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Addendum to the IS412 experiment

Coulomb excitation of neutron-rich nuclei with MINIBALL at REX-ISOLDE: towards the N = 50 shell closure

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Abstract

We propose to study the properties of neutron-rich nuclei towards ^{78}Ni via Coulomb excitation experiments using the REX-ISOLDE facility coupled with the highly efficient MINIBALL array. The first Coulomb excitation experiment in the vicinity of ^{68}Ni at REX-ISOLDE has been successfully performed showing the feasibility of such experiments. The analysis is underway and new and reliable information on $B(E2,0^+\rightarrow 2^+)$ values for ^{74,76}Zn will be obtained. These results will shed light on the evolution of collectivity around the Z=28 proton closed shell and the N=40 neutron subshell. We would like to extend this knowledge to ^{78,80}Zn as well as to ^{68,70}Ni. In addition, we expect to perform multiple step Coulomb excitation of ^{74,76}Zn. Our calculations show that with an energy of 3.1 MeV/nucleon cross-sections of these reactions are significantly increased. We request 24 shifts of beam time for ^{74,76,78,80}Zn, specific target-ion source developments to improve the production and selectivity of the short lived zinc and nickel isotopes and 21 shifts of beam time for nickel isotopes.

Introduction

The structure of nuclei in the region around neutron-rich nuclei with Z ~ 28 has been a subject of considerable studies [1-7, 9-13]. The motivation for these studies comes from the desire to investigate neutron-rich nuclei below the N = 50 major shell gap with the eventual goal of studying doubly magic ^{78}Ni, a very neutron-rich doubly magic nucleus that can be studied in a foreseeable future. While there are many predictions for this nucleus, it is not definitely known to what extent and how the single particle levels – and, as a consequence, the magic numbers - move in regions with such a large neutron excess. In addition, the details of the structure of nuclei in this region and ^{78}Ni in particular are of interest for astrophysical calculations since they lie at the beginning of the r-process path [15].

Many experiments have been performed in order to extract information on the nuclear properties of isotopes in the region around ^{68}Ni (subshell closure at $N = 40$) and the doubly magic ^{78}Ni nucleus. Mainly decay [5, 7, 9, 14], ground state [1] and long lived isomeric states [3-4, 6, 10, 14] properties have been deduced while data from collective excitations are still scarce [11-13]. In order to further study the structure of nuclei with $40 < N \leq 50$ and in particular the delicate interplay between single-particle properties and their interaction with the underlying core and collective phenomena, a program to measure Coulomb excitation of neutron-rich Zn and Ni nuclei was started at REX-ISOLDE [21].

After technical developments on the REX-EBIS and TRAP have been accomplished, radioactive beams of species lying in the vicinity of neutron-rich ^{68}Ni and ^{78}Ni are now available at the REX-ISOLDE facility with beam energies of 2.2 and 3.1 MeV/nucleon. Thus, in last October, Coulomb excitation of ^{74}Zn and ^{76}Zn beams below the Coulomb barrier was performed for the first time and valuable information on their $B(E2, 0^+_{g.s.} \rightarrow 2^+_1)$ values were obtained. We propose to continue this program to investigate by Coulomb excitation the nuclear structure of neutron-rich ^{78,80}Zn and ^{68,70}Ni. In association with the REX-ISOLDE facility, we will use the highly efficient Ge MINIBALL array for the detection of γ-rays and the segmented CD detector system for the detection of scattered particles.

Status on the recent experiment of Coulomb excitation of ^{74,76}Zn

In order to study the feasibility of Coulomb excitation experiments in the vicinity of ^{68}Ni, the first experiment on Coulomb excitation of Zn neutron-rich nuclei was performed last October at REX-ISOLDE (IS412). Radioactive beams of ^{74}Zn and ^{76}Zn with a maximum intensity at 60 keV of up to 1.3×10^8 ions/s were successively accelerated at an energy of 2.2 MeV/nucleon through REX-ISOLDE. They impinged on a 1.7 mg/cm^2 thick ^{120}Sn target. The scattered charged particles were detected by the CD-detector while coincident γ-rays from the Coulomb excitation were detected by the MINIBALL array. Coincident particle-γ events have been selected from the particle-γ time spectrum as shown in figure 1 and figure 2 for ^{74}Zn and ^{76}Zn respectively. Figure 1 shows the γ-rays in coincidence with the ^{74}Zn ions scattered into the CD detector. A Doppler broadened γ-ray transition of 606 keV can be observed, corresponding to the de-excitation of Coulomb excited ^{74}Zn beam on a ^{120}Sn target. Similarly, figure 2 shows the γ-rays in coincidence with the Coulomb excited ^{76}Zn ions scattered into the CD detector and a Doppler broadened γ-ray transition of 599 keV can be observed from the de-excitation of Coulomb excited ^{76}Zn beam on a ^{120}Sn target. Note that these are preliminary spectra and that Doppler corrections have not yet been applied.

The maximum intensities that could be delivered by the ISOLDE separator were 1.3×10^8 ions/s for ^{74}Zn and 3.2×10^7 ions/s for ^{76}Zn. However, due to both a punctual electronics problem and too high instantaneous count rates in the CD detector, the experiment was realised at reduced intensities of about 2×10^3 accelerated ions/s on the ^{120}Sn target for both ^{74}Zn and ^{76}Zn. At these intensities, we ran ^{74}Zn for 30 hours and ^{76}Zn for 31 hours. During part of beam time laser on and laser off spectra were accumulated in order to disentangle the contribution of surface ionised Ga and other isobaric contaminants. We expect a final result with a 15 % total uncertainty.

Note that a Coulomb excitation measurement of ^{72}Zn ($T_{1/2}$=46.5 h) could not be performed because of its very long half-life. But, apart from this, the aim, as phrased in the initial proposal [21]: "… to perform a first set of experiments which will allow to test the feasibility of Coulomb excitation experiments using REX-ISOLDE and the MINIBALL detectors in this region as well as to get new and reliable experimental data …" (on ^{72,74,76}Zn) has been met with the first experimental campaign. Therefore we feel confident that the next step in this experimental campaign to investigate the nuclear structure in this part of the nuclear chart, as outlined below, can be undertaken.

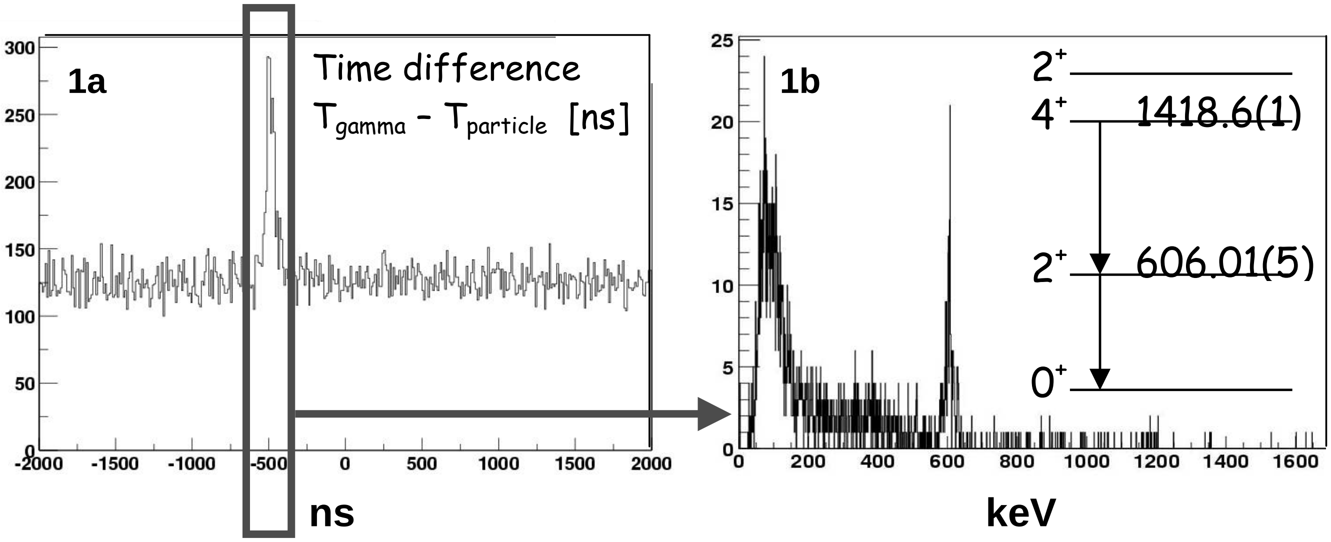

Figure 1a (left): ^{74}Zn γ- particle time coincidence window, figure 1b(right): ^{74}Zn coincident γ-ray spectrum

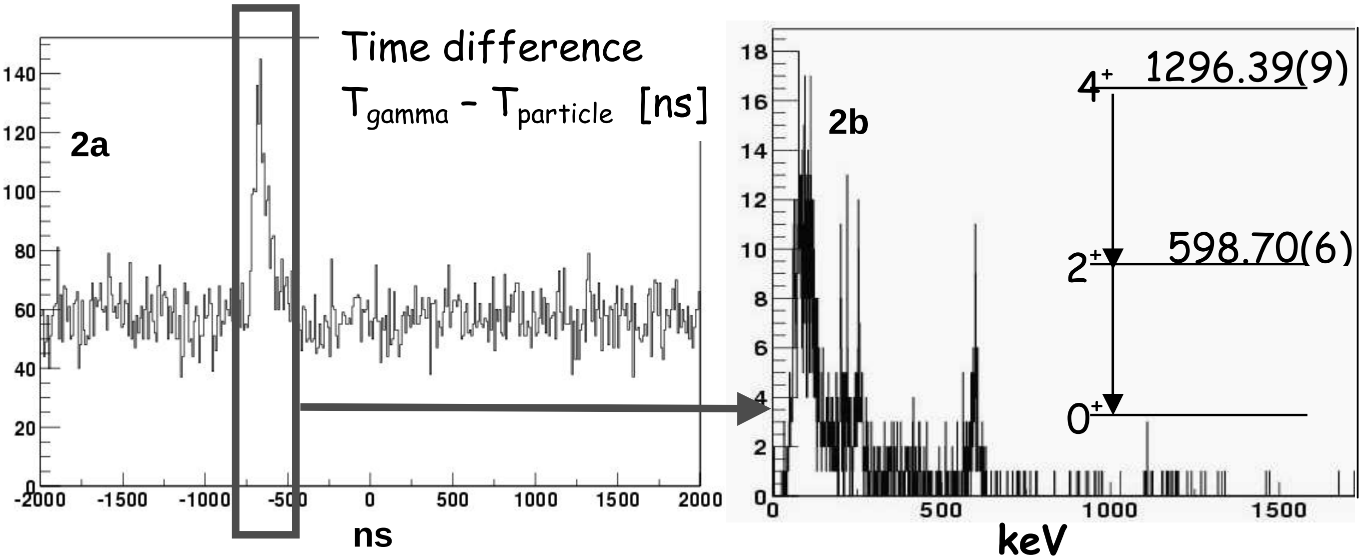

Figure 2a (left): ^{76}Zn γ- particle time coincidence window, figure 2b(right): ^{76}Zn coincident γ-ray spectrum

Physics case for this addendum

Ni isotopes

Because of its peculiar behaviour, ^{68}Ni has been the object of many studies for the past years. This interest arose 20 years ago [1,2] from the first observation of the 2^+ state at an unexpectedly high energy (2.033 MeV) compared to the neighbouring Ni nuclei whereas the second 0^+ state was observed at a lower energy of 1.77 MeV. These characteristics (high energy of the 2^+ state and 0^+ state below) were interpreted as the signature of a "quasi magic" nucleus.

Since then, many experimental observations have tested the supposed magicity of ^{68}Ni [3-7, 9-10]. The most recent experimental work concerned the measurement of the quadrupole transition probability B(E2) of the first excited state obtained from Coulomb excitation of ^{68}Ni at relativistic energies [12]. This work showed that, even though the B(E2) value is incredibly low – indication that would reinforce the hypothesis on the magic character of ^{68}Ni, such a behaviour could be explained by the specificity of the orbitals involved ($p_{3/2}\ f_{5/2}\ p_{1/2}\ g_{9/2}$) and by the scattering of a neutron pair across the N = 40 subshell.

More recent theoretical calculations [16] indicate that only a fraction of the B(E2) strength is contained in the $0_{g.s.}^+ \rightarrow 2_1^+$ transition while most of it is collected in excited states around 5 MeV in which proton excitations contribute a lot.

It is interesting to note that this special character of ^{68}Ni is washed out when adding or removing protons as e.g. evidenced in the low 2^+ excitation energies and the large B(E2) values in the Zn isotopic chain. In addition, the first excited 2^+ state in ^{72}Ni has been recently identified showing the continuous lowering of the 2^+ states beyond the N=40 shell [14]. Also, from the combination of beta decay studies, laser spectroscopy studies and mass measurements (performed at ISOLDE and LISOL), peculiarities in the structure of ^{70}Cu became clear showing that ^{68}Ni does not fully behave like a core nucleus [17-18].

Zn isotopes

Apart from the interest in the nickel isotopic chain, its closest even-even neighbours, the zinc isotopes, present many interesting features. At REX-ISOLDE we have the unique opportunity to study via Coulomb excitation the very neutron-rich Zn nuclei up to ^{78}Zn and even ^{80}Zn which is lying at the neutron shell closure N=50. These measurements will show the evolution of collectivity towards the closed N=50 neutron shell. Figure 3 [18] shows the energy systematics of the even-even Zn isotopes from ^{60}Zn (N=30) to ^{78}Zn (N=48). Beyond ^{70}Zn (N=40) a drop in the excitation energy of the first excited 2^+ state is visible while it rises again towards N=50. The aim of the proposed experiment will be to determine the quadrupole transition matrix elements as they should reflect the degree of collectivity present in these states. Note also that the energy of the 2^+ state in ^{78}Zn is still under discussion as none of the two experiments that have identified γ-rays in ^{78}Zn could firmly assign the order of the 4^+-2^+-0^+ cascade [18-19]. The present proposal will definitely be able to solve this problem.

Recently at GANIL an intermediate energy Coulomb excitation experiment of ^{74}Zn and ^{70}Ni has been performed [24]. It will be very interesting to compare our results obtained with beam energies below the Coulomb barrier (and thus with "safe energies") with those results.

In conclusion, further experimental investigations both of the nickel isotopic chain and of neighbouring nuclei with Coulomb excitation is needed as it will help to further understand the interplay between single and collective excitations in the region around ^{68}Ni. In addition, Coulomb excitation of isotopes as neutron-rich as ^{78}Zn and ^{80}Zn (the latter being semi-magic) will provide crucial information on the evolution of magicity in regions with large neutron excess.

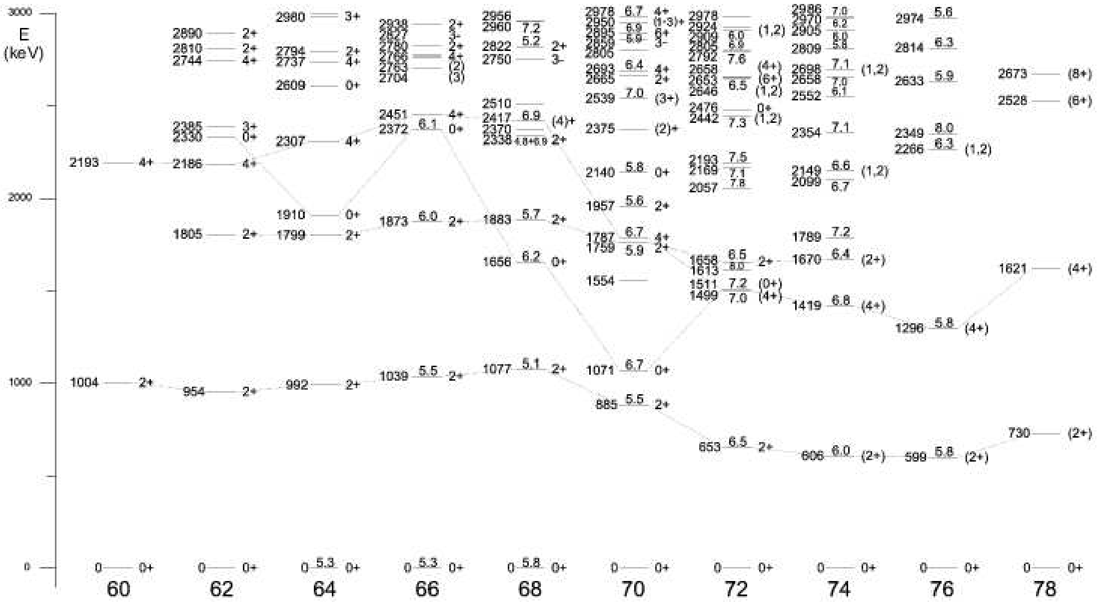

Figure 3: energy systematic in the even-even Zn isotopic chain

Physics goals

With this addendum to the IS412 proposal we aim at:

- Determining with an improved accuracy the B(E2, $0^+ \rightarrow 2^+$) for ^{74,76}Zn. The previous experiment proved the feasibility of Coulomb excitation of radioactive ion beams in the vicinity of ^{68}Ni. However, due to the used reduced intensities of the incident beams, the uncertainties on the B(E2) values obtained from this measurement will not reach values better than 15 %.

- Measuring the B(E2, $2^+ \rightarrow 4^+$) values of these isotopes, thus providing complementary information on their structure, in particular on the character of the excitation.

- Firmly identifying the 2^+ state of ^{78,80}Zn and measuring the corresponding B(E2, $0^+ \rightarrow 2^+$) of these isotopes.

- Measuring the B(E2, $0^+ \rightarrow 2^+$) values of ^{68,70}Ni.

Available information on the nuclei of interest as well as cross-sections is summarised in table 1. Information on ^{68,70}Ni is taken from reference 12. Information on the energies of the excited states of ^{74,76,78}Zn is taken from references 19, 22 and 23. The unknown B(E2) values for the Zn isotopes were obtained by using the ANTOINE shell model code with the effective proton and neutron charges e_π=1.9e, e_ν=0.9e and using the ($p_{3/2}$ $f_{5/2}$ $p_{1/2}$ $g_{9/2}$) shell model space with ^{56}Ni as a core [25].

	E(2^+), keV	B(E2, $0^+ \rightarrow 2^+$), e^2fm^4	σ, barn	E(4^+), keV	B(E2, $2^+ \rightarrow 4^+$), E^2fm^4	σ, barn
^{68}Ni → ^{120}Sn	2033	255	$6.9\ 10^{-3}$		-	-
^{70}Ni → ^{120}Sn	1264	410	$3.1\ 10^{-3}$		-	-
^{74}Zn → ^{120}Sn	606	1770	1.16	1418	718	$1.4\ 10^{-2}$
^{76}Zn → ^{120}Sn	599	1605	1.11	1296	680	$1.9\ 10^{-2}$
^{78}Zn → ^{120}Sn	730	1155	0.84		-	-

Table 1: Energy of E(2^+) levels, B(E2, $0^+ \rightarrow 2^+$) values for ^{68,70}Ni, ^{74,76,78}Zn and E(4^+), B(E2, $2^+ \rightarrow 4^+$) values for ^{74,76}Zn with corresponding values for the cross section at an energy of E=3.1 MeV/u and using a ^{120}Sn target.

Experimental conditions

Coulomb excitation

The Coulomb excitation cross-sections have been calculated using the code GOSIA following the prescriptions given in [20]. The evolution of cross sections for Coulomb excitation as a function of the target material is shown in figure 3 for ^{72,74}Zn both at 2.2 and 3.1 MeV/nucleon. As mentioned in the proposal P-158 [21], even though Ni seems to be the best target, it does not fulfil the safe distance condition for all scattering angles at a beam energy of 3.1 MeV/u. On the contrary, a Sn target is well suited at almost all scattering angles.

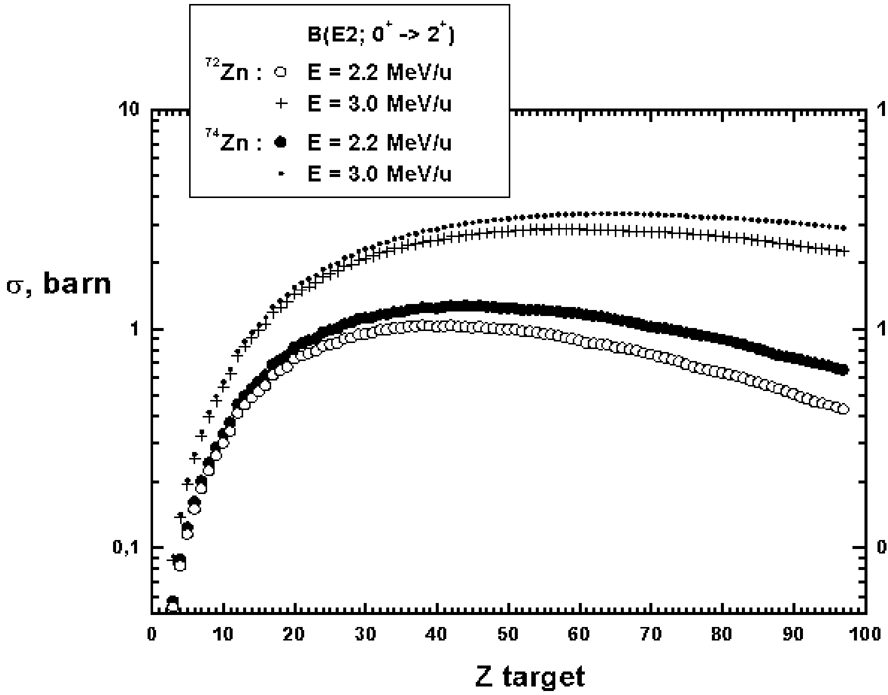

Figure 4: Total Coulomb excitation ($0^+ \rightarrow 2^+$) cross sections for ^{72,74}Zn depending on the charge of the target.

The cross sections for Coulomb excitation of the first 2^+ excited states in ^{74,76,78}Zn and ^{68,70}Ni as well as multiple-step Coulomb excitation of ^{74,76}Zn 4^+ states are shown in table 2. They are integrated over the safe angles covered by the CD detector for both targets.

Beam	Target	Safe angle	Differential cross-sections (in mb/sr × mg/cm^2)	
			$0^+ \rightarrow 2^+$	$2^+ \rightarrow 4^+$
^{74}Zn	^{58}Ni	24.4°	39	0.31
	^{120}Sn	47.4°	184.3	2.2
^{76}Zn	^{58}Ni	23.5°	44	0.45
	^{120}Sn	45.4°	177.3	3.1
^{78}Zn	^{120}Sn	43.6°	134.4	-
^{68}Ni	^{120}Sn	49.2°	1.1	-
^{70}Ni	^{120}Sn	46.8°	0.5	-

Table 2: Coulomb excitation cross-sections of different isotopes and transitions integrated over the safe angles in the laboratory system for ^{58}Ni and ^{120}Sn targets

Experimental set-up, count rates and requested beamtime

We would like to measure Coulomb excitation of neutron-rich Zn isotopes produced by ISOLDE from the proton bombardment of a Uranium Carbide target and ionised using a resonance ionisation laser ion source. A laser shutter as well as a Ge detector at the beam dump will be used in order to disentangle contamination from isobaric species. The γ-rays from the Coulomb excitation will be detected by the MINIBALL array, consisting of 24 six-fold segmented Ge-detectors. The coincident scattered charged particles will be detected by the CD-detector, a highly segmented double-sided silicon strip detector. We assume a γ-ray efficiency of 10 % at 1 MeV. The Ge-detector segmentation will allow Doppler correction of the γ-ray spectra. The calculation of the angular distribution of the de-exciting γ-rays based on [19] shows that the emission is practically isotropic: the correlative function $W(\theta_{\gamma\text{-Zn}})$ is in diapason $0.8 < W(\theta_{\gamma\text{-Zn}}) < 1.2$ for all angles. We assume that the primary ISOLDE rate will be reduced by a factor of 1/100 due to the transmission efficiency through REX-ISOLDE. The number of expected events in the photopeak is summarised in table 3 for a 2 mg/cm^2 ^{120}Sn target assuming an energy loss of 18 MeV/(mg/cm^2) in the target.

We typically need 10^3 counts in the photopeak for an accurate determination of the B(E2) value. Therefore we request for this addendum a total of 45 shifts of beam time using a Uranium Carbide target.

The first 24 shifts will be dedicated to the study of neutron-rich zinc isotopes up to ^{80}Zn. The first 5 shifts will be used to set up and calibrate the accelerator (3 shifts) and the detectors (2 shifts). A calibration run of a stable ^{66}Zn beam can be used in order to fully take into account the kinematics and other effects needed to understand the unfolding of the B(E2) values. A maximum of 2 shifts are in principle needed to measure the B(E2) values of the 2^+ and 4^+ states of ^{74}Zn. A number of 6 shifts are then required to measure the B(E2) values of the 2^+ and 4^+ states of ^{76}Zn with a reasonable accuracy. The measurement of the B(E2) value of the 2^+ state of ^{78}Zn will take 8 shifts. Finally, we request 3 shifts in order to test the measurement of ^{80}Zn Coulomb excitation.

For the study of ^{68}Ni, we request an additional beam time of 21 shifts. Despite a low count rate, a measurement of ^{68}Ni B(E2, $0^+\rightarrow2^+$) value below the Coulomb barrier is essential in order to confirm the result obtained at relativistic energy [12].

	Primary ISOLDE yield (atoms/s)	Beam energy at the entrance of the target (MeV/u)	Weighted $\sigma_{2+\to0+}$ (barn)	Weighted $\sigma_{4+\to2+}$ (barn)	Events in the photopeak (counts/hour)		Number of shifts
					$2^+\to0^+$	$4^+\to2^+$	
^{74}Zn	1.3×10^8	3.1	1.16	$1.4\ 10^{-2}$	5416	65	2
^{76}Zn	3.2×10^7	3.1	1.11	$1.9\ 10^{-2}$	1283	22	6
^{78}Zn	1×10^6	3.1	0.84	-	30	-	8
^{80}Zn	1×10^5	3.1					3 (test)
^{68}Ni	8×10^5	3.1	$6.9\ 10^{-3}$	-	$2\ 10^{-1}$	-	21
^{70}Ni	2×10^4	3.1	$3.1\ 10^{-3}$	-	$2.3\ 10^{-3}$	-	-

Table 3: Brief summary of the expected yields, weighted cross sections, counting rates and shifts required for the nuclei that will be investigated using a 2 mg/cm^2 thick ^{120}Sn target. The cross-sections are weighted over the target assuming a beam energy loss of 18 MeV/(mg/cm^2) in the target.

Request for target developments

In order to extend these studies to even more neutron-rich nickel and zinc isotopes we request a special target development program to increase the production rate and the purity of the ^{80}Zn and ^{82}Zn beams as well as for the $^{A>68}$Ni beams. This issue has been discussed with the target-ion source group and several options can be studied [26]. We would like to request a specific target-ion source test beam time that will be devoted to this specific question.

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