Inelastic scattering of ^{72,74}Ni off a proton target

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Abstract. Inelastic scattering of ^{72,74}Ni off a proton target was performed at RIBF, RIKEN, Japan. The isotopes were produced by the fission of ^{238}U on a thick Beryllium target and were then selected and identified on an event-by-event basis using the BigRIPS separator. Selected isotopes were focused onto the liquid hydrogen target of the MINOS device and gamma rays from the reactions were measured with the DALI2 array. The energy of the ions in the middle of the target was 213 MeV/u. Outgoing particles were identified using the ZeroDegree spectrometer. Here, we report on the current status of the data analysis and preliminary results for the proton inelastic scattering cross sections for both isotopes.

1. Introduction

The study of very neutron-rich exotic nuclei has recently attracted a great deal of scientific attention and offers a unique opportunity to test the shell evolution as a function of isospin. This evolution reflects properties of the nucleon-nucleon interaction, as well as the importance of the proton-neutron tensor force [1], and thus, allows a better insight into the fundamental properties of the nuclear force. The reduced $E2$ transition strength, $B(E2)$, for the $0^+ \to 2^+$ transition in even-even nuclei is a fundamental quantity in measuring the degree of collectivity of a nucleus. Moreover, in order to distinguish the relative importance of the contribution of protons and neutrons to the collectivity, neutron and proton multipole matrix elements should be obtained. These matrix elements are particularly important for neutron- or proton-rich nuclei, where the motion of protons and neutrons can be significantly different. The proton multipole matrix element, M_p, reflects only the contribution of the protons to the collectivity, and can be directly related to the $B(E2)$ value. The neutron matrix element, M_n, can be determined by means of a hadronic probe, for example proton inelastic scattering, which is sensitive to both protons and neutrons. Following the approach by Bernstein *et al.* [2, 3], the ratio of neutron-to-proton matrix elements can be expressed as

$$\frac{M_n}{M_p} = \frac{N}{Z}\left[\frac{\delta_{p,p'}}{\delta_C} + \frac{Zb_p}{Nb_n}\left(\frac{\delta_{p,p'}}{\delta_C} - 1\right)\right], \qquad (1)$$

where δ_C is the deformation length measured by the electromagnetic probe, $\delta_{p,p'}$ is the deformation length measured with the hadronic probe, and b_p and b_n are the external-field proton and neutron interaction strengths of the hadronic probe. The ratio b_n/b_p is approximately 3 for proton scattering with a relative proton kinetic energy below 50 MeV and approximately 1 at 1 GeV [3, 4]. Thus, by combining measurements of Coulomb excitation, which yields the $B(E2)$ value, and proton inelastic scattering, the ratio of proton-to-neutron matrix elements can be obtained.

Of particular interest is the behavior of proton and neutron collectivity in isotopes with a single closed shell, for example in the Nickel isotopes with $Z = 28$. Because of the difficulty in producing very exotic neutron-rich isotopes, until recently the measurement of the $B(E2)$ value by means of Coulomb excitation was limited to ^{70}Ni. In 2014 a measurement of the $B(E2)$ value for ^{74}Ni yielded a deformation length of $\delta_C = 0.78 \pm 0.13$ fm [5]. In earlier measurements of ^{74}Ni by inelastic scattering on a proton target, a deformation length of $\delta_{p,p'} = 1.07(16)$ fm was deduced [6]. The combination of these two measurements resulted in $M_n/M_p = 2.4 \pm 0.8$, as reported in Ref. [5]. This value is larger than the $M_n/M_p = N/Z$, which is expected for a pure isoscalar collective excitation, and may indicate an enhancement of the neutron contribution to the structure of neutron-rich Nickel isotopes towards the expected shell closure at ^{78}Ni.

In this proceeding, we report on a second measurement of the proton inelastic scattering cross-section for ^{74}Ni performed at intermediate energies, as well as the first measurement of proton inelastic scattering of ^{72}Ni. We describe the performed experiment, the status of the data analysis and preliminary results. The deformation length previously reported for ^{74}Ni is preliminarily confirmed within uncertainty and, using the $B(E2)$ value reported in Ref. [5], the ratio of proton-to-neutron matrix elements has been calculated.

2. Experimental setup

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF), operated by the RIKEN Nishina Center and the Center for Nuclear Study of the University of Tokyo as a part of the first SEASTAR campaign [7]. A detailed description of the experimental conditions can be found in a previous article [8]. A ^{238}U primary beam was accelerated to an energy of 345 MeV/nucleon and impinged on a 3-mm-thick Beryllium target at the entrance of the BigRIPS separator [9]. The $B\rho - \Delta E - B\rho$ technique was used to select the secondary isotopes of interest around ^{71,73}Co, in this case ^{72,74}Ni. Secondary fragments were identified on an event-by-event basis: The atomic number of each ion (Z) was deduced from an energy loss measurement in an ionization chamber placed at the focal plane F7; the mass-to-charge ratio (A/Q) was determined combining the position and angle measurements performed at the focal planes F3 and F5 using Parallel Plate Avalanche Counters (PPACs) and the Time-of-Flight (ToF) measured between two plastic scintillators placed at the focal planes F3 and F7. The MINOS device [10], composed of a 10 cm long liquid hydrogen target surrounded by a Time Projection Chamber (TPC), was placed at the focal plane F8 in order to perform proton inelastic scattering. In the present analysis the information given by the TPC was not used. A case where it was can be seen in Ref [8]. The energy of the Nickel isotopes in the middle of the target was 213 MeV/u. To detect the γ-rays emitted after the reaction, the DALI2 array [11] was placed around the target. It consisted of 186 NaI(Tl) detectors covering angles from 7 to 115 degrees (integrated along the target length) relative to the beam axis. The full-energy-peak efficiency of the array was determined using a detailed `Geant4` [12] simulation and was found to be 14% at 1.33 MeV with an energy resolution of 6.2% (FWHM) for a stationary source. After the target, reaction products were identified using the ZeroDegree spectrometer [9]. In this case, the ionization chamber used to determine the Z of the outgoing ions was placed at the focal plane F11. The position and angle measurements were performed with PPACs placed at the focal planes F9 and F11 and the ToF was measured with plastic scintillators placed at the same focal planes. Figure 1 shows the particle identification performed for the incoming as well as for the outgoing ions. The gates used to select incoming and outgoing ^{72,74}Ni isotopes are shown

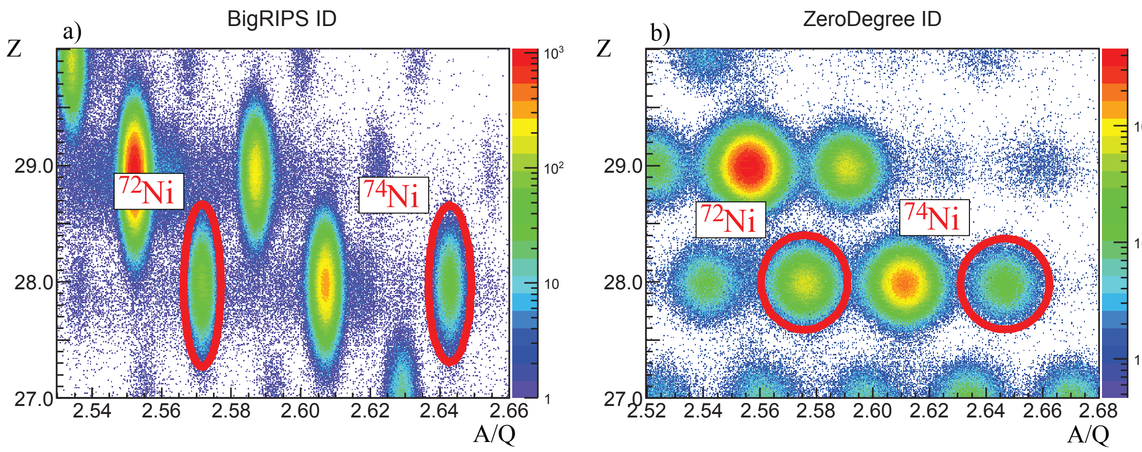

Figure 1. Particle identification obtained for a) the BigRIPS separator and b) the ZeroDegree spectrometer. Gates used to select ^{72,74}Ni isotopes incoming and outgoing are shown.

in both cases. A total of 4.6×10^6 ^{72}Ni and 1.5×10^6 ^{74}Ni isotopes impinging on the liquid hydrogen target were finally registered in the ZeroDegree spectrometer.

3. Results

The γ-rays measured in coincidences with the particle gates shown in Figure 1 were corrected to take into account the Doppler shift. For this purpose, the decay was assumed to occur at the center of the target, and the velocity was assumed to be the average of the measured incoming and outgoing velocities with a constant offset, which considers the energy loss in different detectors along the beam line in the F8 area. Figure 2 shows the Doppler-corrected γ-ray spectra obtained for ^{72,74}Ni. For the case of ^{72}Ni two transitions are observed at energies 1092(4) keV and 830(11) keV, in good agreement with the reported $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions, respectively. For ^{74}Ni a transition with energy 1023(6) keV is clearly seen as well as a noticeable structure at 734(16) keV. The two energies are also in agreement with the reported $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ $\gamma-$ray transitions. To obtain the proton inelastic scattering cross

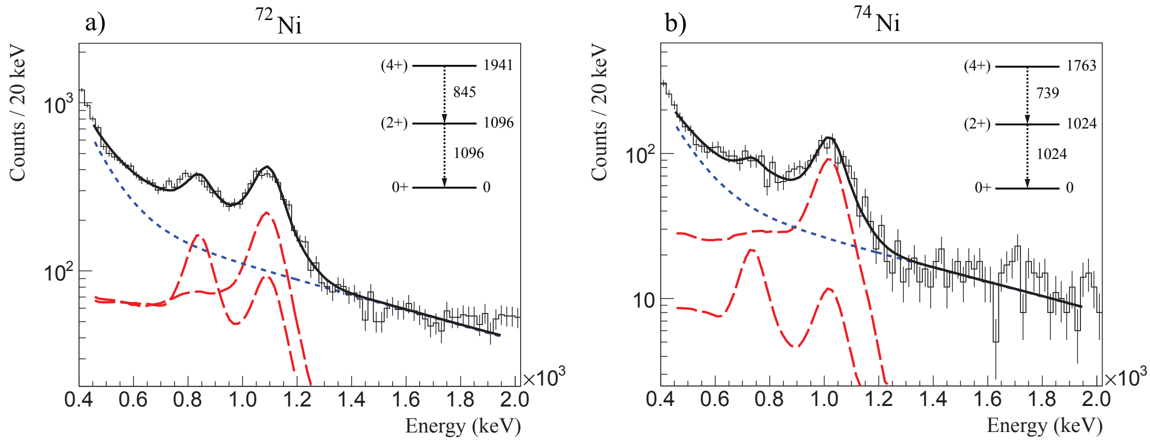

Figure 2. Doppler-corrected γ-ray spectra for a) ^{72}Ni and b) ^{74}Ni, measured with the DALI2 array. Simulated responses for the 2^+ transition and for the $4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade are shown, as well as the double exponential used as background and the total fit.

sections to excited states, each spectrum was fitted using the simulated response functions of the DALI2 array and a double exponential function to take into account the background. The simulation included the experimentally determined individual resolution of each crystal. The fits are shown in Figure 2 together with the experimental data. The fitting procedure was performed for different add-back conditions and the results obtained agreed within error bars. In each case, the feeding contribution from the 4^+ decay was subtracted. Possible feeding from higher lying states has not been observed but should be considered in more detail. The error in the calculated cross section includes the statistical uncertainty of the fit, 6% uncertainty in the efficiency of the DALI2 array, the statistical uncertainty on the number of incident ions and a 2% uncertainty in the target thickness. Following this procedure we obtained a preliminary cross section for the occurrence of the $2^+ \rightarrow 0^+$ transition of $\sigma_{p,p'} = 3.8 \pm 0.5$ mb for ^{72}Ni and $\sigma_{p,p'} = 4.3 \pm 0.6$ mb for ^{74}Ni. In order to obtain deformation lengths from the measured cross sections, the ECIS-97 code [13, 14] was used. The calculation included a first order, harmonic vibrational model together with the KD02 potential [15]. In the model, volume, surface and spin-orbit potentials were chosen to have the same deformation. However, we stress that this is a preliminary approach because the KD02 optical potential has been tested up to 200 MeV only, which is below the energy used in this experiment. Nevertheless, among the available potentials this is the one that better suits the experimental conditions. The preliminary values for the deformation lengths obtained with ECIS-97 are $\delta_{p,p'} = 0.93 \pm 0.07$ fm for ^{72}Ni and $\delta_{p,p'} = 0.98 \pm 0.05$ fm for ^{74}Ni. It is noted that the value obtained for ^{74}Ni agrees within error bars with the previous measurement of $\delta_{p,p'} = 1.07(16)$ fm performed by Aoi *et al.* [6]. Using Eq. (1) and the $B(E2)$ value reported by Marchi *et al.* [5], we obtain a neutron-to-proton matrix elements ratio of $M_n/M_p = 2.2 \pm 0.6$ for ^{74}Ni. In this calculation the values of b_n and b_p were chosen as 0.9 and 0.3 respectively following Ref. [5]. As the energy used in this experiment is higher than the one reported in Ref [5], further calculations of b_n and b_p are still needed. For ^{72}Ni no Coulomb excitation data is available, therefore the determination of the proton-to-neutron matrix elements ratio is not feasible.

4. Summary

We performed proton inelastic scattering for ^{72,74}Ni. Preliminary analysis results in a cross section for the occurrence of the $2^+ \rightarrow 0^+$ transition of $\sigma_{p,p'} = 3.8 \pm 0.5$ mb for ^{72}Ni and $\sigma_{p,p'} = 4.3 \pm 0.6$ mb for ^{74}Ni. Using coupled-channel calculations, the deformation lengths of the first 2+ states of both isotopes were obtained. For the case of ^{74}Ni, combination of our result with existing Coulomb excitation data, yields $M_n/M_p = 2.2 \pm 0.6$, which is consistent with the result obtained using previous (p, p') measurements.

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