Proposal to the INTC committee

Probing the semi-magicity of ^{68}Ni via the ^{3}H(^{66}Ni,^{68}Ni)p two-neutron transfer reaction in inverse kinematics

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1 Physics motivations

Recently, the persistence of the $N = 40$ harmonic oscillator shell gap in neutron rich nuclei at Z=28 has been studied both experimentally [1, 2] and theoretically [3, 4, 5]. The semi-magic nucleus ^{68}Ni has been the subject of special attention: despite the high energy of the first excited 2^+ state [6] (see Fig.1), its low-reduced transition probability $B(E2; 2_1^+ \rightarrow 0_1^+)$ [1, 2] and the presence of an excited 0^+ state below it [7], mass measurements [8, 9] have not revealed a clear N=40 shell gap. It has been suggested that the semi-magic properties of ^{68}Ni arise due to the parity change between the pf shell and the $1g_{9/2}$ orbital [10]. In this framework, the nature of low lying 0^+ states in ^{68}Ni have recently been discussed [11]. By comparing ^{68}Ni to its valence counterpart, ^{90}Zr, it has been inferred that the first excited 0^+ state would be formed by almost pure neutron 2p-2h excitation. Nonetheless, it is not yet well understood if this state is a pure $\nu(p_{1/2})^{-2}$ excitation or if its wavefunction is a mix of different 2p-2h excitations. The same argument could be applied to higher excited 0^+ states in ^{90}Zr, for which neutron analogues should be present in ^{68}Ni but remain unobserved. For example, the $\nu(f_{5/2})^2$ state could have been seen at 2.2 MeV excitation energy, but in the same paper the authors show that this 0_3^+ state is also a good candidate for a proton intruder state. These theoretical conclusions need therefore experimental confirmation.
Moreover, the spin of the 0_3^+ state has been tentatively assigned with the help of transition probability considerations [12] but no clear assignment of the spin could be made. The spin of the 2_2^+ state also remains to be confirmed.
We propose to perform the two-neutron transfer reaction ^{3}H(^{66}Ni,^{68}Ni)p using the ISOLDE radioactive ion beam at 2.7A MeV and the MINIBALL + T-REX setup to characterize the 0^+ and 2^+ states in ^{68}Ni.

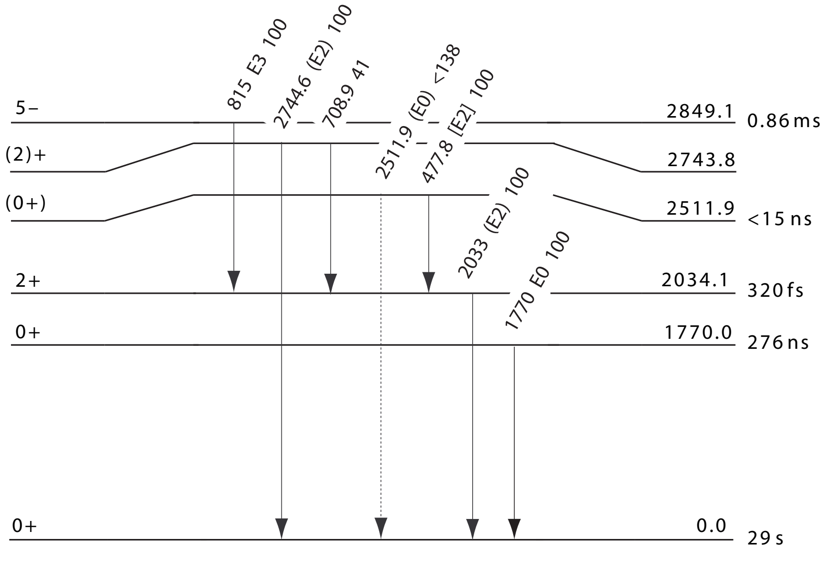

Figure 1: Level Scheme of ^{68}Ni. Adapted from ENSDF.

2 Experimental method

Two neutron transfer reactions are known to be excellent probes for the 2p-2h neutron states in medium-mass nuclei [13, 14]. The study of the ^{3}H(^{66}Ni,^{68}Ni)p two-neutron transfer reaction in inverse kinematics will make it possible to probe the nature of the excited states in ^{68}Ni. At the same time, spectroscopy of ^{67}Ni will be performed through the ^{3}H(^{66}Ni,^{67}Ni)d reaction (Q=-0.45 MeV). The comparison of this reaction mechanism with the (d,p) reaction (Q=3.58 MeV) from ISOLDE experiment IS469 [15] will be used to get complementary information on the structure of ^{67}Ni. In this experiment, due to the Q-matching, different states will be populated, enabling the determination of spectroscopic factors for the low lying states. The emitted hydrogen isotopes will be detected and identified in the T-REX charged particle array [16]. The excitation energy spectrum and the angular distributions of the emitted protons will be used to determine the spin of the states populated in ^{68}Ni. Since the energy separation of the low-lying states in ^{68}Ni is known to be quite large, the energy levels can be separated with the proton energies alone at backward center of mass angles, as seen on Fig.2. The identification of states above 2.5 MeV excitation energy will be performed by detecting emitted γ-rays with the MINIBALL Ge-array. The obtained angular distributions will be analyzed in the Coupled Reaction Channel framework. The elastically scattered tritons will provide the optical potential for the entrance channel, and the (t,d) reaction will be used to determine the strength of the couplings in the two-step transfer process.

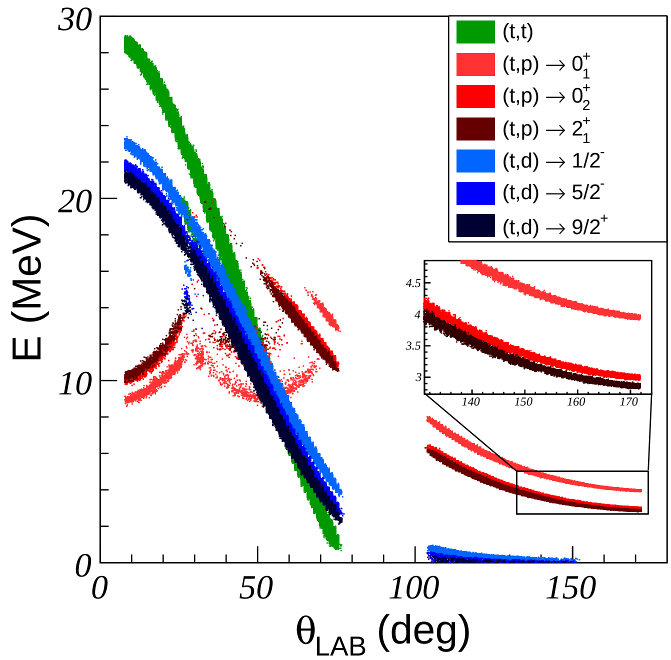

Figure 2: Simulated Energy/Angle correlations for the protons, deuterons and tritons from the different reactions considered here.

2.1 Experimental setup

The T-REX silicon array [16] will be used to detect and identify the escaping light particles, with a total angular coverage of about 65%. It consists of two double sided segmented silicon telescopes (so-called *CD* detectors) in the forward and in the backward direction, and eight planar silicon telescopes (called *Barrel*) around 90° lab as schematized on Fig.3. The backward *CD* is 500 μm thick and is segmented in 16 annular strips (θ-coordinate) in the front and 24 radial segments (ϕ-coordinate) on the back. It will be used for total

energy measurement as it is thick enough to stop all protons and deuterons.
The forward *CD* telescope, consisting of two layers, will mainly be used to detect and identify the elastically scattered tritons and deuterons from the one neutron transfer reaction. Most of the protons from the (t,p) reaction will punch through this telescope. The first layer is 500 μm thick and is segmented in 16 annular strips (θ-coordinate) in the front and 24 radial segments (ϕ-coordinate) on the back. It is used for ΔE measurement and it is surrounded by a 1500 μm detector segmented in 4 quadrants providing a measurement of the residual energy E.
The eight *Barrel* detectors are also ΔE/E telescopes. The ΔE layer, 140 μm thick is segmented in 16 resistive strips, perpendicular to the beam axis. The E detectors are 1000 μm thick and are not segmented.
A thin Mylar foil will be added in the forward direction in order to stop the elastically scattered Ti atoms of the target. The MINIBALL Ge-array will be used to identify high-lying states, together with the 2^+_1, 2^+_2 and 0^+_3 states which decay by γ-rays.
A delayed coincidence setup will also be installed at the beam-dump location in order to tag the $9/2^+$ isomer in ^{67}Ni and possibly the E0 transition from the 0^+_2 to 0^+_1 state in ^{68}Ni.

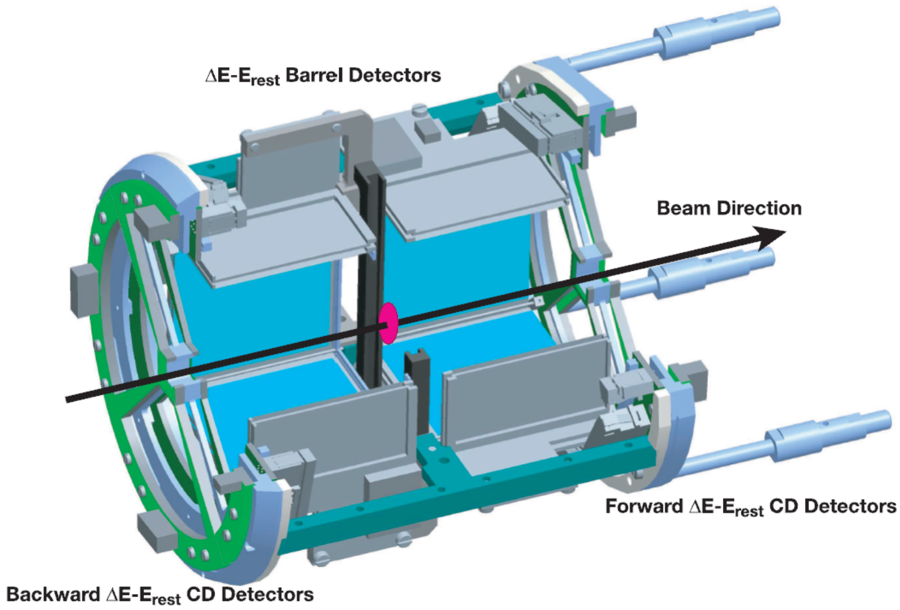

Figure 3: Schematic view of the T-REX silicon array.

2.2 Beam production

The ^{66}Ni beam will be produced by the standard UC$_x$ target and ionized with RILIS. An average rate of 3×10^6 pps at the target location was achieved during the IS469 experiment, with a beam purity better than 99%.

2.3 The radioactive tritium target

The tritium target is based on a thin strip of 500 μg/cm^2 thick metallic Ti foil loaded with an atomic ratio ^{3}H/Ti of 1.5 corresponding to a target thickness of 40 μg/cm^2 equivalent ^{3}H. With an activity of less than 10 GBq, this tritium-loaded Ti foil target is permitted following CERN Specification No 4229RP20070405-GD-001 [17]. It has been safely and successfully used for the study of ^{32}Mg through the ^{3}H(^{30}Mg,^{32}Mg)p two-neutron transfer reaction [18, 19]. It is also planned to be used for the IS499 experiment which aims at studying the onset of deformation and shape coexistence in ^{46}Ar via the ^{3}H(^{44}Ar,^{46}Ar)p reaction [20].

3 CRC calculations and simulations

In order to avoid fusion with the Ti backing of the target, the beam energy must be limited to 2.7A MeV (the fusion barrier is around 180 MeV).
The Q-value of the (t,p) reaction is 5.12 MeV and -0.45 MeV for the (t,d) one neutron transfer reaction. At the incoming beam energy of 2.7A MeV, the sequential two-neutron transfer reaction process can not be neglected. Calculations were performed in the Coupled Reaction Channel (CRC) framework, according to the coupling scheme presented in Fig.4. The three first states of ^{67}Ni were considered as possible intermediate states, and the angular distributions were calculated for the transitions to the three first states of ^{68}Ni. For the sake of simplicity, the deuteron breakup was not included but its influence is assumed to be minor. The spectroscopic amplitudes for (t,d), (d,p) and (t,p) transitions to the considered states were evaluated using the single particle orbitals occupancy numbers found in [3].

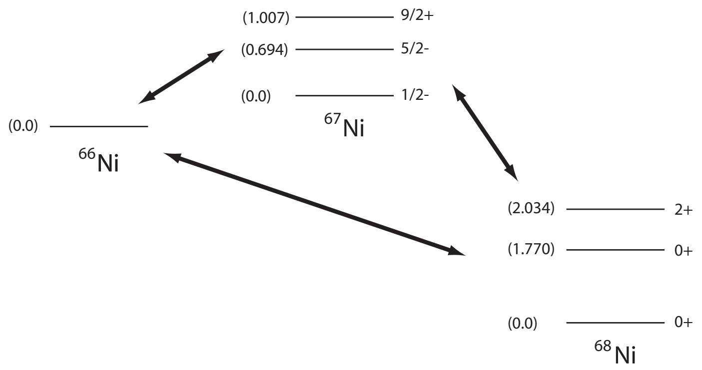

Figure 4: Coupling scheme used in the CRC calculations.

The results of the calculations are shown on Fig.5. Note that the coupling to the sequential transfer channel has a small influence. However, the angular momentum mismatch for the pair transfer is was not taken into account in the CRC calculations. If the 0_2^+ state in ^{68}Ni is a pure $\nu(g_{9/2})^2$ state, which is the worse conceivable case, we estimate the cross section to be only 5% of the one calculated. If this state is mixed with the ground state, the cross section will then be higher. Moreover, by comparing our results with the systematics of (t,p) transfer reactions on the nickel chain found in [21, 22], we found that the amplitude of the cross section to the 2_1^+ state appears to be large compared to the lighter Ni isotopes, for which the transition yield is around 5% of the ground state to ground state transition yield. We therefore renormalize the calculated rates in order to make the counting rate estimates.

The calculated distributions were used as input for GEANT4 [23] simulations of the expected light charged particle emissions and the expected detector response of the T-REX setup. The kinematics of the (t,d) reaction allows deuterons to be emitted at

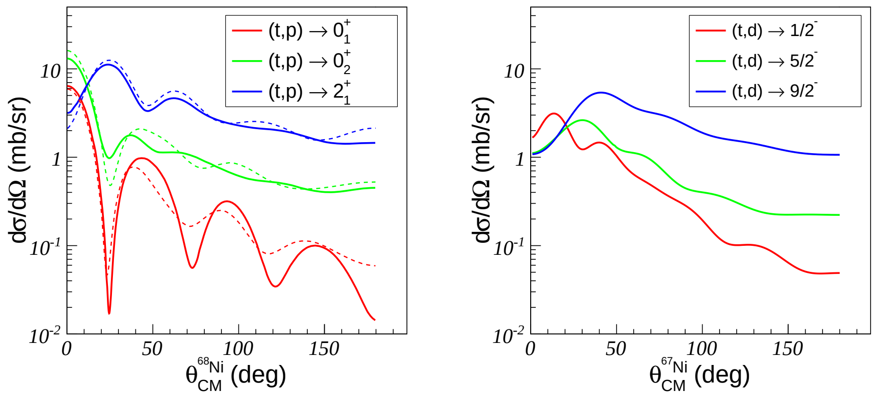

Figure 5: Angular distributions calculated in the CRC framework. Left panel: for the 2-neutron transfer reaction *(t,p)*. Dashed lines represent the direct pair transfer. Solid lines are used for the sequential+direct transfer. Right panel: Results for the 1-neutron *(t,d)* transfer reaction to ^{67}Ni.

backward angles. Nonetheless, due to the negative Q-value of this reaction, the deuterons carry very little energy. It will then be possible to discriminate between protons and deuterons at backward angles using the correlation between the energy and the angle of the particles as shown in Fig.2.

The forward detection system will be mainly used to study the one-neutron transfer reaction and the elastic scattering. It will be possible to identify the light hydrogen isotopes through a ΔE/E correlation.

4 Rate estimates and beam time request

The counting rate estimates are presented in Table.1, assuming an incoming intensity of 3×10^6 pps. The calculated cross sections for the transition to the excited states of ^{68}Ni are renormalized as stated in section 3. To obtain sufficient statistics to reconstruct the angular distributions, *i.e.* 7000 counts in the silicon array, **27 shifts are required**. Additionally, we ask for **3 shifts** for the beam tuning. **In total, the beam time request amounts 30 shifts**.

Table 1: Count rate estimates for the ^{3}H(^{66}Ni,^{68}Ni)p and the ^{3}H(^{66}Ni,^{67}Ni)d reactions.

reaction	E_{state} (keV)	J^π	σ (mb)	Events/h	Total number of events
^{3}H(^{66}Ni,^{68}Ni)p	0.0	0^+	6.64	690	1.5×10^5
	1770	0^+	0.33	34	7300
	2034	2^+	0.53	55	11800
^{3}H(^{66}Ni,^{67}Ni)d	0.0	$1/2^-$	0.39	40	8700
	694	$5/2^-$	1.15	119	25800
	1007	$9/2^+$	5.84	610	1.3×10^5

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