EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

IS587: Characterising excited states in and around the semi-magic nucleus ^{68}Ni using Coulomb excitation and one-neutron transfer

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Abstract: This status report aims to reassert the physics case for IS587 with a view to retain the shifts already granted for Coulomb-excitation studies of ^{66,68}Ni and the one-neutron transfer reaction in to ^{69}Ni. Since the original proposal was accepted, there was a further addendum and letter of clarification that sought to clarify technical matters, which will not be repeated here. No shifts were scheduled for IS587 prior to CERN's

second long shutdown (LS2). In this status report, we present and update on complementary experiments studying the neutron-rich nickel isotopes along with new theoretical interpretations of the lowest-lying 0^+ and 2^+ states.
The aim of this proposal is to measure, simultaneously, the $B(E2; 2^+_1 \rightarrow 0^+_1)$ value and the spectroscopic quadrupole moments of the 2^+_1 state in ^{66,68}Ni. This serves as a direct test of recent Monte-Carlo Shell Model (MCSM) calculations that predict shape coexistence in these isotopes. In addition the ^{68}Ni(d,p) reaction will be used to populate excited $\frac{5}{2}^+$ states in ^{69}Ni, leading to direct information on the $N = 50$ shell gap. Miniball will be used for both the Coulomb-excitation and transfer experiments, utilising the T-REX particle detector array in a way that they can be run consecutively, using the same beam from HIE-ISOLDE.

Remaining shifts: 30/30 shifts
Installation: MINIBALL + T-REX

1 Physics case

1.1 Shape coexistence near $N = 40$

Shape coexistence in nuclei now appears across the chart of nuclides and the topic has been extensively studied in recent years with a number of theoretical and experimental approaches, recently reviewed in a series of papers [1–9]. Recent experimental work in the region around $N = 40$ has revealed strong evidence for a new region of shape coexistence around ^{68}Ni, utilising β-decay [10–14], multi-nucleon transfer reactions [15, 16], intermediate-energy Coulomb excitation [17] and lifetime measurements [18]. Excited 0^+ states, proposed to be the band-heads of intruder configurations, have been characterised in Monte-Carlo Shell Model (MCSM) calculations [3, 19] as variously belonging to prolate, oblate and spherical configurations. The total energy surface for ^{68}Ni obtained in the calculations (see Fig. 1) show three minima corresponding to the spherical ground state, plus excited coexisting oblate and prolate configurations. The corresponding level scheme, also shown in Fig. 1 and reproduces the observed levels well, indicating that the 2^+_1 state is in fact a member of the oblate band.
Experiments focused on populating excited 0^+ states in ^{66}Ni and measuring their lifetimes reveal a type of shape isomerism where the decays to the 2^+_1 are strongly hindered [16]. This is the result of a large barrier between the oblate and prolate configurations, reproduced by the MCSM calculations. As yet, no direct measurement of the shape of excited states in the neutron-rich nickel isotopes has been made. For the band head 0^+ states, this proves to be essentially impossible since they do not possess a spectroscopic quadrupole moment and they lie too high in energy for a complete quadrupole sum rules analysis [20]

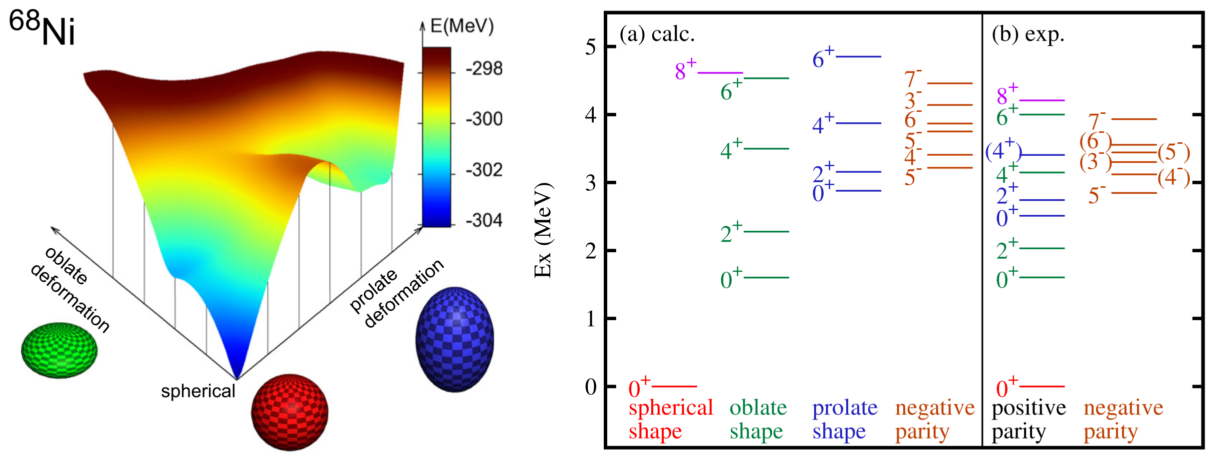

Figure 1: Three-dimensional total energy surface (left) and level scheme of ^{68}Ni (right) obtained from the Monte-Carlo shell model calculations [19] compared to the experimentally observed levels. Figures taken from Ref. [3]. Note that the surface obtained for ^{66}Ni (Fig. 1 of Ref. [16]) is remarkably similar to that of ^{68}Ni shown here.

to be performed. Therefore, the only way to determine the true shape of intruder configurations in these nuclei, and subsequently confirm the interpretation of type II shell evolution [3], is via a measurement of the $Q_s(2^+)$ states in Coulomb excitation.
Large-scale shell-model calculations have described the appearance of shape coexistence in ^{78}Ni and a new island of inversion about ^{74}Cr [21], similar to that proposed about ^{64}Cr [22]. This comes on the back of high-profile experimental efforts in this extremely exotic region [23–25]. Most recently, a pair of 2^+ states has been observed at a similar energy in ^{78}Ni itself [26], giving a strong indication that deformed states persist at low excitation energy even in this doubly-magic system.

1.2 The $N = 50$ shell gap

Approaching the doubly-magic ^{78}Ni, it is crucial to understand the evolution of the shell gap at $N = 50$, both to benchmark single-particle behaviour and to understand intruder configurations predicted in large-scale shell model calculations. Recent experimental work in this region [23–25] has benefited from advances in a number of facilities around the world, including ISOLDE. Beyond the $N = 40$ sub-shell closure, the evolution of $\nu d_{5/2}$ and $\nu g_{9/2}$ orbitals play a dominant role in the ground and excited states in the nickel isotopes. In particular, the deformation in the Fe [27, 28] and Cr [29, 30] isotopes south of ^{68}Ni is proposed to be driven by the $\nu d_{5/2}$ orbital, where the second island of inversion is predicted [22]. One-neutron transfer reactions in these systems pins down the $\nu d_{5/2} - \nu g_{9/2}$ energy gap, by locating the excited $5/2^+$ states above the $9/2^+$ ground state.
Previous transfer reactions in Ni isotopes near $N = 40$ have been performed at REX-ISOLDE, using Miniball and T-REX [31, 32]. So far it has only been possible to measure excited states in ^{69}Ni using β-decay [33, 34], isomeric decay [35] and the neutron knockout reaction, $p(^{70}\text{Ni},^{69}\text{Ni})d$ [36]. The one-neutron transfer reaction $d(^{68}\text{Ni},^{69}\text{Ni})p$ has been performed at GANIL [37, 38], but this study was limited by the resolution of the particle

spectrum, which limited the conclusions and precision of the observed states in ^{69}Ni. Furthermore, the high energy of the reaction, 25 MeV/u, was not well matched for the $l = 2$ transfer to the $5/2^{+}$ states of interest.

2 Proposed experiments

2.1 Coulomb excitation of ^{66,68}Ni

We propose to perform Coulomb-excitation of ^{66,68}Ni with the primary purpose of determining the spectroscopic quadrupole moments, Q_s, of the first-excited 2^{+} states in these nuclei. Simultaneously, we will also determine the $B(E2; 0^{+}_{1} \rightarrow 2^{+}_{1})$ values independent of previous measurements [39, 40] by normalising to the target excitation.
The details of the experimental setup and method have previously been presented in the original proposal [41], the addendum [42] and further in the letter of clarification [43]. Those details will not be repeated here since there are no changes to the proposed method. In order to achieve a precision of 10% in the $B(E2)$ value and < 15 $e$fm^2 in $Q_s(2^{+}_{1})$, the data have to be segmented into four angular ranges, each with $\simeq 100$ counts in the $2^{+}_{1} \rightarrow 0^{+}_{1}$ transition. Gosia calculations [44, 45] have been performed to determine the number of shifts required to achieve these conditions, and simulated data was analysed to extract the expected precision. The beam time request is summarised in Table 1, while the result of the simulation assuming three different values of the the quadrupole moment in ^{68}Ni is shown in Fig. 2, showing an expected precision of $\simeq 10$ $e$fm^2 in $Q_s(2^{+}_{1})$.
In the case of ^{66}Ni, a similar precision will be reached but with a much higher level of statistics. This fact will also allow us to study systematic uncertainties much more rigorously, which can then be applied also to the ^{68}Ni case, taking advantage of running the experiments with an identical experimental setup.

2.2 One neutron transfer reaction ^{68}Ni(d,p)

HIE-ISOLDE is uniquely placed to deliver a ^{68}Ni beam at the optimal energy to populate $5/2^{+}$ states in ^{69}Ni, leading to a determination of the $\nu d_{5/2} - \nu g_{9/2}$ shell gap above $N = 40$. Using Miniball and T-REX, as was done in the analogous $d(^{66}\mathrm{Ni},^{67}\mathrm{Ni})p$ reaction [31, 32], one can select individual excited state with the high-resolution of the γ-ray detection in Miniball. Angular distributions in T-REX will be used to determine the angular momentum transfer and hence the spin of the final states populated in ^{69}Ni.
The beam energy is chosen to be 5.0 MeV/u, well matched for the $l = 2$ transfer required to populate the excited $5/2^{+}$ states around 2.5 MeV/u. If there are indeed two such states, they should preferentially decay to the $9/2^{+}$ ground state with a γ-ray energy matching the excitation energy. Moreover, relative spectroscopic factors can be determined using this setup, which will give more information on the final state configurations when compared to shell model calculations.
DWBA calculations using the FRESCO code [46] were performed to estimate the cross-section of one-neutron transfer to excited states in ^{69}Ni. Spectroscopic factors (SF) of 1 are assumed for all populated states, giving an integrated cross-section for the $5/2^{+}$ state

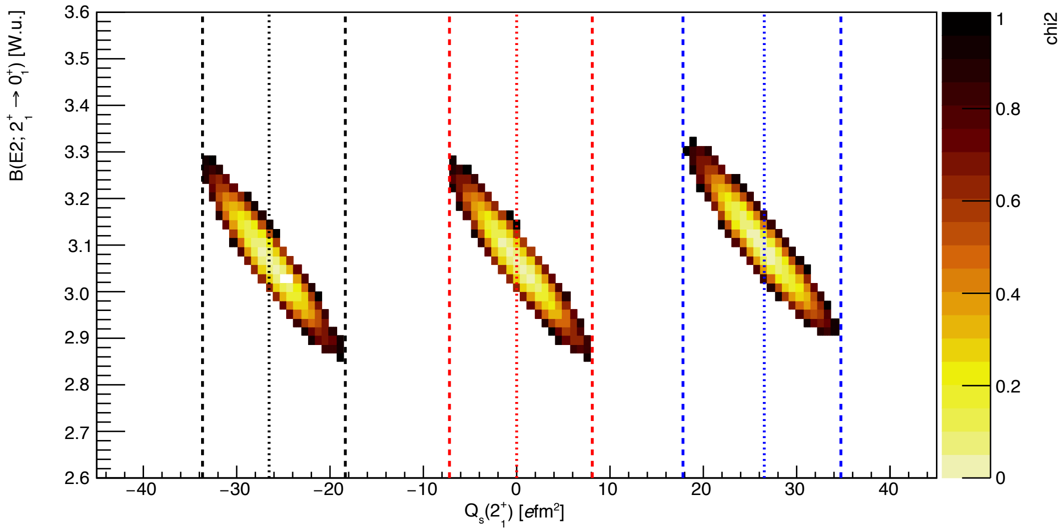

Figure 2: A simulated two-dimensional χ^2 surface plot, for the transitional and diagonal matrix elements (fit parameters) of the 2^+_1 state in ^{68}Ni. It is cut at $\chi^2_{\mathrm{min}} + 1$ representing the 1σ contour. For this simulation, five centre-of-mass angular ranges were assumed, corresponding to four projectile and one target ranges in the laboratory frame. The uncertainties on the γ-ray intensities were assumed to be statistical plus a 3% systematic uncertainty from the determination of the relative efficiency for detecting γ rays from the projectile and target.

of interest of 122 mb. To determine the proton count rate, a standard reduction factor of 0.6 for the spectroscopic factors has been taken into account (see [47, 48]) and the angular coverage of the T-REX barrel detectors assumed to be 40%. A relatively thick target of 0.2 mg/cm^2 is planned to be used in order to increase the count rate, with the reduced resolution being recovered by γ-ray gating where the efficiency is around 4%. In the 9 shifts accepted by the INTC in the original proposal, this gives a total of 840 coincident proton-γ events in the backwards angles of T-REX.

2.3 Beam-time request

In the past few years of operation at ISOLDE, neutron-rich Nickel beams have been used a number of times. In our letter of clarification to the INTC in 2017 [43], we removed the request for ^{70}Ni beam due to the large amount of isobaric contamination that was observed in two beam times of 2016. The target units used at that time, #568 and #586, used graphite and Ta ion sources sources, respectively. Both ion sources show 2-3 orders of magnitude higher yield for ^{70}Ga over ^{70}Ni, and studies by the TISD group suggest that while moving to the neutron converter will improve the contaminant ratio, the yield of ^{70}Ni also drops significantly [49].
For the case of ^{66}Ni, the beam production is large and the contaminant is more than an order of magnitude smaller than the beam of interest. In order to have precise normalisation to the target excitation, the beam purity will have to be monitored throughout the run with RILIS lasers blocked (so-called laser on/off measurements) and utilising the

zero degree ionisation chamber at Miniball. The same is true for ^{68}Ni, where the ^{68}Ga is expected to have higher intensity, requiring more precision in determining the beam composition. Regular laser on/off runs will be used to track any changes in the Ga/Ni ratio. In the case that the contaminant is very large, we will have to revert to the method of subtracting the laser off data from the laser on data in the Coulomb-excitation experiment, which incurs a 50% duty cycle to the measurements.
In addition to the shifts already approved as laid out in Table 1, two shifts were approved for the setup and optimisation of the RILIS lasers and beam energy and mass changes, which requires retuning of the HIE-ISOLDE linac.

Table 1: Summary of the beam-time request. The primary yield is taken to be the intensity of the 1^+ ions from the primary target, injected to the REX linac. We assume a proton current of 2 μA, a post-acceleration efficiency of 5% and a maximum rate of 2×10^6 ions/s is at Miniball.

	Yield (1/μC)	Beam Energy	$I_\gamma(2_1^+)$	$I_{p-\gamma}(5/2^+)$	Shifts
^{66}Ni - Coulex	1×10^8	4.0 MeV/u	3400/shift		4
^{68}Ni - Coulex	1×10^6	4.0 MeV/u	24/shift		15
^{68}Ni$(d,p)^{69}$Ni		5.0 MeV/u		93/shift	9

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