EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the INTC Committee

Coulomb excitation of neutron-rich nuclei between the N=40 and N=50 shell gaps using REX-ISOLDE and the Ge MINIBALL array

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Abstract

We propose to perform Coulomb excitation experiments of neutron-rich nuclei in the vicinity of ^{68}Ni towards ^{78}Ni using the REX-ISOLDE facility coupled with the highly efficient MINIBALL array. Major changes in the structure of the atomic nucleus are expected around the N = 40 subshell closure. Recent B(E2) measurements suggested that ^{68}Ni behaves like a doubly magic nucleus while neutron-rich Zn isotopes with N>38 exhibit a sudden increase of B(E2) values which may be the signature of deformation. We would like to check and test these predictions for neutron-rich nuclei in the vicinity of N = 40 and N = 50 shell closures like ^{72}Zn, ^{74}Zn, ^{76}Zn, ^{68}Ni, ^{70}Ni. Our calculations show that an energy upgrade from 2.2 to 3 MeV/nucleon will be of crucial importance for a part of our study while some nuclei can still be very efficiently studied at an energy of 2.2 MeV/nucleon. Therefore, to perform our experiment in an efficient way, we request 21 shifts of beam time before the energy upgrade 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. Then, after the energy upgrade, we will request additional shifts of beam time to continue our study.

Introduction

The region around ^{68}Ni (subshell closure at N = 40) and the doubly magic ^{78}Ni nuclei is of interest because of its delicate interplay between single-particle properties and

their interaction with the underlying core and collective phenomena. These nuclei have already been intensively investigated but mainly decay and ground-state (as well as long lived isomeric state) properties have been deduced yet. These properties contain of course very valuable information but the picture is not complete. Coulomb excitation experiments can provide important and complementary information.

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 a beam energy of 2.2 MeV/nucleon. This energy is sufficient to perform in a very efficient way sub barrier Coulomb excitation of some of these very exotic species. Therefore we propose to use these new possibilities to investigate by Coulomb excitation the nuclear structure of neutron-rich nuclei in the region of ^{68}Ni and ^{78}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.

Physics motivations

An important goal of nuclear structure physics is the determination of the behaviour of nuclei far from stability. Recent theoretical investigations [1,2] suggest that the structure of the atomic nucleus is different going from the valley of stability to the drip lines. In particular, new shell closures may appear [3,4,5] (or disappear [6,7]) when increasing the number of neutrons. One famous example is the measurement of the first 2+ excited states and B(E2) values along the Ni isotopic chain (see figure 1).
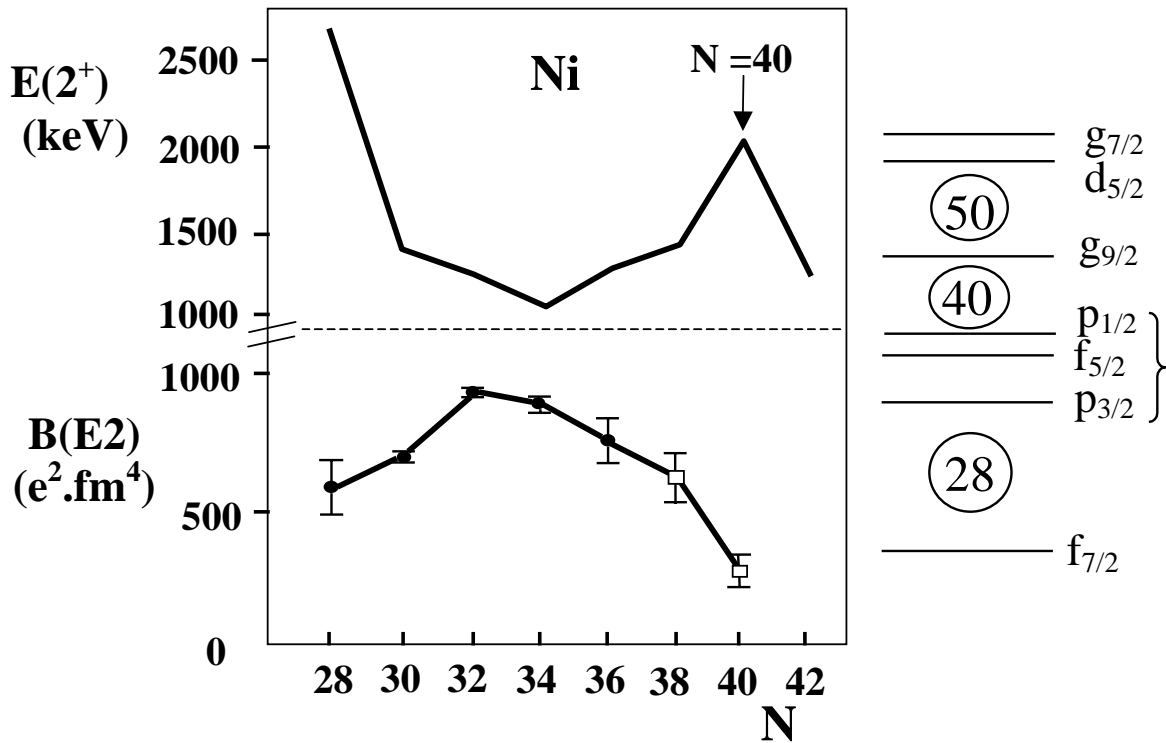

Figure 1 : E(2$^+$) and B(E2) systematic in the Ni isotopic chain. Very recent B(E2) values obtained from the GANIL experiment [3] are shown with open squares.

While the evolution of the 2+ excited state energy suggests the location of neutron shell and subshell closures at N = 28 and N = 40 respectively, the B(E2) values

clearly indicate a stronger reduction of collectivity when approaching the N = 40 subshell closure than at the N = 28 shell closure. In contrast, no shell closure effect is seen in the observed neutron separation energies and their differences [8]. Furthermore, the apparent shell closure effect seems to be washed out immediately with the addition of one single neutron [5]. The large B(E2) value of ^{56}Ni is now understood as originating from the wide possibility of making particle-hole quadrupole excitation across N,Z = 28 in the fp shells for protons and neutrons and a consequence of a strong proton-neutron interaction characterizing N = Z nuclei.

The B(E2) value of ^{68}Ni is surprisingly low and can be compared to that of a doubly magic nucleus. The low B(E2) value may be due either to the presence of the subshell closure at N = 40 or to the specific (p1/2, g9/2) orbitals involved. If this low value can be explained by the presence of the N = 40 subshell closure, it is predicted that the strength of this subshell closure will gradually decrease with the addition or removal of nucleons as a consequence of pairing effects and these effects will finally lead the nucleus to deformation. The Zn isotopic chain (see figure 2) illustrates perfectly this evolution from subshell closure to deformation. Up to ^{68}Zn, the B(E2) values exhibit a behaviour similar to the Ni isotopic chain but, starting at N=40, the B(E2) values suddenly deviate exhibiting a behaviour similar to the Ge isotopic chain.

This is why an extended survey of the whole region will bring crucial information about how the structure of the atomic nucleus develops with the number of neutrons and protons.

Because of the intensities that can be provided by REX-ISOLDE, the highly efficient MINIBALL array is the ideal tool to perform Coulomb excitation experiments. Since sub barrier Coulomb excitation is a very well known process, the results will provide new and reliable experimental data for a better description of the shell model far from stability as well as on the evolution of collectivity in this region which is also relevant for the description of the r-process.
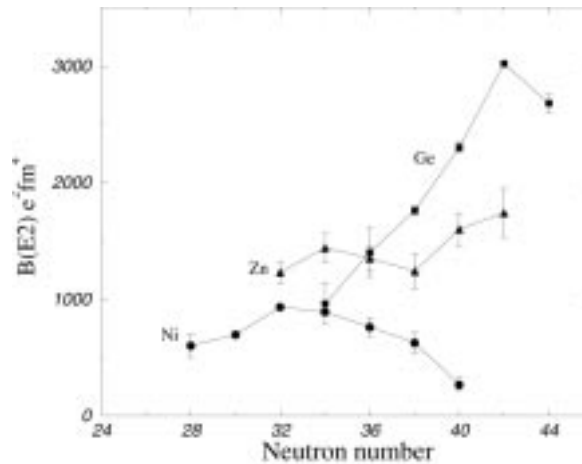

Figure 2 : B(E2) systematic in the Ni-Zn-Ge isotopic chains

We propose to split our experiment into two main parts in order to make the best use of the beam energies available at REX-ISOLDE. In the first part, we will use the current beam energy of 2.2 MeV/nucleon and our proposal will be devoted to the study of the evolution of collectivity through the N = 40 subshell closure in the Zn isotopic chain up to ^{76}Zn and to the measurement of B(E2,2+→4+) values in neutron-rich Zn isotopes. In the second part, we will perform Coulomb excitation of the Ni isotopic chain with a beam energy of 3 MeV/nucleon.

As a future project, we also plan to perform Coulomb excitation of odd nuclei and with isomeric beams. Coulomb excitation at intermediate energies has been performed on even nuclei but, because of the large γ-ray background at low γ-ray energy and poor energy resolution, the measurement of low γ-ray transitions as in the case of odd-even and odd-odd nuclei is cumbersome. Hence sub-barrier Coulomb excitation is an advantageous method to perform such measurements.

Coulomb excitation parameters

In this proposal, we would like to study Coulomb excitation of a number of nuclei lying in the vicinity of ^{68}Ni and ^{78}Ni. Therefore we will firstly determine the Coulomb excitation cross-sections of the considered nuclei. The total cross section of electric quadrupole Coulomb excitation of a (A_p, Z_p)-projectile on a (A_t, Z_t)-target is:

$$\sigma_{E2} = \left(\frac{Z_t e}{\hbar v_i}\right)^2 \frac{1}{4a^2} B(E2) f_{E2}(\xi, \eta_i) \quad (1)$$

where $a = \dfrac{Z_t Z_p e^2}{2m_0 v_i v_f}$ is the distance of closest approach in head-on collision, $m_0 = A_t A_p/(A_t + A_p)$ is the reduced mass, (v_i, η_i), (v_f, η_f) are the velocities and the Sommerfeld parameters $\eta_{i,f} = \dfrac{Z_t Z_p e^2}{\hbar v_{i,f}}$ for ingoing and outgoing particles respectively, $\xi = \eta_f - \eta_i$ is the adiabaticity parameter and the function $f_{E2}(\xi, \eta_i) = f_{E2}(\xi) \cdot R_2(\eta_i, \xi)$ is tabulated in [9].

These calculations have been performed for different even-even nuclei. For some of them, the energies of the first 2+ state as well as B(E2) values have already been determined in previous experiments like, for example, ^{68}Ni and ^{72}Zn (see figure 1, table 1 and references [3,4,10]) and these values are used for our calculations. When only the energy of the 2+ excited state was known (like, for example, ^{70}Ni [5,11]), we used the values from theoretical calculations given in the literature ([3] for example) in order to extract an estimate for the B(E2) values.

	E(2$^+$), keV	B(E2, 0$^+$→2$^+$), e^{2}fm^4	σ, barn	E(4$^+$), keV	B(E2, 2$^+$→4$^+$), e^{2}fm^4	σ, barn
^{68}Ni → ^{58}Ni	2033	255	0.003			
^{70}Ni → ^{58}Ni	1264	410	0.05			
^{72}Zn → ^{58}Ni	653	1740	0.80	1500	900	0.07
^{74}Zn → ^{58}Ni	606	1760	0.94	1418	700	0.08

Table 1 : Energy of E(2$^+$) levels, B(E2, 0$^+$→2$^+$) values for ^{68,70}Ni, ^{72,74}Zn and E(4$^+$), B(E2, 2$^+$→4$^+$) values for ^{72,74}Zn with corresponding values for the cross section at an energy of E=2.2 MeV/u and using a ^{58}Ni target.

Conditions for Coulomb excitation

A rough criterion for the possibility of Coulomb excitation of a nucleus is set by the adiabaticity parameter ξ<1. This condition is valid for Coulomb excitation of the Zn isotopes on all considered targets at the energy of 2.2 MeV/u as well as 3.0 MeV/u. This is also the case for ^{70}Ni but for ^{68}Ni this condition is not fulfilled at the energy of 2.2 MeV/u for practically all targets (see further on, figure 5).

In order to extract accurate B(E2) values from Coulomb excitation measurements we should be sure that there is no nuclear interaction between the target and the projectile. Necessary and sufficient conditions for this are the following:

1. The distance of closest approach depending on the scattering angle θ_{CMS} has to be greater than the safe distance D_S:

$$\frac{Z_t Z_p e^2}{2E_{CMS}}(1+\varepsilon) > D_S = R_t + R_p + S \qquad (2)$$

where $\varepsilon = 1/\sin(\theta_{CMS}/2)$ is the classical orbit eccentricity of the motion of the projectile nucleus in the Coulomb field of the target, θ_{CMS} and E_{CMS} are the angle and the energy in the centre of mass respectively, $R_t = r_0 A_t^{1/3}$, $R_p = r_0 A_p^{1/3}\left(1 + \beta_2\sqrt{5/4\pi}\right)$ are maximal nuclear radii taking into account the nuclear deformation parameter β_2 which can be obtained from the estimate of the B(E2) value: $\beta_2 = \frac{4}{3}\pi\sqrt{\dfrac{B(E2; 0^+ \to 2^+)(e^2 fm^4)}{Z_p A_p^{2/3} r_0^2 (fm)}}$ [13], r_0 is equal to 1.28 fm and S is minimal distance of the nuclear surfaces.

Our calculations show that condition (2) is valid for all angles θ_{CMS} in the case of the collision of Zn, Ni nuclei on ^{58}Ni target at energy E_{lab} = 2.2 MeV/u while at E_{lab} = 3.0 MeV/u it is valid only for the angles smaller than the limit angle (see table 2).

2. The Sommerfeld parameter has to be significantly greater than unity: $\eta >> 1$. For Coulomb excitations of ^{68,70}Ni and ^{72,74}Zn on ^{58}Ni target η exceeds 70.

Projectile	B(E2; $0^+ \to 2^+$), $e^2 fm^4$	β_2	θ_{limit} for		θ_{max}
			S=5.0 fm	S=3.0 fm	
^{68}Ni	250	0.09	36°	47°	58°
^{70}Ni	410	0.11	34°	44°	55°
^{72}Zn	1740	0.20	35°	46°	53°
^{74}Zn	1760	0.20	34°	44°	51°

Table 2: The limit angles in the laboratory system. For angles greater than θ_{limit} the distance of closest approach is less than the safe distance in the case of ^{68,70}Ni and ^{72,74}Zn projectiles on ^{58}Ni target (E_{lab} = 3.0 MeV). θ_{max} is the maximal angle for the projectile in the laboratory system.

Coulomb excitation of neutron-rich Zn isotopes

Our first attempt is to check the feasibility of Coulomb excitation experiments using the REX-ISOLDE beams of A > 30. From the calculations which are summarized in figure 3 and table 1 and considering the ISOLDE production rates, the best candidate to perform a test experiment is ^{72}Zn and Ni as a target. The total cross section for ^{72,74}Zn at the energy of E = 2.2, 3.0 MeV/u depends on the charge of the target as shown in figure 3. The relation between the charge and the mass of the target comes from the Weizsäcker formula:

$$Z = \frac{0.72A^{-1/3} + 93.3}{1.44A^{-1/3} + 92A^{-1}} \qquad (3)$$

This measurement of the B(E2) value of ^{72}Zn will allow us to check the result of a previous experiment performed at GANIL at intermediate beam energy [14]. Furthermore, we will determine the B(E2) value with an accuracy significantly higher than the current one which is of 12 %. In a second step, we will measure the B(E2) values of ^{74}Zn and ^{76}Zn.
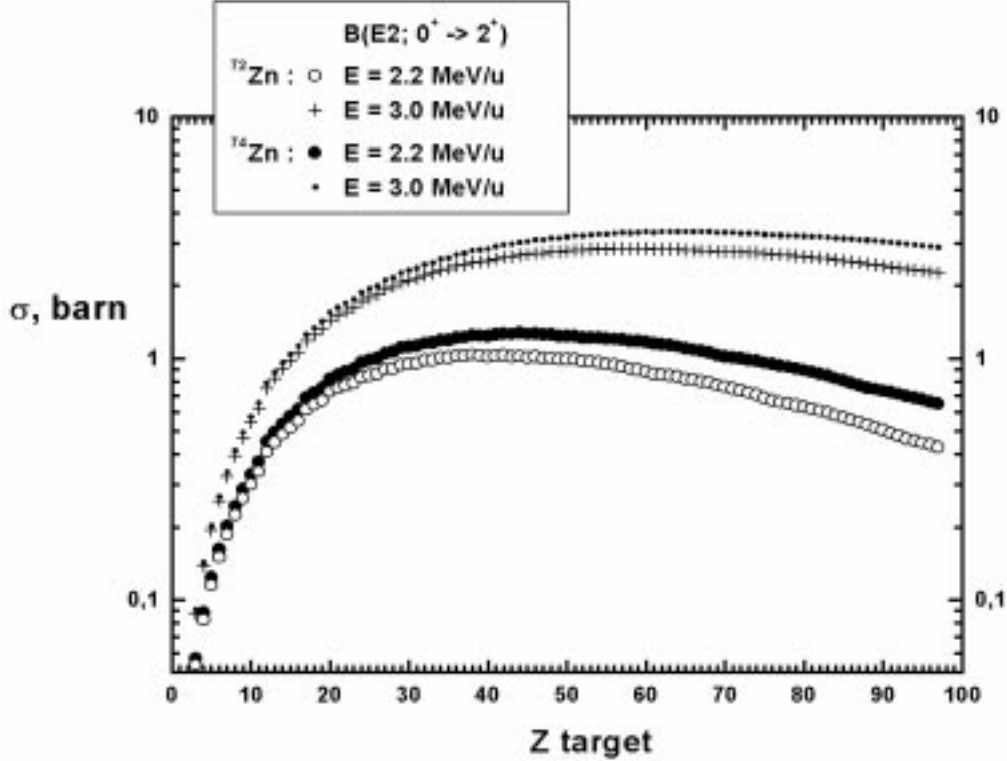

Figure 3: Total Coulomb excitation $(0^+ \rightarrow 2^+)$ cross sections for ^{72,74}Zn depending on the charge of the target.

According to our calculations, we also expect if possible to measure the B(E2) value of the 2+ → 4+ transition (see figure 4) of ^{72,74}Zn and the B(E2) value of the 2+ state of ^{76}Zn for the first time. The total cross section for a double E2 excitation can be estimated according to [9] as:

$$\sigma_{E2E2} \approx \frac{1}{4} a^{-2} \sigma_{E2}(0^+ \rightarrow 2^+) \sigma_{E2}(2^+ \rightarrow 4^+) \quad (4)$$

The B(E2, $2^+ \rightarrow 4^+$) 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 [15]. The 4_1+ state of ^{72}Zn has been observed for the first time in the recent work of A.N. Wilson et al. [16]. One has to mention that this state lies within 1 keV from the 0_2+ state located at 1499 keV. Therefore our measurements of the cross-section of the 4+ state may be influenced.

Coulomb excitation of neutron-rich Ni isotopes

Our calculations clearly show the necessity to wait for the beam energy upgrade from 2.2 to 3 MeV/nucleon (see figure 5) since we gain nearly one order of magnitude in the cross-sections. Furthermore, for ^{68}Ni, the adiabaticity parameter ξ becomes larger than 1 at the maximum cross-sections for a beam at 2.2 MeV/nucleon. The B(E2)

value of [68]Ni has already been measured at intermediate energies at GANIL [3] and a second measurement at low energy will provide a reliable confirmation of this measurement since sub barrier Coulomb excitation is a very well known process. The main goal of this part of the proposal is to see the evolution of the B(E2) values in even Ni isotopes beyond N = 40. An increase is expected but should be verified and quantified.
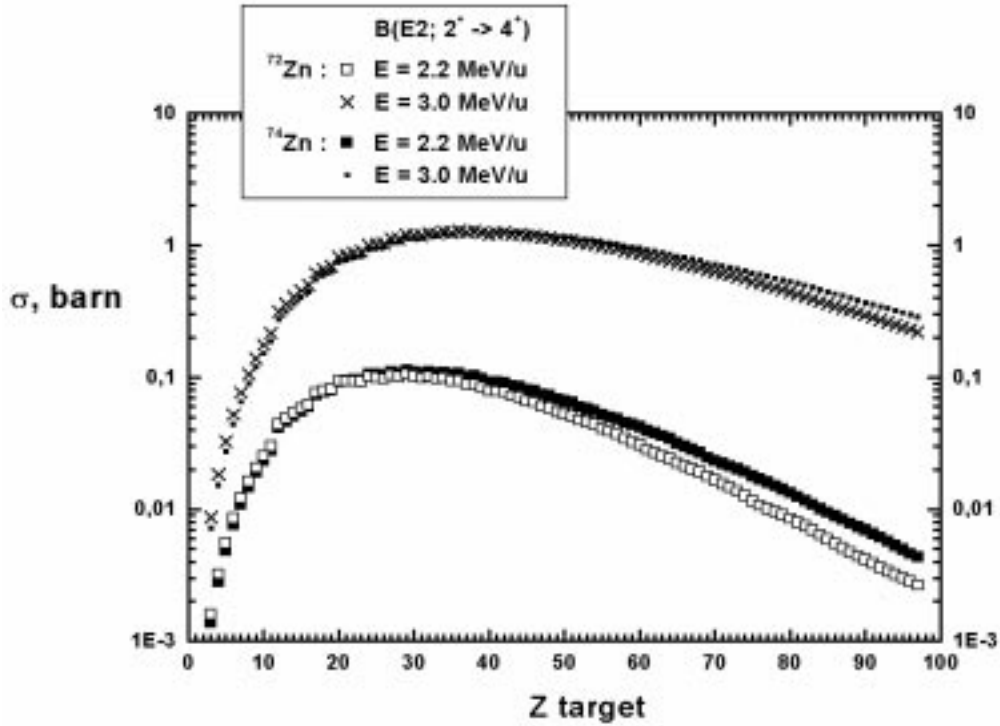

Figure 4: Total Coulomb excitation ($0^+ \rightarrow 2^+ \rightarrow 4^+$) cross sections for [72,74]Zn depending on the charge of the target.

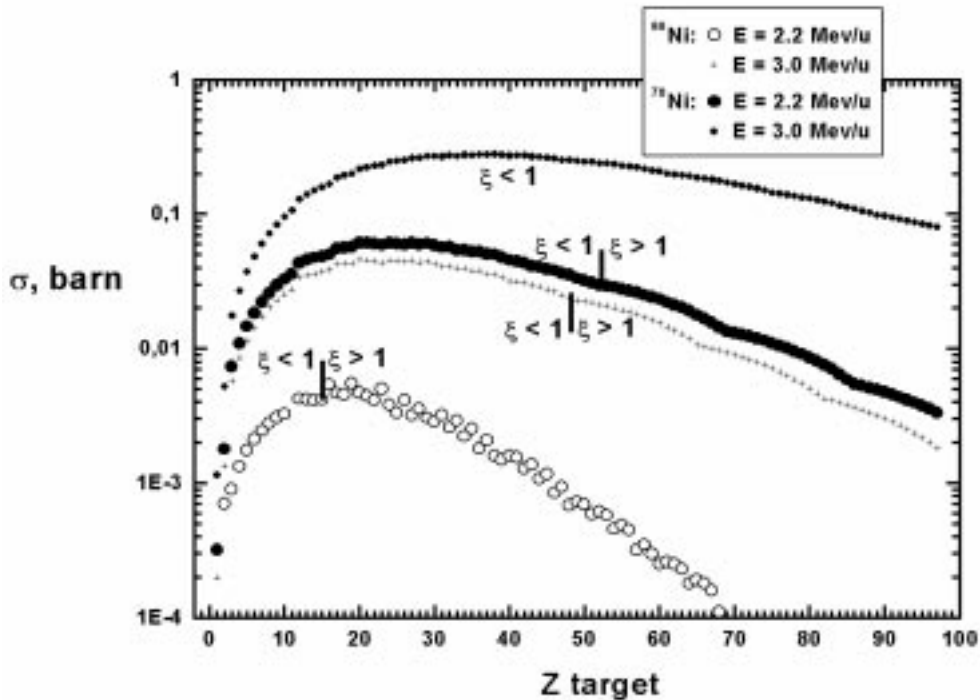Figure 5: Total Coulomb excitation cross sections of [68,70]Ni depending on charge of the target.

Outlook: odd nuclei and isomeric beams

In a longer perspective, we want also to use Coulomb excitation on odd mass and odd-odd nuclei in this neighborhood. As an outlook we present two interesting cases for measuring the B(E2) values of neutron-rich Cu isotopes. The nucleus of [69]Cu, for example, exhibits two 7/2- excited states at about the same energy, one of these excited states corresponding to a spherical configuration (namely [68]Ni + 1 proton) while the other one corresponds to a deformed configuration (namely [70]Zn – 1 proton) [17]. The nucleus of [70]Cu is also an extremely interesting case since REX-ISOLDE offers the unique possibility to produce and study the Coulomb excitation of the isomeric states lying in this nucleus [18].

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 U Carbide target using a resonance ionisation laser ion source. 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 [9] 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. In the numbers given below, we assume to get a pure beam of the desired isotope. This is not always the case. To improve the purity of the beam will thus be another key issue of this experiment in order to demonstrate the feasibility of Coulomb experiments at REX-ISOLDE. The number of expected events in the photopeak is summarised in table 3 for a 2 mg/cm^2 Ni target assuming an energy loss of 25 MeV/(mg/cm^2) in the target.

	Primary ISOLDE yield (atoms/s)	Beam energy at the entrance of the target (MeV/u)	Weighted $\sigma_{2+\rightarrow0+}$ (barn)	Weighted $\sigma_{4+\rightarrow2+}$ (barn)	Events in the photopeak (counts/hour)		Number of shifts
					0+→2+	2+→4+	
[72]Zn	4.10^7	2.2	0.44	$3.1\ 10^{-2}$	1300	92	2
[74]Zn	2.10^6	2.2	0.55	$3.5\ 10^{-2}$	81	5.2	9
[76]Zn	1.10^6	2.2	0.50	-	37	-	4
[68]Ni	8.10^5	3	$1.6\ 10^{-2}$		$9.5\ 10^{-1}$	-	-
[70]Ni	2.10^4	3	$1.4\ 10^{-1}$		$2.1\ 10^{-1}$	-	-

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 ^{58}Ni target. The cross-sections are weighted over the target assuming a beam energy loss of 25 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 the first period 21 shifts of beam time using a U Carbide target. The first 5 shifts will be dedicated to set up and calibrate the accelerator (3 shifts) and the detectors (2 shifts). A calibration run (1 shift) of a stable

^{70}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 ^{72}Zn. A number of 9 shifts are then required to measure the B(E2) values of the 2+ and 4+ states of ^{74}Zn with a reasonable accuracy. Finally, during the last 4 shifts, we will measure the B(E2) value of the 2+ state of ^{76}Zn.

Following the results of this first experiment, we will introduce a new beamtime request in order to continue these studies for the Ni isotopes. The present primary ISOLDE production rates (see table 3) and the rather conservative REX-ISOLDE efficiency estimate of 1 % makes the experiment right now even at 3 MeV/nucleon unfeasibly long (see table 3). But there is quite some room for improvements such as an ion source with a faster release for Ni, a higher REX-ISOLDE efficiency and eventually a further energy upgrade.

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