

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letter of Intent I-109)

Coulomb excitation ^{74}Zn - ^{80}Zn (N=50): probing the validity of shell-model descriptions around ^{78}Ni

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Abstract

A study of the evolution of the nuclear structure along the zinc isotopic chain close to the doubly magic nucleus ^{78}Ni is proposed to probe recent shell-model calculations in this area of the nuclear chart. Excitation energies and connecting B(E2) values will be measured through multiple Coulomb excitation experiment with laser ionized purified beams of $^{74-80}\text{Zn}$ from HIE ISOLDE. The current proposal request 30 shifts.

Requested shifts: 30 shifts

Beamline: MINIBALL + CD-only

1. Introduction

Studying the region around the doubly magic nucleus ^{78}Ni with the $Z=28$ and $N=50$ shell closures is particularly interesting for testing the validity of the contemporary nuclear models and for unraveling new aspects of the interactions used in these models (see e.g. [1-4]). Especially the evolution of single-particle and collective phenomena between the harmonic oscillator shell closure at $N=40$ and the shell closure at $N=50$ challenges our understanding of the nuclear structure. In this region the transition from harmonic oscillator to spin-orbit type shell closure is manifested and the neutron $g_{9/2}$ neutron orbital plays an important role in this process [1-4]. In recent years, intense experimental and theoretical work has resulted in a substantial progress in our understanding of the nuclear structure in this region, but still several questions remain.

The $N=50$ energy gap appears to evolve when going from ^{68}Ni ($N=40$) to ^{78}Ni ($N=50$). This might be due to the repulsive character of the effective three-body force [5]. Constraining its size is one of the main requirement for future developments and tests of the effective interactions with the inclusion of many-body forces [3], as well as for the validation of empirical monopole interactions, such as those proposed in [4].

Different effective interactions have been proposed in recent years and large shell model calculations using such interactions have been performed to probe their reliability [1-4]. These effective interactions are normally developed as result of fittings calculations over a large number of experimental energy data on nuclei around e.g. $Z=30$ as the one proposed in [1].

The nuclei around ^{78}Ni are particularly interesting to test the validity of the shell-model calculations. Moreover, their properties shed light on the importance of excitations across the $N=50$ and $Z=28$ shell closures.

Although a substantial set of experimental data (energy levels, reduced transitional matrix elements, life time) has been accumulated in this region of the nuclear chart, the conclusions drawn from them seem contradictory. Also conflicting results exist between the life time of the 4^+ state in ^{74}Zn as deduced from Coulex measurements or from direct life-time measurements using the Recoil-Distance Doppler shift method. The possibility of the weakening of the $N=50$ closure has been anticipated e.g. in Ref. [6-9] while the contrary has been deduced by other authors [10,11].

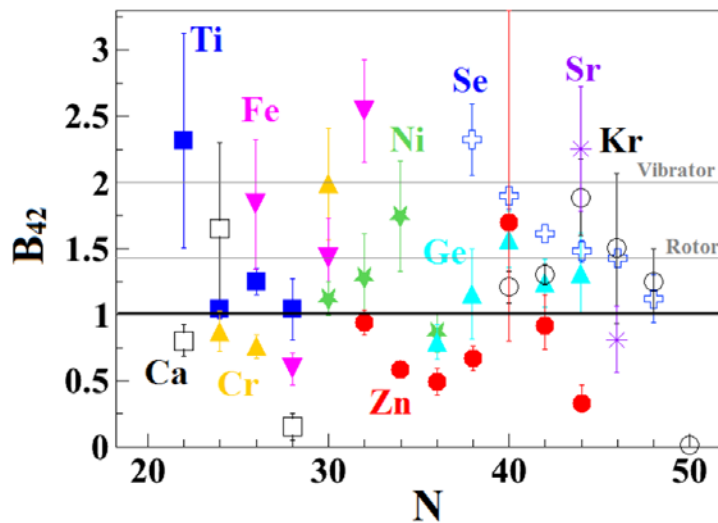


Fig.1 Ratio of experimental $B_{42} = B(E2; 4^+ \rightarrow 2^+) / B(E2; 2^+ \rightarrow 0^+)$ for nuclei with $20 \leq Z \leq 40$

It should be noted that the $B_{42} = B(E2; 4^+ \rightarrow 2^+) / B(E2; 2^+ \rightarrow 0^+)$ ratios resulting from the recent RDDS measurement in $^{72,74}\text{Zn}$ are lower than 1, similarly to what was found for light stable

Zn nuclei. This ratio is expected to be larger than 1 for collective excitations (2 for harmonic oscillator, 1.4 for rigid rotor). A B_{42} systematic for medium mass nuclei with N from 20 to 50 is shown in Fig. 1. Among the available data in this mass region, the zinc isotopes have the lowest B_{42} ratio, suggesting a no-collective nature of the excitations. As stated in [12], the only situation where a B_{42} ratio lower than one occurs is when the seniority is a good quantum number. In such situation, the $B(E2;2^+ \rightarrow 0^+)$ increases up to mid shell whereas the $B(E2;4^+ \rightarrow 2^+)$ decreases. Such a behaviour seems to be observed for the zinc isotopes with a maximum of B_{42} at N=40 and lowering towards N=44.

The latter Coulomb excitation studies in the neutron-rich Zn isotopes up to the N=50 revealed the energy of the first 2^+ state and the $2^+ \rightarrow 0^+$ transition matrix element in the ^{80}Zn nucleus (these in fact are the only states observed in this nucleus) and both observables indicate a significant influence of the N=50 shell closure [10,11].

Information on other excited states in ^{80}Zn is lacking while their energy could be directly compared to the recent shell model calculations [1].

Finally, below $Z=28$ a surprisingly swift onset of deformation has been observed experimentally from beta-decay, in-beam studies and proton-knock out reactions [13-18]. Further study of these phenomena is essential.

Coulomb excitation at low beam energy [24] offers nowadays an excellent tools to obtain energies of the low-lying levels, including no-yrast states, as well as $B(E2)$ values.

The data will be compared to recent shell-model calculations using ^{56}Ni as a core [1] and ^{48}Ca [2,4]. This will yield valuable information on the evolution of the $d_{5/2}$ neutron orbits in the vicinity of ^{78}Ni .

2. Previous experiments

Excited states in ^{80}Zn can in principle be studied in the beta decay of ^{80}Cu ($T_{1/2}=170$ ms), however, beam intensities at in-flight facilities or at ISOLDE or other ISOL facilities [19-21] prevents detailed decay studies and only the half-life of ^{80}Cu has been determined so far. For ^{78}Zn , a cascade of excited states has been identified up to spin 6^+ [20].

Deep-inelastic reactions can in principle be used to study the excited yrast-states in far unstable nuclei but so far no extra information on ^{80}Zn was obtained [22,23].

Finally intermediate energy Coulomb excitation mainly populates the first 2^+ state, preventing to extract information on other excited states.

Low-energy Coulomb excitation on $^{74-80}\text{Zn}$ has been measured at ISOLDE, CERN in 2006 – 2007 (IS412) yielding $B(E2, 2^+ \rightarrow 0^+)$ values in $^{74-80}\text{Zn}$, $B(E2, 4^+ \rightarrow 2^+)$ values in $^{74-76}\text{Zn}$ and the energy of the first excited 2^+ state in ^{80}Zn (N=50) [10,11].

As shown in picture Fig.2 from [10], in $^{74-76}\text{Zn}$ the level 4^+ is clearly populated but the poor statistics collected in the $4^+ \rightarrow 2^+$ transition determines a quite large error bar in the extracted transitional matrix element (up to 28% in ^{76}Zn). The data were analysed with the Coulomb excitation analysis code GOSIA [25] and, on the assumption of the quadrupole moment of the 2^+ state $Q(2^+) = 0$ eb, the half-life of the 2^+ states in $^{74-80}\text{Zn}$ were estimated.

However, recent independent measurements of the half-life of 2^+ state in ^{74}Zn with the Recoil-Distance Doppler Shift method reported a value of 27.0 (2.4) ps [26] and 28.5 (3.6) ps [C. Louchart, to be published]. This result combined with the Coulomb excitation cross-sections measurement results in a positive quadrupole moment of the 2^+ state in ^{74}Zn .

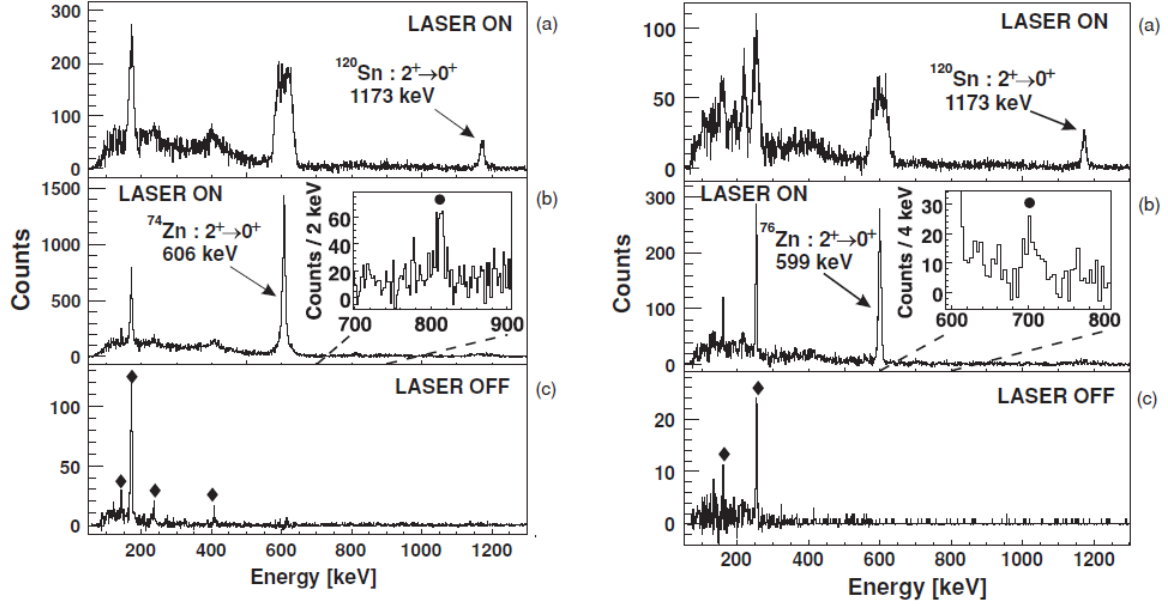


FIG. 2. Coulomb excitation spectra for the $A = 74$ (left) and $A=76$ (right) : (a) prompt coincident with a recoiling target particle, random subtracted and Doppler corrected for the de-exciting target nucleus, during laser ON periods; (b) prompt coincident with a scattered beam particle, random subtracted and Doppler corrected for the de-exciting beam nucleus, during laser ON periods. The filled circle indicates the $4^+ \rightarrow 2^+$ transition in $^{74,76}\text{Zn}$; (c) same as (b) but during laser OFF periods. The several de-excitation γ rays from the target and zinc nuclei are indicated with text labels, de-excitation lines from the isobaric contaminant are indicated with diamonds.

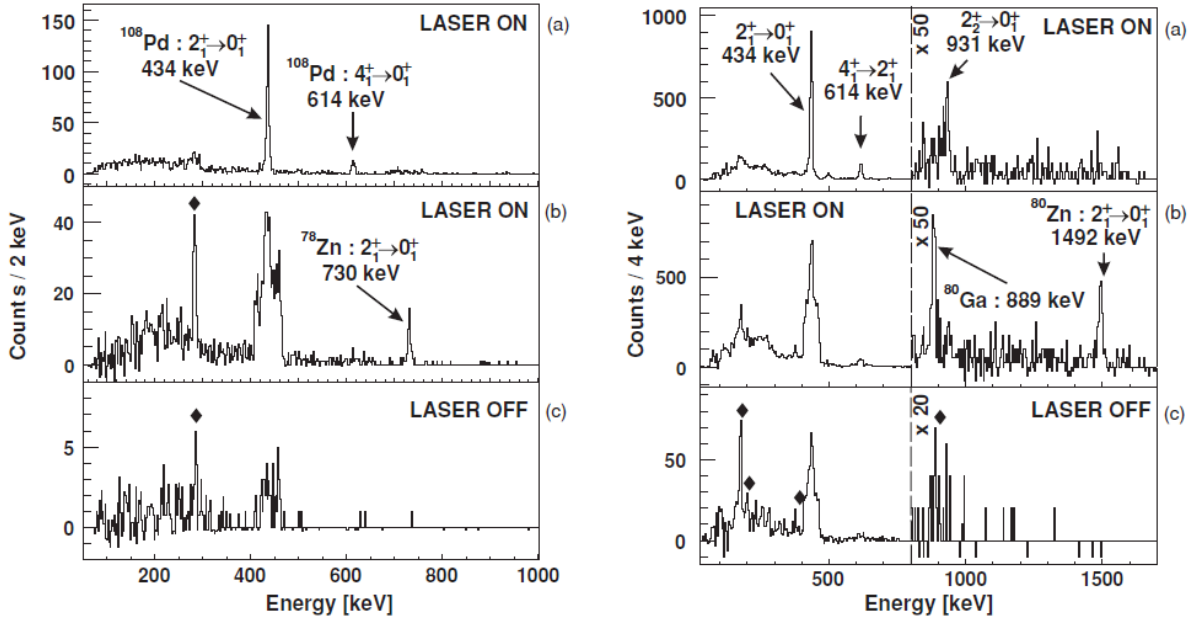


FIG. 3. Similar spectra as in Fig.2 but for $A=78$ (left) and $A=80$ (right)

Moreover, the $B(E2, 4^+ \rightarrow 2^+)$ extracted from the direct life-time measurement of the 4^+ state $(116 \pm 32, -10) e^2 fm^4$ is in conflict with the larger value $(507 \pm 74) e^2 fm^4$ reported in [10] (see Fig.4).

In Fig.3 the spectra collected during 4 shifts and 14 shifts, respectively, with $^{78,80}\text{Zn}$ are shown. In both nuclei, it was not possible to observe the population of the 4^+ state.

Finally, Fig.4 summarize the experimental values for $B(E2; 2^+ \rightarrow 0^+)$ and $B(E2; 4^+ \rightarrow 2^+)$. The existing shell model calculations for two different interactions are also added.

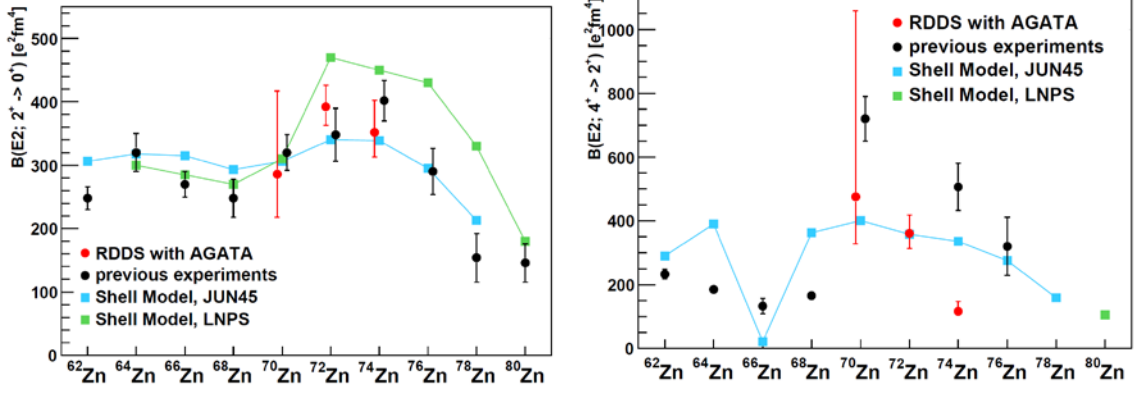


FIG. 4 (a) Transition probabilities $B(E2; 2^+ \rightarrow 0^+)$ and (b) $B(E2; 4^+ \rightarrow 2^+)$ of the Zn isotopes. Filled circles: experimental values (for $A \geq 74$, IS412[10]), dashed lines: JUN45 interaction [1], solid lines: LNPS interaction [28]. Effective charges of ($ep = 1.5; en = 1.1$) and ($ep = 1.5; en = 0.5$) were used, respectively, for the calculation in the JUN45 and LNPS interactions.

In view of the recent results on the half-life measurement, it appears extremely important to collect more data on ^{74}Zn , but also on $^{76-80}\text{Zn}$, in order to improve the error bars in the transitional matrix elements corresponding to the $4^+ \rightarrow 2^+$ transition and to perform a more complete GOSIA analysis to investigate eventually onset of deformation in the neutron-rich Zn isotopes.

3. The physics case

So far the knowledge on the nuclear structure of ^{80}Zn is limited to some ground state properties (half-life, mass) and to the energy of the first excited 2^+ state and the $B(E2)$ value, as observed for the first time at ISOLDE [11].

The level scheme of ^{78}Zn up to the 6^- state has recently been studied in a beta-decay study [20], while a high-lying isomer (8^+) was identified in [27]. Transitional matrix elements are known up to the 2^+ state in ^{78}Zn and up to the 4^+ states in $^{74,76}\text{Zn}$, the latter with quite large error bars.

The aim of the present proposal is to populate yrast and no-yrast states by multiple-step Coulomb excitation in Zn. Using the higher beam energy and intensity available with HIE-ISOLDE, higher-lying states will be excited more efficiently while still remaining in the regime of safe Coulomb excitation in order to extract reliable E2 matrix elements.

Concerning ^{80}Zn , the expected beam intensity and the, according to the shell model calculations, spherical nature of this nucleus will not allow us to perform Coulomb excitation at safe energy to populate other states apart from the 2^+ state. Therefore our first aim is to identify new excited states in ^{80}Zn (most probably the 4^+ state). The energy of the excited states in ^{80}Zn as well as their population cross sections supplies direct information on the $N=50$ and $Z=28$ shell stability in this nucleus with two protons outside ^{78}Ni .

For $^{74-78}\text{Zn}$, we aim to determine the unknown $B(E2)$ values of the excited yrast and no-yrast states and to reduce the uncertainty of previously measured $B(E2)$.

Beams of neutron-rich Zn isotopes have been used at REX-ISOLDE. Using the RILIS technique, relatively pure beams of Zn can be delivered with suitable intensities.

4. Experimental setup and feasibility

These experiments will be performed with the MINIBALL germanium detector array equipped with a segmented silicon array in the forward direction.

The Zn isotopes can be produced using the UC_x primary target, equipped with a quartz transfer line to absorb a major part of the largely produced and surface ionized Rb, and ionized with RILIS. From the previous experiment, we expect contamination in the Zn beam due also to Ga surface ionized. We can precisely discriminate the events triggered by the Rb and Ga contaminants by using the laser ON/laser OFF run mode, as shown in Ref. [10].

The beam intensity at Miniball is expected to be approximately 10⁴ pps for ⁸⁰Zn and between 10⁶ - 10⁵ for ^{74,76,78}Zn. The factor ~5 increases in the beam intensity compared to the previous experiment [10,11], run in 2007, is due to the better performances of the transmission through the REXTRAP-EBIS achieved in the last years (around 5%) [29].

For the beam time estimates of ⁷⁴⁻⁷⁸Zn, expected cross sections were calculated with the GOSIA code on ¹⁹⁶Pt target, 5mg/cm² thick. The beam energy was chosen to be close to the safe energy calculated for the maximum LAB projectile scattered angle equal to 50 degrees corresponding to ~95% of the safe energy.

It should be noted, however, that both the projectile and target are detected in the angular range covered by the segmented silicon detector. For the events corresponding to the recoil detection, the safe energy condition is no longer satisfied at 4.55 MeV/u and in consequence these data cannot be used for B(E2) determination. On the other hand, such experimental conditions favour population of higher-lying states, in particular the 4+ level in ⁸⁰Zn, which observation is among the main goals of this proposal. The reported rate estimates for ⁸⁰Zn listed in Table 1 correspond to recoil detection between 15 and 50 degrees in the LAB frame.

The calculations for ⁷⁴⁻⁷⁸Zn are based on the B(E2,2⁺→0⁺) and B(E2,4⁺→2⁺) matrix elements extracted from our previous experiment. In the case of ⁸⁰Zn, B(E2) estimates from shell-model calculations are used (K.Sieja, private communication).

Yields were calculated assuming the well-known gamma-ray efficiency of Miniball and the aforementioned beam intensities.

isotope	Energy (MeV/u)	Intensity (pps)	2 ⁺ →0 ⁺	4 ⁺ →2 ⁺	6 ⁺ →4 ⁺
⁷⁴ Zn	4.55	5·10 ⁵	6.9·10 ⁴	2235	n.n.
⁷⁶ Zn	4.55	5·10 ⁵	5.4·10 ⁴	1470	n.n.
⁷⁸ Zn	4.55	10 ⁵	5100	37	0.15
⁸⁰ Zn	4.55	10 ⁴	130	20	0.00012

Table1. Expected counting rates per shift.

Expected counting rates in the photo peak per shift for the Coulomb excitation of ⁷⁴⁻⁸⁰Zn accelerated beams are shown in Table1. The counts rates in the 6⁺→4⁺ transition in ^{74,76}Zn are not included because no calculated or measured values are known.

It should be noted that, if the B(E2) values extracted from lifetime measurement were used for ⁷⁴Zn, a 5 times lower counting rate were obtained.

From these expected rates, in order to accumulate enough statistics, **30 shifts** of beam time are requested: 3 shifts for ⁷⁴Zn, 3 shifts for ⁷⁶Zn, 12 shifts for ⁷⁸Zn and 12 shifts for ⁸⁰Zn.

Shifts for setting REX are not included. According to these calculations, we will be able to identify the 4⁺ state in ⁸⁰Zn, other no-yrast states in ⁷⁶⁻⁸⁰Zn and to measure the B(E2,4⁺→2⁺) in ⁷⁴⁻⁷⁸Zn. Possibility of determination of the B(E2,4⁺→2⁺) in ⁸⁰Zn will depend on the collectivity of the 4⁺ state.

5. Safety aspects

The same as for Miniball at REX-ISOLDE

6. References

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *Miniball* + *CD* (*double side silicon strip detector*)

Part of the Choose an item.	Availability	Design and manufacturing
MINIBALL + only CD	<input type="checkbox"/> Existing	<input type="checkbox"/> To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD] installation.

Additional hazards: n.p.