EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

Cu decay into neutron-rich Zn isotopes: shell structure approaching ^{78}Ni

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Remaining shifts: 7 shifts

Abstract: This report presents the status of the IDS experiment IS622, which aimed to study the evolution of the proton shell gap and the stability of the neutron shell gap, N = 50, near the double magic ^{78}Ni [1] in the neutron-rich Zn isotopes. We used a Cu beam to populate excited states in the Zn isotopes via β decay. Using the HPGe clovers, we greatly enhanced the studied level schemes and obtained P_n values. Thanks to the superior $LaBr_3$(Ce) timing resolution, we were also able to measure lifetimes in the tens of ps range. During the first run in 2018, it was not possible to use all the shifts and it was not possible to measure ^{77}Zn or collect enough statistics for ^{78}Zn. Thus, we apply to retain the 7 unused shifts to complete the original goals of the experiment.

1 Motivation, experimental setup/technique

A detailed discussion of the motivation, the method and the experimental set-up with all references can be found in the original proposal [2]. Hence a summary of the scientific motivation and the experimental set-up will be briefly presented here.

The region around nickel isotopes (Z = 28) is the ideal testing ground for nuclear models. In particular, to study the evolution of the single-particle and collective phenomena between harmonic-oscillator N = 40 sub-shell closure ($^{68}_{40}$Ni$_{28}$ [3]) and the N = 50 shell closure ($^{78}_{50}$Ni$_{28}$ [4]). The persistent magicity of N = 50 and Z = 28 in ^{78}Ni could only recently be experimentally demonstrated in last generation fragmentation facilities [1] by tentatively measuring its (2^+_1) and (4^+_1) states. But this isotope is still out of reach of current generation ISOL facilities to perform more stringent test of its magic nature. We have to turn then to the Zn isotopes (with only two more protons than Ni) to perform in-depth nuclear structure studies in this exotic region.

Useful information can be deduced by the study of odd-even Zn isotopes. It is well-known the existence of a strong tensor interaction between the $\nu g_{9/2}$ orbital and the $\pi f_{7/2}$ orbital and pf proton sub-shell ($p_{3/2}$, $f_{5/2}$, $p_{1/2}$). This interaction is attractive between the $\nu g_{9/2}$ and the $\pi f_{5/2}$ single-particle orbit, but repulsive between $\nu g_{9/2}$ and $\pi f_{7/2}$. This interaction causes a reduction on the energy gap between the $\pi f_{5/2}$ and $\pi f_{7/2}$ proton orbitals as neutrons gradually fill the $\nu g_{9/2}$ orbital, with a maximum at ^{78}Ni ($N = 50$) [5]. As a consequence, when going toward more neutron-rich nuclei, the monopole part of the residual interaction plays a dominant role determining the properties of the quasi-particle states and the interaction among them. An inversion of the $p_{3/2}$ and $f_{5/2}$ proton orbitals was predicted and later observed in ^{75}Cu by *Flanagan et al.* [6]. This orbital inversion has not been confirmed for the Zn isotopes in the region.

This interplay between different closed and open shells also gives rise to the shape-coexistence phenomenon. So far it was believed to happen in specific regions which had one magic number or semimagic number for one of the nucleons but an open shell of the other one, north-east of ^{56}Ni [7]. But very recent laser spectroscopy results [8] have shown the presence of shape coexistence in ^{79}Zn. If the closest odd-Zn nucleus to the doubly-magic ^{78}Ni presents this effect, it can be expected to happen at even lower energies in lighter ones in the mid-shell. It is, thus, most interesting to search for low-lying

0^+ states on even Zn isotopes approaching ^{80}Zn, as they will reveal critical information on the magicity of N = 50 and the presence of shape coexistence in the region.

In light of the recent results, it is clear the necessity to investigate and extract new experimental information about the Zn isotopes. This information will prove to be an invaluable input for future Large-Scale Shell-Model calculations and improve our understanding of this particular region of the nuclear chart.

But the interest in the neutron-rich Zn isotopes does not focus only on their nuclear structure. The magicity of N = 50 far from stability plays a crucial role in the rapid neutron-capture (r) process, so it is of great importance in the field of astrophysics. The r-process is assumed to be an extremely fast sequence of neutron captures and β decays, responsible for the nucleo-synthesis of most of the elements heavier than Fe. The r-process path goes through the neutron-rich regions, with the so-called waiting points (bottle necks) happening at the magic numbers. Thus some of the most important physics parameters for the theoretical model predictions are the β decay, half-lives and the β-delayed neutron emission branches of the nuclei around the waiting points, such as ^{78}Ni with $N = 50$. While this nucleus remains inaccessible to ISOL facilities, valuable information can be extracted from neutron-rich Cu beams. The β-n branches for these isotopes present large uncertainties and conflicting measurements, and thus, experiments with Cu beams present a perfect opportunity to measure β-n branches with a very high astrophysical value. Moreover, it has been shown that the neutron-capture rate of ^{78,79}Zn can cause the largest change (at least 15%) in the overall abundance pattern [9], so any information about these nuclei will help constrain the theoretical models.

Experimental setup

The experiment was performed at IDS using 4 HPGe clover detectors for high precision gamma spectroscopy and 2 LaBr$_3$(Ce) crystals and one thin plastic scintillator for β-particles in close geometry for fast timing (see Fig 1). The beam was implanted in an aluminiced mylar moving tape at the center of the array. Appropriate cycles to minimize the beam contaminants were employed for each different mass. The collaboration plans to use the same setup but with a new tape station provided by KU Leuven in the remaining shifts.

2 Status Report

Accepted Isotopes: $^{74-78}$Cu.

Performed Isotopes: $^{74-76}$Cu and ^{78}Cu partially.

The experiment was carried out at the ISOLDE Decay Station (IDS) setup in May-June 2018. The yields were lower than was previously measured. However, the Ga contamination was not more than 1 order of magnitude higher than the most exotic Cu isotope measured, a level that can be easily handled in the off-line analysis. No presence of Rb isobaric contamination was observed during the experiment. The Resonance Ionization

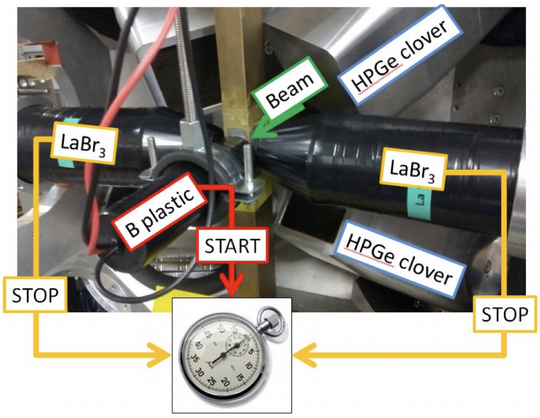

Figure 1: Scheme of the setup at IDS for fast-timing and β decay.

Laser Ion Source (RILIS) is fundamental for the yield production of Cu beams. During this experiment two different lasers schemes were employed. The traditional scheme based on UV lasers were set-up, however it required continuous interventions to keep a constant laser power onto the primary target. Therefore, The RILIS team tested a new laser scheme using Ti:Sa laser developed at TRIUMF. With this new scheme we observed an improvement of 20% in the yield production and the interventions were reduced by a third.

During the course of the experiment, the Cu yield production by the target dropped by almost one order of magnitude for the most exotic case, ^{78}Zn. As a consequence, the experiment could not run any $A = 77$ beam. Nevertheless, the less exotic isotopes, $^{73-75}$Cu, and the exotic ^{78}Cu were measured without any further incident.

Some highlights about the analysis

The data analysis is in at an early stage, but we can present some preliminary results from the β decay of ^{78}Cu and the γ spectroscopy of its daughters. According to the literature, the P_n in ^{78}Cu is higher than 50%. *Van Roosbroeck et al.* obtained a lower limit, $\geq$ 65(20)% [10] and *Korgul et al.* measured a value of 65(8)% [11]. From the data acquired in 2018, we can deduce a preliminary value of 55(7)%, in agreement with previous results but slighter lower than them.

Regarding to the level scheme populated by the β and β-delayed neutron decay of ^{78}Cu, several new γ-ray lines have been observed for both daughter nuclei, see Fig. 2. For ^{77}Zn, the two γ decay lines at 115 and 689 keV reported by *Van Roosbroeck et al.* were also observed [10]. In addition, two new lines at 244 and 932 keV has been observed, both in coincidence with the 114 keV line. The level scheme for ^{78}Zn has been also investigated. All the known transitions has been confirmed and in addition, four new γ transitions above the (6^-) state at 3105 keV have been observed for the first time and placed in the level scheme, as it is shown in Fig 2. The $8^+ \to 6^+$ transition was observed in γ singles, still, how the 8^+ state is populated from the (5^-) g.s. of the mother nucleus is not fully understood, but it calls into question those assignments. Moreover if we consider that the β decay experiments from Ref. [10, 11] did not observe this isomeric level, we see that the placement of this state in the g.s. band is tenuous at best. Running the additional shifts would allow us to obtain enough statistic to see the $8^+ \rightarrow 6^+$ transition in $\gamma\gamma$ and confirm its placement in the level scheme. Given the uncertainty around this level, a re-measurement of this value is desirable. We expect to extract more information about the β decay of ^{78}Cu in further analysis, as well as for the rest of nuclei measured, including extracting lifetimes. Although collecting more data of ^{78}Cu would be beneficial for the reduction of the errors for the lifetime of the 8^+ isomer state and the P_n in ^{78}Cu. And it will help to the comprehension of this key nucleus.

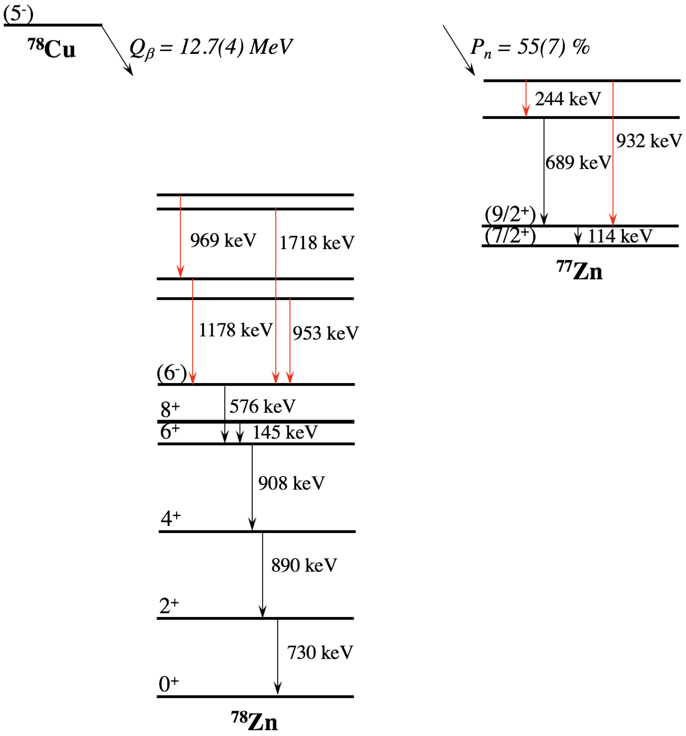

Figure 2: Preliminary deduced β decay scheme of ^{78}Cu Red arrows represent the new γ lines observed and the black arrows are taken from the literature [10, 11].

3 Future plans

Future plans with remaining shifts:

(i) Envisaged measurements, beam energy, and requested isotopes.
The second part of the experiment IS622 will be devoted to study the β-decay and the lifetime of the excited states in ^{77,78}Zn (7 shifts in total). This measurement requires the standard UC$_x$ target source with neutron converter and the quartz line in conjunction with the laser ionization source (RILIS). We strongly support the use of the laser scheme developed at TRIUMF based on Ti:Sa lasers for the Cu isotopes. During the run in 2018, this new scheme was employed and proved to be reliable and very stable during the experiment.

(ii) Have these studies been performed in the meantime by another group?
No and it cannot be performed anywhere else. Only ISOLDE can provide this neutron-rich Cu isotopes with enough intensity. For example, the ISOLDE direct competitor, TRIUMF, has not developed this exotic Cu beams.

(iii) Number of shifts required for each isotope
During the run in 2018 we were not able to collect any data at all for ^{77}Zn via β decay of ^{77}Cu beam implantation and as it was mentioned before in Section 2, increasing the statistic for ^{78}Zn will allow to improve the accuracy for the lifetime of the 8^+ isomer state and the P_n value. Hence, we would like to request the use of the 7 shifts, distributed at is shown in Table 1, for the achievements of the goals of the IS622 proposal.

Isotope	$T_{1/2}$	Yield [ions/μC]	β-γ_{LaBr}-γ_{LaBr} [Counts/shift]	β-γ_{LaBr}-γ_{Ge} [Counts/shift]	Shifts
^{77}Cu	469 ms	$2.0{\cdot}10^3$	15	75	3
^{78}Cu	342 ms	$2.0{\cdot}10^2$	4.6	23	4

Table 1: Summary of the yields expected, counts expected for the most relevant transitions applying β-γ_{LaBr}-γ_{LaBr} and β-γ_{LaBr}-γ_{Ge} coincidences, and the shifts estimated for ^{77,78}Cu. Adapted from the original proposal [2].

Summary of requested shifts: 7.

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