

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of shell evolution in the Ni isotopes via one-neutron transfer reaction in ^{70}Ni

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Abstract:

This proposal aims at the study of the single particle properties of the neutron-rich nickel isotopes, specifically of the ^{71}Ni isotope via a $^{70}\text{Ni}(d,p)^{71}\text{Ni}$ reaction. The ^{70}Ni beam will be delivered by HIE-ISOLDE at 5.5 MeV/u onto a 1.0 mg/cm² CD₂ target. The protons produced in the (d,p) reaction will be detected with the T-REX silicon array either in singles or in coincidence with γ rays recorded by MINIBALL. The experimental results will be compared with large-scale shell-model calculations using effective interactions that involve large valence spaces for protons and neutrons, with excitations beyond the Z=28 and N=50 shell gap. This comparison will permit the study of the single-particle orbital $d_{5/2}$ that together with the quasi-SU3 partner $g_{9/2}$ gives rise to the collectivity in this region and has direct implications on the ^{78}Ni .

Requested shifts: 39 shifts, (split into 1 run over 1 year)

Installation: [MINIBALL + T-REX]

1 Scientific motivation

Magic numbers are a key feature in finite fermionic systems since they are strongly related to the underlying mean field. Their existence and stability suggested the presence of closed shell configurations which led to the development of the Shell Model of atomic nuclei. Recently, theoretical predictions and experimental results have indicated that magic numbers can change depending on the N/Z ratio, thus implying a more local applicability [1, 2, 3]. For example, the tensor component of the residual interaction is expected to strongly depend on the specific orbits being filled and acts in all nuclear regions, not necessarily close to the drip-lines [4, 5]. The tensor force results in the attraction between orbitals with anti-parallel spin configuration and a repulsion between orbitals with parallel spin configuration. Recently, structural changes in different mass regions due to the tensor mechanism have been discussed [6, 7, 8, 9, 10]. The magic numbers at N=20 and 28 disappear with increasing N/Z ratio and new magic numbers at N=14, 16 and 32 seem to appear. It is also predicted that the Z=28 gap for protons in the pf-shell reduces when moving from ^{68}Ni to ^{78}Ni , as a result of the attraction between the proton $f_{5/2}$ and the neutron $g_{9/2}$ orbits and the repulsion between the proton $f_{7/2}$ and neutron $g_{9/2}$ configurations, thus modifying or even inverting the effective single particle states. It is by now well established that the ^{68}Ni isotope presents a subshell gap at N=40, confirmed by various recent studies and initially suggested by the discovery of its second excited 0^+ state and a large excitation energy for the 2^+ state (2033 keV) [11, 12]. Since the properties of ^{78}Ni are still questioned, neutron-rich Ni, Co and Cu isotopes have been the object of many theoretical and experimental studies. Specifically, the neutron-rich Ni region has been experimentally studied via intermediate-energy Coulomb excitation [13], beta decay [14], transfer reactions [15, 16] and recently via lifetimes measurements of the 2^+ states of very neutron-rich Ni isotopes at MSU. This list does not pretend to be exhaustive since new publications appear almost daily in refereed journals. A step forward in the understanding of the region and the nature of the NN interac-

tion at large N/Z ratios is the study of the single-particle character of the states in the odd neutron-rich nickel isotopes. Spectroscopic information on these isotopes can shed light, among other properties, on the evolution of the Effective Single-Particle Energies (ESPE). The evolution of the ESPE of the $g_{9/2}$ and $d_{5/2}$ orbitals play a central role in the deformation of neutron-rich nickel isotopes. These two orbitals, in fact, characterised by $\Delta J = \Delta L = 2$, which can be described with a quasi-SU3 symmetry, drive the nuclear deformation, giving rise to large quadrupole moments [17].

Via the experimental study of the single-particle character of the first excited states of ^{71}Ni , by means of the $^{70}\text{Ni}(d,p)^{71}\text{Ni}$ reaction, we will be able to measure the evolution of the ESPE of the neutron orbitals around the Fermi surface. Relative spectroscopic factors and at least an estimate of the absolute spectroscopic factor of the populated states should also be obtained. The experimental values will be directly compared with recent large-scale shell-model calculations that consider a large valence space for proton $\pi(f_{7/2}, f_{5/2}, p_{1/2}, p_{3/2})$ and neutron $\nu(f_{5/2}, p_{1/2}, p_{3/2}, g_{9/2}, d_{5/2})$ orbitals, thus allowing for simultaneous excitations across $Z = 28$ and $N = 50$ gaps [18, 19]. The main focus of this proposal is the $5/2^+$ state coming from the neutron single-particle $d_{5/2}$ configuration, not yet observed in ^{71}Ni , that will help to elucidate the ESPE of the $d_{5/2}$ and therefore to assess the strength of the quasi-SU3 quadrupole in the nickel isotopes when going towards ^{78}Ni . The knowledge of the evolution of the $d_{5/2}$ - $g_{9/2}$ energy difference as a function of the neutron number when approaching ^{78}Ni is here crucial for calculating the ESPEs around ^{78}Ni , probing the predictive power of the different residual interactions. The $(5/2^+)$ state at 813 keV that has been observed in ^{71}Ni [20], see Fig. 1, does not correspond to the $\nu d_{5/2}$ configuration but it is mostly a three-particle cluster state with minor contribution of other orbitals mixing [20]. Instead, the $5/2^+$ state due to the single-particle configuration $\nu d_{5/2}$ is expected to lie at around 2.0-2.5 MeV [22]. Experimentally, the $5/2^+$ state ($\nu d_{5/2}$) in ^{69}Ni was observed at around 2.6 MeV [15].

Figure 1 shows the known spectroscopic information for ^{71}Ni , taken from Refs. [20, 21], where all the spins and parities of the states are tentative. Although the $d_{5/2}$ state is expected to be the most populated, the proposed experiment will probably also help to determine the spin and parity of other ^{71}Ni states populated in this transfer experiment. From the analysis of the proton angular distributions, the amount of orbital angular momentum transferred can be determined and will limit strongly the possible configuration of the corresponding states, permitting the spin and parity assignment in the majority of cases.

2 Experimental method

In the proposed experiment, excited states in ^{71}Ni will be populated via the single-neutron transfer reaction $^{70}\text{Ni}(d,p)^{71}\text{Ni}$ in inverse kinematics, using a beam of ^{70}Ni at 5.5 MeV/u impinging on a 1.0 mg/cm² deuterated polyethylene CD₂ target. A production yield of ^{70}Ni as high as 2×10^5 at/ μC has been measured in the ISOLDE target using an UC_x target [23]. The ^{70}Ni isotope will be laser ionized using RILIS [24], and post-accelerated to 5.5 MeV/u using HIE-ISOLDE and delivered to the MINIBALL target position. Assuming a transmission efficiency for post-acceleration of 5%, and an average proton current

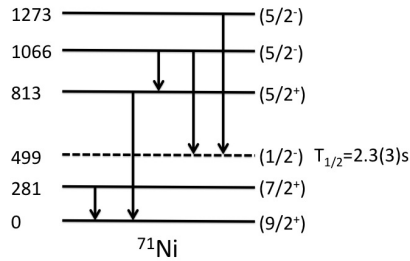


Figure 1: Experimental level scheme of ^{71}Ni , taken from Refs. [20, 21]. The states with the strongest single-particle character are believed to be the ground state ($g_{9/2}$), the 499-keV state ($p_{1/2}$) and the 1066-keV state ($f_{5/2}$).

of $1.4 \mu\text{A}$, a ^{70}Ni beam intensity of the order of $1.4 \cdot 10^4$ pps is expected at MINIBALL. It will be shown in the following paragraph that such beam intensity, coupled to the boost in beam energy to 5.5 MeV/u , enables the measurement of proton angular distributions for the $l=2$ $d_{5/2}$ state.

The experimental setup will consist of the T-REX silicon-detector array [25], together with the MINIBALL [26] γ -ray spectrometer. The silicon-detector array is described in full in Ref. [25]. In brief, it will consist of a barrel of eight planar detector telescopes around 90° and a CD DSSD detector at backward angles. The ΔE detectors of the barrel are approximately $140\text{-}\mu\text{m}$ thick, and the E detectors 1-mm thick. Each ΔE detector is segmented into 16 strips perpendicular to the beam direction. The position information along each strip can be derived from the charge division on a resistive layer. The angular coverage of the forward part of the barrel is from approximately 30° to 76° , that of the backward part is from 104° to 152° . The backward CD DSSD covers angles from 147° to 172° . The angular resolution is approximately 5° . The main contributions to the proton energy resolution come from the short distance of the silicon detectors, the beam spot size (assumed in our calculations to be 3 mm in diameter) and the straggling through the target. The reaction channels of interest were simulated to obtain reliable predictions of the quality of the data, within the assumption of the available beam intensity and the detection setup. The simulations were performed by using the Monte Carlo code based on Geant4 developed by V. Bildstein and K. Wimmer.

The selection of the reaction channel will rely on the E- ΔE technique and on the kinematics of the considered direct reaction. The final selectivity will be enhanced by the high selectivity made possible by the detection of coincident γ rays. The required target thickness (1 mg/cm^2) strongly limits the resolution to approximately 900 keV and most likely it will not be possible to resolve the states only by gating on the protons. The γ -ray gates will instead favour the exclusive selection of the state of interest. The expected resolution for different states can be seen in Fig. 2, which shows the simulated kinematic curves of four states in ^{71}Ni , the $\nu g_{9/2}$ ground-state, the isomeric state at 499 keV (assumed to be of $\nu p_{1/2}$ character), the $\nu f_{5/2}$ state at 1066 keV and the $\nu d_{5/2}$ state, expected at around 2.5 MeV . These curves were obtained assuming a target thickness of 1.0 mg/cm^2 and a beam-spot diameter of 3 mm .

For each of these states DWBA calculations were performed using the codes DWUCK4 [27]

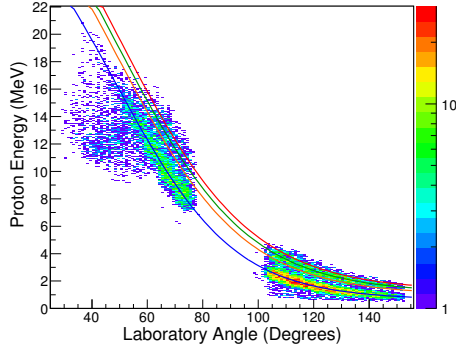


Figure 2: Energy versus laboratory angle for $^{71}\text{Ni}(d,p)$ protons for the 0-, 499-, 1066- and 2500-keV states in ^{71}Ni . For comparison, kinematic curves for each state $g_{9/2}$ (red), $p_{1/2}$ (green), $f_{5/2}$ (orange) and $d_{5/2}$ (blue) are also shown. The proton emission for each state is not isotropic, but consistent with the calculated differential cross sections, see Fig. 3 (left).

and TWOFNR [28], in the zero range approximation. Five different parametrizations of the deuteron and proton optical-model potential were employed [29, 30, 31, 32, 33], yielding similar results. The estimated cross sections were taken from the average of these different calculations. For the $g_{9/2}$ (0 keV), $p_{1/2}$ (499 keV), $f_{5/2}$ (1066 keV) and $d_{5/2}$ (2500 keV) the calculated total cross sections are, respectively, 14.7, 20.4, 12.4 and 93.5 mb (for a spectroscopic factor of 1). The optimum Q-value ($Q=0$ for neutron transfer) should indeed favored the population of states at around 2.0-2.5 MeV. Figure 3 shows the calculated distributions for the states mentioned above.

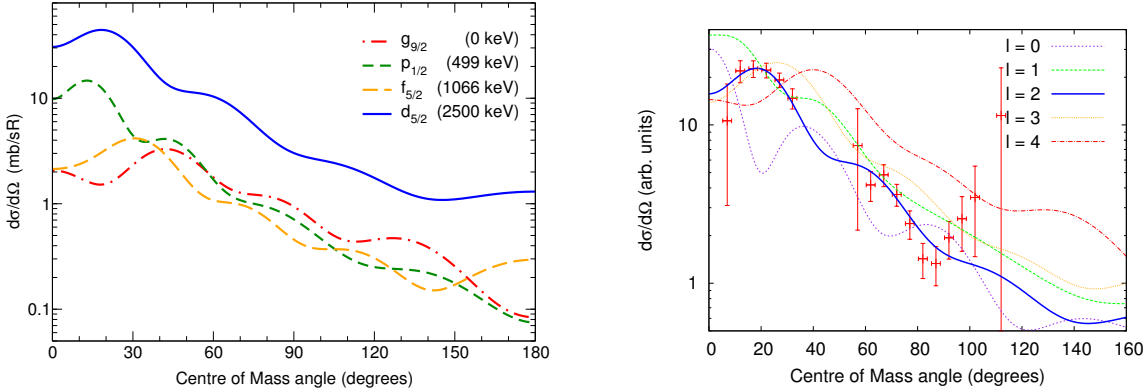


Figure 3: (Left) Differential cross sections for the $g_{9/2}$ ($l=4$), $p_{1/2}$ ($l=1$), $f_{5/2}$ ($l=3$) and $d_{5/2}$ ($l=2$) states in ^{71}Ni . (Right) Angular distributions for the reaction populating the $d_{5/2}$ state at 2.5 MeV, obtained with the simulation of 600 protons detected in the silicon barrel in coincidence with a 2.5 MeV γ ray, together with angular distributions corresponding to angular momentum transfer from $l=0$ to $l=4$.

The $\nu d_{5/2}$ $5/2^+$ state is expected at around 2.5 MeV from shell-model calculations [22] and from systematics (the (d,p) reaction which populated the $5/2^+$ in ^{69}Ni at an excitation

energy of about 2.6 MeV [15]). At this energy the absolute photo-peak efficiency of MINIBALL is around 3.4% [34]. Focusing only on transfer to the $d_{5/2}$ states, for a primary beam intensity of $1.4 \mu\text{A}$ resulting in 1.4×10^4 pps, a $\text{SF}=0.7$, and a target thickness of 1.0 mg/cm^2 , about 0.07 reaction events per second (6000 events/day) can be expected. Due to the limited angular coverage of the detector and the large proton energy at forward angles, only about 50% of these fall in the kinematic 2-d gate for the $d_{5/2}$ state. Assuming a γ efficiency of 3.4%, for 2.5 MeV γ rays, the amount of γ -particle coincidences is approximately 100 counts/day. Figure 3 shows the quality of the proton angular distributions which can be deduced after 6 days of beam time, i.e. using approximately 600 counts. They are clearly sufficient to distinguish between $l=0,1,2,3$ or 4. Furthermore, the cross-section itself will provide some indication, since the $l=2$ transfer is strongly favoured over the other l values.

The contribution of fusion to the overall number of events could in theory prevent an unambiguous determination of the reaction channel. The fusion of the ^{70}Ni beam either with ^{12}C or ^2H , both present in the plastic target, yields a cross-section for proton emitting channels of 130 mb (approximately 17% of the total fusion cross section). The majority of channels evaporates mostly neutrons, or alphas, which do not pose any problem. In 2008-2009 J. Diriken et al. [16] studied the $^{66}\text{Ni}(d,p)^{67}\text{Ni}$ reaction with a same setup. The total fusion cross-section for proton-emitting channels was only a factor of 2 lower than our proposed experiment (≈ 60 mb), and no real issue was encountered. The γ -ray gating should reduce almost completely the contamination coming from fusion. We therefore do not expect to encounter any problem.

Important remarks on beam intensity and contamination

Although it has been shown that a ^{70}Ni intensity as low as 1.4×10^4 pps is sufficient for our purposes, currently at REX-ISOLDE a pure ^{70}Ni beam is not available. Large quantities of ^{70}Ga are released together with ^{70}Ni . Even exploiting the different release time of ^{70}Ga and ^{70}Ni , the ^{70}Ga yield would still be 30 times larger than the ^{70}Ni (3×10^6 atoms/ μC compared to 10^5 atoms/ μC) [23]. Simulations performed to study the effects of a new neutron-converter geometry have shown that a significant reduction in the amount of gallium contamination could be achieved, to about 50% of the total intensity [23]. A test using the new neutron converter, scheduled before the end of the year, will clarify the reduction of ^{70}Ga yield with respect to ^{70}Ni . For a successful transfer measurement, in any case, a pure ^{70}Ni beam is not strictly required. The ^{71}Ni data can be discriminated from reaction events originating from the contaminant species, provided that time will be dedicated to collecting data without laser ionization (i.e. removing the ^{70}Ni from the beam cocktail). The required amount of runs with laser-ON and laser-OFF will depend on the beam contamination. For a contamination level between 40-50%, as many shifts should be allocated to collecting data with laser ON and OFF, i.e. 6 extra days of beamtime. If the contamination is less than 30%, 3 extra days of beamtime should suffice. The request we make is based on the 50% contamination scenario.

Summary of requested shifts: Based on the previous calculated rates we request 36 shifts of beamtime plus 3 shifts for beam setup.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

Part of the	Availability	Design and manufacturing
MINIBALL + T-REX	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL + T-REX installation.