent with the predictions. However how the triaxial/γ-soft character develops in ^{60}Zn and its ground-state shape are open questions.

Shell-model calculations, using a pairing plus quadrupole-quadrupole force in a *fpg* model space [11], predict a prolate-to-oblate transition in these N=Z nuclei above ^{56}Ni by moving from the ^{60}Zn to ^{68}Se, see Fig. 2 on the left, and a shape coexistence for the ^{60}Zn, ^{64}Ge and ^{68}Se nuclei, see Fig. 2 on the right, being the 2^+_2 and 0^+_2 close to the 2^+_1. The spectroscopic quadrupole moment is calculated to be of the order of -20 efm^2 in ^{60}Zn and to have a sudden change in sign when moving from ^{64}Ge to ^{68}Se. The moment of inertia extracted from the measured rotational bands in ^{68}Se [12] seems to confirm this theoretical prediction, at variance with the results in Ref [10]. The lifetimes measured in the ground-state and side band in ^{64}Ge [9] are consistent with a triaxial rigid rotor model. Presently, the predicted oblate side band in ^{60}Ni awaits for confirmation and both B(E2) values and the spectroscopic quadrupole moment are not yet determined. Indeed, energy-density functional (EDF) calculations, by using the DD-PC1 functional does not predict coexistence for the ^{60}Zn, rather a γ-soft potential, which turns into a spherical one when reaching ^{70}Zn [13]. The results of the calculations for ^{60}Zn are shown in Fig. 3 [14],

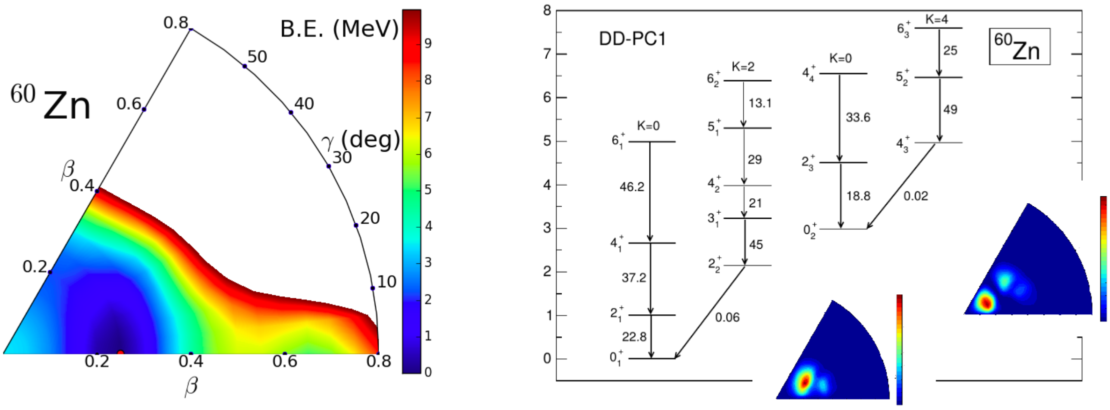

Figure 3: On the left, EDF-calculated potential energy surface. On the right, EDF-calculated level scheme and probability distributions for the wave functions corresponding to the ground-state and first excited 0^+ state [14]. B(E2) values in W.u. are also given.

on the left. In Fig. 3, on the right, the predicted level scheme is also shown together with the probability distributions for the wave functions corresponding to the ground-state and first excited 0^+ states. The transition strengths are expected to be 22 W.u. and 37 W.u. for the $2^+_1 \rightarrow 0^+_1$ and $4^+_1 \rightarrow 2^+_1$ transition, respectively.

The physics motivation outlined in the present proposal is to investigate the collectivity of the low-lying states of ^{60}Zn. This will be primarily achieved by determining the transition matrix elements ($\langle 0^+_1 \| E2 \| 2^+_1 \rangle$, $\langle 2^+_1 \| E2 \| 4^+_1 \rangle$) describing the structure of the low-lying 2^+ and 4^+ states. Secondarily, the determination of the spectroscopic quadrupole moment will be attempted by extracting the diagonal matrix element ($\langle 2^+_1 \| E2 \| 2^+_1 \rangle$).

2 Experimental details and rate estimation

A beam energy of 260 MeV (4.3 MeV/u) from HIE-ISOLDE is well suited to enhance the probability of multi-step Coulomb excitation in the safe Coulex mode. This in particular will allow population of the 2^+ state and enable the determination of the unknown B(E2; $0^+_1 \rightarrow 2^+_1$) value. The 4^+ state will be also populated and the B(E2; $2^+_1 \rightarrow 4^+_1$) value determined. The Zn isotopes of interest are produced using ZrO_2 target irradiated with the proton beam from the PS Booster [15]. The expected yield is 2.1x10^5 pps/μC [16]. With a proton current of 2 μA, the expected maximum beam intensity, on target, will be around 4.2x10^4 pps, assuming a transmission efficiency of 10%.

We propose to use an annular double-sided CD Si strip detector (DSSD) placed at forward angles, covering an angular range from 16° to 53° in the laboratory system, which corresponds to a large solid angle range in the centre-of-mass system (20°$< \theta_{CM} <$145°). The expected low-energy detection threshold, 5÷10 MeV, will allow for the detection of either the scattered Zn projectile or the recoiling Pt target nuclei (left panel of Fig. 4). In fact, the detection of the heavy partner corresponds to the Zn ions scattered at larger angles, from 55° to 130° in the laboratory system, see Fig 4, on the right, greatly enhancing the

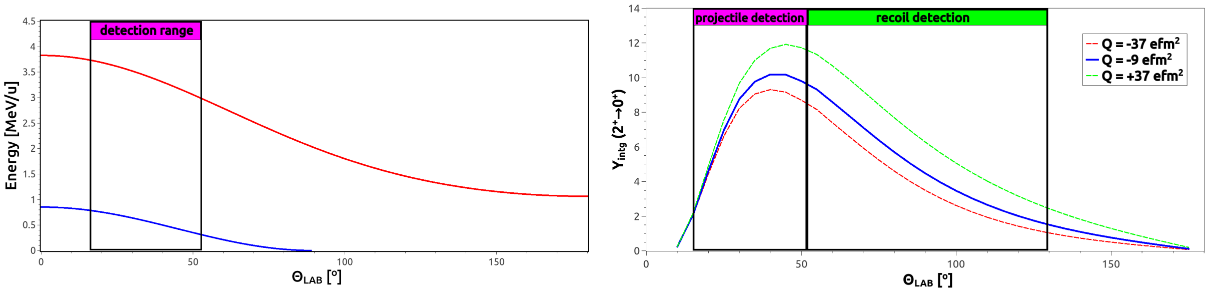

Figure 4: Left panel: Kinetic energies, after the reaction at the end of the target, of scattered ^{60}Zn projectiles (red curve) and recoiling ^{194}Pt target nuclei (blue curve) for an incident energy of 4.3 MeV/u. Right panel: differential cross section of the $2^+_1 \rightarrow 0^+_1$ transition as a function of projectile scattering angle. Calculations were performed with the GOSIA code for the oblate, Q>0, and prolate, Q<0, rotational limit in ^{60}Zn. Solid curve is obtained considering the value predicted by the theory [14].

sensitivity of the setup.

De-excitation γ rays will be observed with the MINIBALL germanium detector [17] array, consisting of 8 triple clusters, in coincidence with the scattered particles allowing a precise event-by-event Doppler correction to be made and a significant reduction of the γ-ray background following the beta decay of the radioactive beam particles. For the MINIBALL detector array we have assumed a γ-ray detection efficiency of ~8% at 1332 keV.

The expected γ-ray yields following the Coulomb excitation of a ^{60}Zn beam incident on a 2 mg/cm^2 ^{194}Pt target at a "safe" energy of 260 MeV, below the Coulomb barrier, have been calculated with the GOSIA code [18] and are shown in the Table 1. The intensity of Pt target transitions are also reported as they will be used for normalization purpose. In performing these calculations, the available experimental information on excitation energies has been used. The reduced transition probabilities, in case of ^{60}Zn, are based on the most recent theoretical calculations [14].

As a second objective of the present proposal, the determination of the quadrupole moment will be also attempted. The differential cross section has been calculated as a function of spectroscopic quadrupole moment, considering as a upper/lower limit the calculated rotational limit (Q=±37 efm^2) for the ^{60}Zn, see Fig. 4, and our value of reference, which is deduced from the theoretical calculations (Q=-9 efm^2) [14], see the right panel of Fig 4.

The possibility to measure the quadrupole moment strongly depends on the error associated to the $2^+_1 \rightarrow 0^+_1$ yield measurement in coincidence with each angular subrange, which should be limited to few %. The magnitude of the calculated influence of the quadrupole moment on Coulomb excitation cross section in ^{60}Zn and the expected important reduction of the spectroscopic quadrupole moment as compared to the rotational value make this case similar to that of ^{44}Ar [19]. There, a similar statistics allowed for determination of the quadrupole moment with the absolute error of 3 efm^2 (which translated into a relative error of 40%). Considering the expected $2^+_1 \rightarrow 0^+_1$ γ-ray yield for ^{60}Zn, similar precision should be reachable, although at the limit. In order to keep the statistical error

Table 1: Expected γ-ray yields per day for the transitions in ^{60}Zn and ^{194}Pt. The calculations were performed with the Coulomb excitation code GOSIA for a 260-MeV ^{60}Zn beam incident on a 2 mg/cm^2 ^{194}Pt target.

Transition	Energy [keV]	Yield [counts/1day]	Yield [counts/6days]
Zn			
$2^+_1 \rightarrow 0^+_1$	1003	1580	9480
$4^+_1 \rightarrow 2^+_1$	1189	16	96
Pt			
$2^+_1 \rightarrow 0^+_1$	328	9374	56244
$4^+_1 \rightarrow 2^+_1$	482	670	4020

at the level of few % for each of the 4-5 ranges of scattering angles, 6 days of beam time are requested (18 shifts).

3 Remarks on beam intensity and contamination

^{60}Zn beam has been delivered at ISOLDE from a ZrO$_2$ target, using a tungsten surface ion source, and RILIS ionization scheme. The level of ^{60}Ni, and to a lesser extent ^{60}Fe, possible isobaric contaminants, if present in the beam, would impact on the measurement. No data are available on the level of impurity from ISOLDE, however if present, should not exceed 5x10^{7}pps dc current in the focal plane of the separator. Different possibilities are available to reduce these A=60 isobaric contaminants by using a different ion source, the characteristic release time of ^{60}Zn and the mass difference with respect to the contaminants. Combining the various approaches, the gain can be a factor ∼100. Considering a final 15-20% contamination scenario an extra day (3 shifts) is demanded to run in laser off mode. However to test/improve beam purity a devoted TISD test is demanded before the experiment.

Summary of requested shifts: 18 shifts (6 days)+ 3 shifts (1 days) laser off

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *MINIBALL + CD-only*

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, MINIBALL + T-REX] 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]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
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			
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]: ... kW