EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

The (t,p) reaction on ^{66}Ni

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Abstract: We propose a measurement of the $t(^{66}\mathrm{Ni},p)$ reaction at 5 MeV/u to populate states in ^{68}Ni below ~4 MeV. A precise determination of the energy of the first excited 0^+ state at 1770(30) keV and confirmation, or otherwise, of the recently proposed $J^\pi = 0^+$ $2p2h$ state at 2202 keV are amongst the objectives of this measurement. There is also the possibility to confirm J^π for the tentatively assigned 3^- level and its cross section. Shell models show large components of $\nu(p_{3/2}g_{9/2})$ configurations for yrast 3^- levels in the Ni isotopes, which could drive octupole collectivity. For this study, outgoing protons will be analysed by a solenoidal spectrometer with a Q-value resolution of ~100 keV. Cross sections to excited states will shed light on their neutron configurations and in turn the shell structure present in ^{68}Ni. Angular distributions will allow J^π assignments.

Requested shifts: 18 shifts
Installation: Solenoidal spectrometer

1 Physics case

Motivation.—The nucleus $^{68}_{28}$Ni$_{40}$ has long been considered doubly magic after it was discovered that the first-excited state has spin and parity 0^+ [1] (see Fig. 1) and that the first 2^+ state is high in excitation energy – located at 2033 keV [2] – and decays with a low $B(E2; 2^+ \to 0^+)$ transition strength [3] compared to neighbouring nuclei. There is contradictory evidence from mass measurements, which suggests that $N = 40$ may be, at best, only a weakly magic subshell closure [4]; several theoretical efforts (e.g. [5, 6, 7]) have similarly disputed the magicity of ^{68}Ni.

Among the low-lying states is a third 0^+ state at 2511 keV. Also, a recently reported 0^+ isomer at 2202 keV was proposed to be a proton two-particle, two-hole state corresponding to a rather large deformation (possibly superdeformation) according to shell-model calculations [8, 9]. The existence of this isomer was shortly thereafter called into question [10]. The calculated superdeformed state may instead correspond to the one at 2511 keV which was shown conclusively to be a 0^+ state [10], with energy close to the predicted value [9]. Given that three of the four lowest-lying states in ^{68}Ni are 0^+ states, theoretical efforts to understand their nature are underway. However, more input from experimental data are desired.

One deficiency in our knowledge of the 0^+ states is the precise value for the energy of the 0^+_2 level. The work by Bernas *et al.* [1] using the ^{70}Zn(^{14}C,^{16}O) reaction, reported an energy of 1770(30) keV; however, given that their measured energy for the first 2^+ state (and possibly higher-lying states as well) from that same work differs considerably from the known value [2200(30) keV compared to the well-established 2033 keV], there may be a sizable systematic error in the measurement. A follow-up experiment by the same group exhibited similarly large systematic errors for known states in both ^{67,68}Ni [11]. No subsequent studies have directly observed this state. Bernas *et al.* deduced a half-life, $t_{1/2} = 211(50)$ ns, from the timing of e^+e^- pairs produced in the $E0$ decay of this state, but obtained no additional excitation-energy information [12]. Other studies have inferred its existence from the observation of delayed 511-keV pair-production gamma rays from its depopulation [3, 13]. A more precise half-life of 270(5) ns was established in Ref. [3].

In Ref. [10], and supported by observations in Ref. [14], a newly identified 3302-keV level in ^{68}Ni was tentatively assigned $J^\pi = 3^-$. Shell-model (SM) calculations using the jj44b and JUN45 interactions show a large component of the $\Delta l = \Delta j = 3$, $\nu(p_{3/2}g_{9/2})$ configuration for the yrast 3^- levels in ^{64,66,68}Ni, which could be expected to drive octupole collectivity [14]. The JUN45 calculated energies are in particularly good agreement with the measured values, while the jj44b predictions are ~ 400 keV low; this is surprising, as the absence of octupole collectivity in the SM calculations usually implies the experimental energies are driven lower than the predictions. This could suggest that the neutron configuration alone is insufficient to drive the octupole collectivity or that the 3302-keV level in ^{68}Ni is not the 3^- [14]. The proposed experiment could establish whether this assignment is correct.

The (t,p) reaction allows direct access to states in ^{68}Ni with the moderately intense ^{66}Ni beam available at HIE-ISOLDE. This reaction populates non-yrast states which may not be otherwise seen in gamma-ray decay work. With sufficient statistics, accurate determinations of the excited energies can be made (e.g. for the 1770(30)-keV state), and angular distributions can be used to firmly assign J^π (e.g. the tentatively assigned 3^- level discussed above). The cross sections will help provide information on the single-particle nature of ^{68}Ni by probing the strength of neutron configurations.

Comment on previous studies with (t,p).—The (t,p) reaction on ^{66}Ni has previously been studied at ISOLDE in September 2011 using T-REX and Miniball (IS504) [15]. A 2.65-MeV/u ^{66}Ni beam was used (slightly lower than maximum REX energy to reduce the possibility of fusion on the Ti foil) with intensity of 4.2×10^6 pps (at the front of Miniball) and purity of >86%. Possibly because of the isomeric nature of the 0_2^+ (with half-life of 250 ns) and also that of the recently reported 0_3^+ at 2202 keV (with half-life of 216 ns) these were not identified in their preliminary analysis. They used a metallic Ti foil, 500-μg/cm^2 thick, loaded with tritium in the atomic ratio ^{3}H/Ti of 1.5 implying 40 μg/cm^2 of ^{3}H. With such low beam energy and a 'thick' target, the charged-particle Q-value resolution was too poor (the order of 1000 keV) to use in isolation without coincident gamma rays. The ground state and 2_1^+ state were seen, but not the 1770-keV state perhaps due to the poor resolution [15]. As such, we seek a measurement of this reaction at a higher energy of 5 MeV/u with a solenoidal spectrometer with the aim of achieving a charged-particle resolution of ~100 keV.

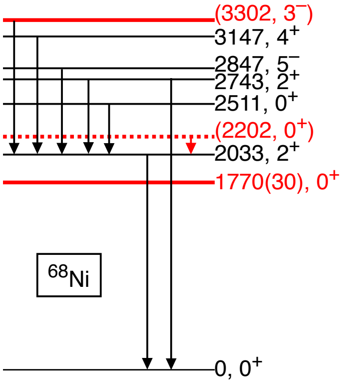

Figure 1: Low-lying states in ^{68}Ni. Highlighted in red are the 1770(30)-keV, 0^+ state [1], the recently disputed 2202-keV, 0^+ state and the newly proposed 3^- level at 3302 keV [10].

2 Experimental details

Solenoidal spectrometer.—The experiment will use a solenoidal spectrometer for momentum analysis of the outgoing protons from the reaction, similar to that in use at Argonne National Laboratory [16, 17]. This spectrometer has significant advantages over conventional charged-particle spectroscopy using silicon detectors for this experiment, beyond the solenoid representing far less complex detector system. Firstly, it results in better proton-energy resolution, where it is not limited by target energy-loss effects. This arises due to the linear function between the centre-of-mass (c.m.) energy and the measured position, and lab energy measured at the axis of the solenoid. Essentially, the lab ion-energy resolution is identical to the c.m. energy resolution. Secondly, the linear nature of this relationship also means that the dispersion between different excited states in the ion-energy and Q-value spectra are the same. In the conventional approach, using Si at fixed angles, the non-linear relationship between proton energy and angle can mean that when moving from an ion-energy spectrum to excitation energy, peaks become compressed by factors of up to three, degrading the effective Q-value resolution. Even for experiments where target energy-loss effects are important in the ion-energy resolution, the resulting Q-value spectrum with a solenoid still benefits from this lack of compression. As an example, a recent $d(^{86}\mathrm{Kr},p)$ measurement achieved an excitation energy resolution of $\sim$70 keV [18]. Some conventional approaches use gamma-ray measurements to recover the excitation-energy resolution. This necessarily introduces an additional efficiency factor of up to 10% due to the coincidence requirement—though it is often mitigated by the use of a thick target on the order of 1 mg/cm^2. A solenoidal system allows good resolution and a large acceptance, sufficient for many purposes, from the measurement of outgoing ions alone.

A Letter of Intent for a solenoidal spectrometer was endorsed by the INTC [19], and significant progress has been made in the preparation of such an instrument for phase-1 HIE-ISOLDE beams.

Reaction kinematics and experimental setup.—A schematic of the experimental set up is shown in Fig. 2. Protons from the (t,p) reaction are scattered into backwards laboratory angles. The Si array is therefore placed upstream of the target in the solenoid. Elastically scattered tritons are scattered downstream where they are measured using an annular Si detector. Recoiling ^{68}Ni ions pass through the hole in this detector and are stopped in a beam dump at the end of the solenoid. The target is $\sim$30 cm downstream of the centre of the solenoid such that proton and triton trajectories are within the homogenous field of the solenoid. Figure 2 also shows the characteristic energy versus Δz kinematic lines for low-lying states in ^{68}Ni—the states of particular interest in this proposal are shown. With a Si array of 70-cm length, we will cover $5^\circ < \theta_{\mathrm{c.m.}} < 45^\circ$ for all states populated via (t,p) up to the neutron-separation threshold at 7.79 MeV.

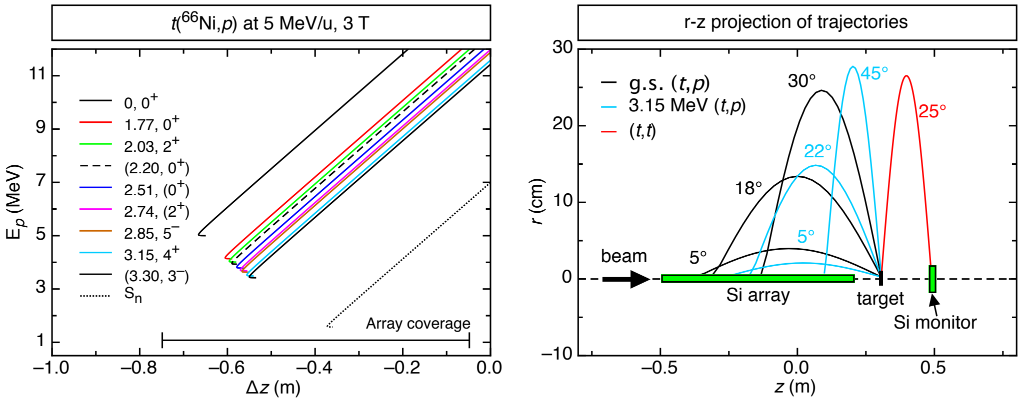

Figure 2: Energy versus Δz of outgoing protons in a solenoidal spectrometer (left) following the (t,p) reaction on ^{66}Ni. A schematic showing proton trajectories projected on the r-z plane. Elastically scattering tritons are also shown along with an annular Si detector to monitor the beam and target. Note the bore is 45 cm, so these orbits are well within the volume. All trajectories of interest fit within the central 1 m.

Kinematics lines from other possible reactions will not interfere with those from the (t,p) reaction. Possible triton-induced reactions include (t,α) where the outgoing α particles go dominantly forward at this energy; the (t,d) reaction, though backwards, only extends to $\Delta z = -25$ cm, and the deuterons are too low in energy to interfere. As such, the proposed measurement can be made without recoil detection, and is, to a degree, independent of the RF structure of the beam. A source of background will be the tail of the proton fusion-evaporation yield which can be reliably subtracted as demonstrated in previous measurements using the Argonne device [20].

Figure 3 shows proton angular distributions following $L = 0$, 2, 3, and 4 transfer. The distributions were calculated using the distorted-wave Born approximation code Ptolemy [21]. $L = 0$ is strongly forward peaked, with a large cross section for transfer to the 0^+ ground state, of the order of 4-5 mb/sr. Excited 0^+, 2^+, and 3^- states are likely to be factors of 10 to 100 lower as seen in systematic (t,p) studies on the stable Ni [22] and Zn [23] isotopes. A representation of the outgoing proton spectrum in Fig. 3 demonstrates that 100-keV FWHM Q-value resolution would enable the extraction of precise yields, energies (to within a few keV given enough statistics), and angular distributions to be extracted for the low-lying states. High-lying states will also be populated, but little is known about these at present [24].

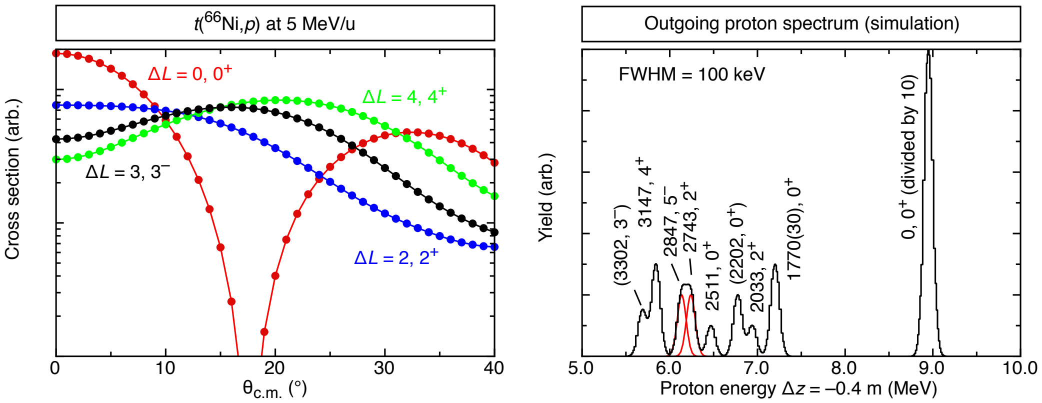

Figure 3: (Left) Angular distributions for $L = 0$, 2, 3 and 4 transfer to 0^+, 2^+, 3^-, and 4^+ states and (Right) a representation of the outgoing proton spectrum under the assumption of 100-keV FWHM resolution. States are labelled by their energy and spin. For the unresolved states, Gaussians (red) show their form.

Target.—A thinner Ti/^{3}H target than used previously at ISOLDE (e.g. [25]) is required for this measurement. The previous target consisted of a metallic Ti foil 500-μg/cm^2 thick loaded with tritium in the atomic ratio ^{3}H/Ti of 1.5 implying 40 μg/cm^2 of ^{3}H. Here, a reduction in the thickness to ∼125 μg/cm^2 Ti and ∼10 μg/cm^2 of ^{3}H would be required to achieve the estimated 100-keV Q-value resolution. At present no such target exists. The development and requirement for safe use of such a target will be explored in the interim period taking advantages of expertise at Munich and Argonne.

Rate estimates and shifts required.—Rate estimates are based on the assumption of an angular coverage of $5° < \theta_{\mathrm{c.m.}} < 45°$, with a 75% efficiency in the azimuthal angle. Cross sections for $0^+_{\mathrm{g.s.}}$, $0^+_{2,3}$, 2^+_1, and 3^- are scaled to the data available from the work on the stable Ni [22] and Zn [23] isotopes. Cross sections to the $0^+_{2,3}$, 2^+_1, and 3^- are comparable integrated over the angle range and so are treated as the same. The integrated cross section for the ground state is ∼70 mb and is between a factor of 10-100 less for the excited states. We assume 1 mb here (a factor of 70 less). For 4×10^6 pps, and an effective target thickness of 10 μg/cm^2 of ^{3}H, we anticipate ∼0.5 counts per second in the ground state, and about 0.01 for excited states. This is approximately 300 counts per shift for an excited state. For angular distributions, 5000 counts is desired which necessitates 15 shifts. A further three shifts are required for set up.

3 Summary

We request 18 shifts of beam time to perform the $t(^{66}\text{Ni},p)$ reaction at 5 MeV/u. We will use a solenoidal spectrometer to analyse the outgoing protons. The number of shifts is based on a beam on 4×10^6 pps of ^{66}Ni on an effective ^{3}H target thickness of 10 μg/cm^2. The results will serve to put our knowledge of excited states in "doubly-magic" ^{68}Ni on a firmer footing. It is expected that a Q-value resolution of 100 keV can be achieved.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: Solenoidal spectrometer

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: MINIBALL + only CD, MINIBALL + T-REX)	☐ Existing	☐ To be used without any modification
Solenoidal spectrometer	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature	4 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe, ~1650 l, LN_2, ~200 l, 1.0 Bar		
Electrical and electromagnetic			
Electricity	0 V, 300 A		
Static electricity			
Magnetic field	$\leq$3.0 T		
Batteries			
Capacitors			
Ionizing radiation			

Target material	Ti:^{3}H (tritium loaded Ti)		
Beam particle type	^{66}Ni		
Beam intensity	4×10^6 pps		
Beam energy	5.0 MeV/u		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibration sources)		
• Sealed source			
• Isotope			
• Activity			
Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant	Helium		
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			

Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 5 kW