EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

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

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L. P. Gaffney[1], F. Flavigny[1], M. Zielińska[2], K. Kolos[4], A. N. Andreyev[5], M. Axiotis[6], D. L. Balabanski[7], A. Blazhev[8], J. Cederkäll[9], T. E. Cocolios[10], E. Clément[11], T. Davinson[12], G. De France[11], H. De Witte[1], D. Di Julio[9], T. Duguet[2], C. Fahlander[9], S. J. Freeman[10], G. Georgiev[13], R. Gernhäuser[14], A. Gillibert[2], T. Grahn[15], P. T. Greenlees[15], L. Grente[2], R. K. Grzywacz[4,16], S. Harissopulos[6], M. Huyse[1], D. J. Jenkins[5], J. Jolie[8], R. Julin[15], W. Korten[2], Th. Kröll[17], A. Lagoyannis[6], C. Louchart[2], T. J. Mertzimekis[18], D. Miller[19], D. Mücher[14], P. Napiorkowski[20], K. Nowak[14], F. Nowacki[21], A. Obertelli[2], R. Orlandi[1], J. Pakarinen[15], P. Papadakis[15], N. Patronis[22], N. Pietralla[17], P. Rahkila[15], R. Raabe[1], G. Rainovski[17], E. Rapisarda[3], P. Reiter[8], M. D. Salsac[2], M. Seidlitz[8], B. Siebeck[8], K. Sieja[21], D. K. Sharp[10], C. Sotty[1], O. Sorlin[11], J. Srebrny[20], M. Taylor[10], P. Van Duppen[1], D. Voulot[3], N. Warr[8], R. Wadsworth[5], F. Wenander[3], K. Wimmer[23], P. Woods[12], K. Wrzosek-Lipska[1]

[1]*KU Leuven, Belgium*; [2]*CEA-Saclay, France*; [3]*CERN-ISOLDE, Switzerland*; [4]*University of Kentucky, U.S.*; [5]*University of York, U.K.*; [6]*NCSR-Demokritos, Greece*; [7]*INRNE-BAS, Bulgaria*; [8]*University of Köln, Germany*; [9]*University of Lund, Sweden*; [10]*Univeristy of Manchester, U.K.*; [11]*GANIL, France*; [12]*University of Edinburgh, U.K.*; [13]*CSNSM, France*; [14]*TU-München, Germany*; [15]*University of Jyväskylä; Helsinki Institute of Physics, Finland*; [16]*Oak Ridge National Laboratory, U.S.*; [17]*TU-Darmstadt, Germany*; [18]*Univeristy of Athens, Greece*; [19]*TRIUMF, Canada*; [20]*HIL University of Warsaw, Poland*; [21]*Université de Strasbourg, France*; [22]*University Of Ioannina, Greece*; [23]*Central Michigan University, U.S*

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Spokespersons:
Liam Paul Gaffney [Liam.Gaffney@fys.kuleuven.be],
Freddy Flavigny [Freddy.Flavigny@fys.kuleuven.be],
Magda Zielińska [magda.zielinska@cea.fr], Karolina Kolos [kkolos@utk.edu]
Contact person: Elisa Rapisarda [Elisa.Rapisarda@cern.ch]

Abstract: It is proposed to investigate the structure of excited states in ^{68,70}Ni$(Z = 28, N = 40, 42)$ via the measurement of electromagnetic matrix elements in a Coulomb excitation experiment in order to study the $N = 40$ harmonic-oscillator shell and the $Z = 28$ proton shell closures. The measured $B(E2)$ values connecting low-lying 0^+ and 2^+ can be compared to shell-model predictions. It is also proposed to perform the one-neutron transfer reaction $d(^{68}\text{Ni},^{69}\text{Ni})p$, with the aim of populating excited states in ^{69}Ni. Comparisons with the states populated in the recently performed $d(^{66}\text{Ni},^{67}\text{Ni})p$ reaction will be useful in determining the role of the neutron $d_{5/2}$ orbital in the semi-magic properties of ^{68}Ni.

Requested shifts: 41 shifts

1 Introduction and physics case

Key to the understanding of how shell structure develops in nuclei are the properties of nuclei around the $N = 40$ harmonic-oscillator shell-gap. New interactions have been developed for contemporary nuclear models [1–3] to help explain the emergence and suppression of magic numbers far from the line of beta-stability [4]. Of a particular interest is the interplay between single-particle and collective behaviour at this "semi-magic" shell closure, where it has been shown that the neutron $g_{9/2}$ orbital plays a crucial role in bringing about the transformation to a spin-orbit type shell closure at $N = 50$ [5]. Proton-pair excitations around the magic numbers are known to give rise to excited 0^+ states [6]. The doubly-magic nuclei ^{16}O ($Z = N = 8$) and ^{40}Ca ($Z = N = 20$) both show evidence of shape coexistence along with many singly-magic systems [7], however, there is a lack of experimental evidence for such states at $Z = 28$, although $\pi - \nu$ residual interactions could lower their energy around $N = 40$ [8].

The ^{68}Ni nucleus itself has been subject to some controversy [9, 10] with doubts cast on the doubly-magic character displayed by the high 2^+_1 energy and relatively low $B(E2; 0^+_1 \rightarrow 2^+_1)$ value [11, 12]. These features are thought to occur predomindantly because of the opposite parities of the $\nu 2p_{3/2}f_{5/2}p_{1/2}$ and $\nu g_{9/2}$ orbitals. More recent precision mass measurements show a local but weak discontinuity in the two-neutron separation energy at $N = 40$ [13], supporting a suppressed shell closure.

Proton-pair excitations across the $Z = 28$ shell gap are predicted to produce a 0^+ state around 2.2 MeV [8]. The 0^+_3 state identified at 2.511 MeV is a possible candidate for a $\pi(2p\text{-}2h)$ state though a lack of experimental information on transition strengths prevent firm characterisation. Further to this, the 0^+_2 state, believed to come about due to neutron-pair scattering to the $g_{9/2}$ orbital [14], has been firmly placed at 1605 keV, e.g. Ref. [15–17], in contradiction with the original and long-standing placement at 1770 keV [18].

Beyond $N = 40$, a striking reduction in the 2^+ excitation energies is observed from ^{70}Ni to ^{76}Ni [19]. The energies of first-excited 2^+ states drop from 1.26 MeV down to 0.99 MeV and are systematically about 0.3 MeV lower than expected from the shell model [20], which suggests that there is some degree of collectivity influencing the structure of nickel nuclei at low excitation energies. A direct measurement of the $B(E2; 0^+_1 \rightarrow 2^+_1)$ value in the Ni could give a quantitative contribution of this effect. Indeed, the first $B(E2)$ measurements at GANIL using Coulomb excitation at 60 MeV/u [21] gave a larger than expected $E2$ strength of $B(E2; 0^+_1 \rightarrow 2^+_1) = 0.086(14)\ e^2\text{b}^2$ ($\delta^c = 0.87(14)$ fm) and confirmed the collectivity in ^{70}Ni. Subsequent proton inelastic-scattering experiments on ^{74}Ni [22] at 80 MeV/u at NSCL provided further evidence for a large $B(E2)$. However, the ^{70}Ni measurement has been put in doubt by a recent direct lifetime measurement ($\tau \approx 5.5$ ps) using the differential plunger technique at NSCL [23], which does not reproduce such a strong enhancement. The extracted, non-collective $B(E2; 0^+_1 \rightarrow 2^+_1) = 0.023\ e^2\text{b}^2$ agrees with the value predicted by the Lisetskiy/Brown model [24], which also reproduces the 2^+ energies through experiment-based modifications of residual interactions. Sieja et al. [25] were able to reconstruct the large $B(E2)$ by expanding the valence space (including $d_{5/2}$ orbital), which is, in principle, a more sound procedure than the phenomenological approach.

Each of the previous Coulex experiments on ^{68,70}Ni were performed at relativistic energies (with the exception of the low-statistics measurement of ^{68}Ni at REX-ISOLDE [12]), the particular conditions of measurement, such as e.g. feeding from higher-energy 2^+ states, could affect the measurements. This would lead to contradictory results and therefore a new measurement, free of such particular experimental bias, is required to reconcile the situation before further theoretical speculations can be made. An independent measurement is also required in order to reveal potential pitfalls in experimental methods using fragmentation techniques before they

are applied to study more exotic isotopes of nickel at RIKEN or FRIB. Furthermore, new experiments have confirmed three pairs of 0^+ and 2^+ states in ^{68}Ni and multiple-step Coulomb excitation should allow their structure to be studied.
To constrain the recent and somewhat conflicting theoretical calculations mentioned previously [1–3, 25], the experimental study of the $d_{5/2}$ orbit through single-nucleon excitation in the region of ^{68}Ni appears to be crucial for understanding the dynamics of nuclear-shape changes around $N = 40$. The direct reaction, $d(^{68}\mathrm{Ni},^{69}\mathrm{Ni})p$, is a precise way to do so and has been performed once in GANIL using a fragmentation beam at 25 MeV/u [26]. Even though at this beam energy, the angular momentum matching favours l-transfer of momentum of $l \geq 2$, a peak in the excitation-energy spectrum has been observed around 2.5 MeV and proposed to be coming from two unresolved $5/2^+$ states. The presence of two states relies on the width of the peak being slightly larger that what is expected in simulations but no gamma-coincidence has been observed in the experiment. Such results pave the way to our understanding of the contribution of the $d_{5/2}$ orbital but may impact drastically on our understanding of its role in this region. Therefore, to conclude on the existence of one or two states, to confirm their spin and parity and measure their decay pattern, we propose to re-measure the $d(^{68}\mathrm{Ni},^{69}\mathrm{Ni})p$ reaction at 5 MeV/u at HIE-ISOLDE using the TREX+MINIBALL setup and a thin CD_2 target.

We propose to perform Coulomb excitation of the ^{68,70}Ni projectiles from HIE-ISOLDE at energies between 3.5 – 4.5 MeV/u upon secondary targets of ^{196}Pt and ^{208}Pb in order to determine the $B(E2)$ values connecting excited 0^+ and 2^+ states in these nuclei. Multi-step Coulomb excitation in ^{68}Ni will determine the collective nature, or not, of excited 0^+ and 2^+ states, whilst a first low-energy Coulomb-excitation measurement of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ in ^{70}Ni will be performed to discriminate between two recent contradictory results leading to different shell-model interpretations. Further to this, we propose to utilise the same ^{68}Ni beam to perform the one-neutron transfer reaction $d(^{68}\mathrm{Ni},^{69}\mathrm{Ni})p$ at 5.0 MeV/u to identify and characterise excited states in ^{69}Ni.

2 Experimental Method

Coulomb excitation (Coulex) at "safe" energies is an excellent tool to access transition strengths connecting low-lying states, where "safe" implies that the interacting nuclear surfaces are separated by a minimum distance of 5 fm. Intermediate or relativistic Coulomb excitation is usually restricted to single-step excitations, but measuring as close to the Coulomb barrier as possible for a wide range of scattering angles, in this case $> 95\%$ for $< 110°$, will allow access to higher-order excitations and thus provide information on matrix elements connecting excited states. The level schemes showing the states which are relevant to this study can be seen in Fig. 1.
Single-neutron transfer reactions into nuclei neighbouring ^{68}Ni are ideally suited in probing the size of the $N = 40$ shell gap. In order to resolve the excited states in ^{69}Ni, it is imperative that γ-rays are measured in coincidence with the protons. From the $d(^{66}\mathrm{Ni},^{67}\mathrm{Ni})p$ reaction [27], it could be shown that the high resolution of the γ-ray energy in MINIBALL in coincidence with the reconstructed energy from the protons in T-REX, which appear as a single unresolved structure, allowed for identification of levels which lie very close in energy.

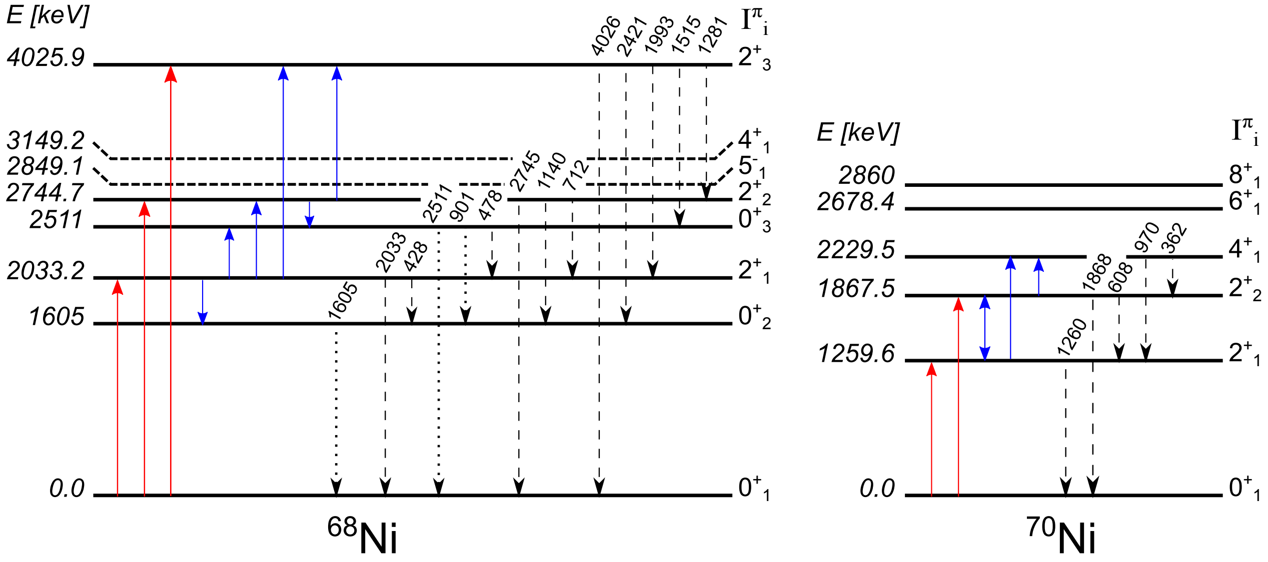

Figure 1: Partial level schemes for ^{68,70}Ni. Single-step Coulomb-excitation paths are shown in red, whilst the most important two-step paths are shown in blue. Some states are populated by multiple paths, but experimentally determined γ-ray branching ratios constrain the relative $B(E2)$ values. De-excitation γ-ray transitions are shown by the dashed arrows and $E0$ decays by dotted arrows with their energies indicated above in units of keV.

2.1 Coulex

To ensure the safe condition is met, a balance has to be struck between beam energy and the maximum centre-of-mass (CoM) scattering angle. For the heavy targets ^{196}Pt and ^{208}Pb, the latter is around 70°, corresponding to a maximum projectile angle in the laboratory frame of $\approx 53°$, for a beam energy of 5.0 MeV/u. The higher CoM angles, via the detection of the target recoil events, obtainable with the lower beam energy of 4.0 MeV/u enhance the all important second-order excitations. A target thickness of 2.0 mg/cm^2 is chosen as a balance between energy resolution and Coulex cross-section.

The MINIBALL Ge-array [28] will be used to detect the de-excitation γ-rays following Coulomb excitation of the excited states. The T-REX silicon array [29] allows for particle detection and identification at forward angles by utilising a Double-Sided Silicon Strip Detector (DSSSD), or CD detector, plus four barrel detectors with the same system repeated in the backwards angles. We intend to remove the barrel detectors in the forward direction to allow the CD detector to be used in a close geometry at 32 mm from the target, where the angular coverage is 15.8°–52.0°. The backwards angles will be configured for the transfer part of this proposal (see Section 2.2). Angular-dependent software gates on particle energy can be used to identify projectiles and recoils and make cuts corresponding to the appropriate centre-of-mass solutions. The granularity of the MINIBALL array and the CD detector allows for Doppler correction to be applied to γ rays emitted in flight.

At 32 mm to the CD detector from the target, the flight time of the nuclei is 1 ns. The half life of the first-excited 0^+ state is 270(5) ns [11], meaning that 93.5% of decays from this state occur when the nucleus is stopped. According to BrIcc [30], 45.1% of the decay goes via e^-/e^+ pair emission, resulting in two back-to-back 511-keV gamma rays upon annihilation of the β^+. Applying time conditions, these events can be detected in the MINIBALL array as a coincidence between a projectile and two gamma rays in geometrically opposite Ge detectors with respect to the implantation point in the CD detector (a similar method has previously been used [31]). This is a very pure method for counting the $E0$ decays and will be almost totally background free. A full GEANT4 simulation is underway to ascertain the detection efficiency for this type of event, but a conservative estimation based on the branching ratio, solid angle coverage and lifetime losses is put at 1.0%.

2.2 Transfer

The transfer part of the experiment will take advantage of the same T-REX chamber as the Coulex does, only the particle detection will be via the emitted protons in the backwards barrel. The 0.2 mg/cm^2-thick CD_2 target will be mounted on the target ladder alongside the Coulex targets meaning that it is not necessary to fundamentally alter the configuration between the experiments and the switch will take a matter of moments. The proposed set-up and technique has been successful for the study of one-neutron transfer reactions on a ^{66}Ni beam [27] and we refer you to this reference for an in-depth description. The particular advantage of this setup over the previous measurement is the ability to measure coincident γ rays with a high efficiency.

3 Beam-time Request

3.1 ^{68}Ni

The primary yield for ^{68}Ni is listed on the ISOLDE yield database as 4×10^5 ions/μC, while the previous Coulex experiment measured a yield at the exit of the HRS of 2.5×10^6 ions/s [12]. This latter measurement though, was hampered by a strong isomeric contamination from Ga which meant that beam could only be taken for the final 8.8 seconds of the 14.4 second supercycle. Furthermore, proton pulses were only taken during the first 5.6 seconds (5/12 in supercycle) meaning a reduction in the maximal proton current. The ^{68}Ni rate at MINIBALL was 1.4×10^4 ions/s. With an improved selectivity from the RILIS laser setup [32], the Ga contamination can be suppressed enough to allow the use of the full beam window. Further improvements are expected to be made in the RILIS setup, however it is difficult to estimate the impact of these other than to say that it will not compromise the ionisation efficiency [32]. Short runs into the ionisation chamber will be made with the laser system in on/off mode to ascertain the composition of the beam throughout the running period. The continuous improvements to the trapping and charge-breeding cycle over the years combined with the HIE-ISOLDE upgrade should improve the efficiency of the post-acceleration to 10% over REX (2%), a factor of 5. Coupling all of these improvements we make an assumption that there will be a factor of 15 increase in the available beam delivered to MINIBALL, i.e. 2.1×10^5 ions/s. Assuming a proton current of 2 μA and a post-acceleration efficiency of 10%, this is equivalent to a primary yield of 1×10^6 ions/μC, which is close to the 8×10^5 ions/μC measured in 2005 [33] and therefore a safe estimate.

3.1.1 Coulex

In order to estimate the expected γ-ray intensities, the computer code GOSIA was employed [34, 35]. The Coulomb excitation cross-section for each state, which depends electromagnetic matrix elements, is calculated for a large number of angular and energy meshpoints to accurately describe the process of scattering through the target with the matrix elements as an input parameter. The same matrix elements also govern the decay of the excited states, and this is calculated in the form of γ-ray intensities for each transition. During the analysis, the matrix elements will be determined in a least-squares fit procedure to the observed γ-ray intensities.

For this proposal, we have assumed the measured value of $\langle 0_1^+||E2||2_1^+\rangle = 15.9(9)\ e^2\mathrm{fm}^2$ [11, 12] to estimate the γ-ray intensities. The $E2$ matrix elements connecting higher-lying states are taken from shell-model calculations [36], where predicted. Extrapolation to other transitions is made using the measured branching ratios (or upper limits) [15].

Table 1: Calculated γ-ray intensities, I_γ, in ^{68}Ni from the GOSIA code, corrected for the efficiency of the MINIBALL array. A ^{68}Ni rate at MINIBALL of 1.5×10^5 ions/s is assumed. Run times for the ^{196}Pt and ^{208}Pb targets are 24 hours and 120 hours, respectively.

Transition $I_i^\pi \to I_f^\pi$ [$\hbar$]	Energy [MeV]	Efficiency [%]	^{196}Pt(^{68}Ni*) (4.5 MeV/u)	^{208}Pb(^{68}Ni*) (4.0 MeV/u)
$2_1^+ \to 0_1^+$	2.0332	5.6	300	871
$0_3^+ \to 2_1^+$	0.4778	13.1	–	≥ 17
$2_2^+ \to 0_1^+$	2.7447	4.0	–	≥ 4
$0_2^+ \to 0_1^+$	0.511(pp)	1.0	5	25

It is proposed to first re-measure the $\langle 0_1^+||E2||2_1^+\rangle$ in ^{68}Ni relative to the ^{196}Pt target excitation which has very well determined matrix elements (e.g. $\langle 0_1^+||E2||2_1^+\rangle = 1.1697(13)$ [37]). A beam energy of 4.5 MeV/u is chosen to maximise the one-step excitation of the 2_1^+, without introducing too large a background from nuclear reactions. A $2_1^+ \to 0_1^+$ intensity of 300 counts can be achieved in one day and then a switch to the ^{208}Pb target will be made to reduce the amount of target excitation that would otherwise dominate the γ-ray spectrum. For this second part of the run, the matrix elements connecting higher-lying states will be measured relative to $\langle 0_1^+||E2||2_1^+\rangle$. Since the two-step excitation is important here, a lower energy of 4.0 MeV/u is required to increase the angular range for safe scattering.
An experimental determination of the $B(E2; 2_1^+ \to 0_2^+)$ is possible via the branching ratio of the 428-keV $2_1^+ \to 0_2^+$ and 2033-keV $2_1^+ \to 0_1^+$ transitions. The 428-keV γ-ray branch is likely to be below the detection limit, so we plan to utilise the 1.6-MeV $0_2^+ \to 0_1^+$ $E0$ transition via the clean detection of back-to-back 511-keV photons. Since the population of the 0_2^+ state is dominated by two-step excitation via the 2_1^+ state, it is directly proportional to $B(E2; 2_1^+ \to 0_2^+)$.
The intensity of the 478-keV $0_3^+ \to 2_1^+$ transition is on the limit of observation due to the expected Compton background from the 2.033-MeV transition, assuming the single particle-like prediction of 0.92 W.u. [36]. If this is a collective transition, a $B(E2)$ of tens to hundreds of Weisskopf units can be expected and the 478-keV transition would be much more intense. Therefore, in these calculations, we present a worst-case condition to achieve the physics goal for this transition.
Population of the 2_2^+ state comes from two majority excitation paths, i.e. 1-step excitation from the ground-state and 2-step excitation via the 2_1^+ state, which together contribute 98% of the total. The relative $B(E2)$s of both paths are known from branching ratios, meaning that the relative excitation strength is also known. The population then only depends on the absolute $B(E2; 2_2^+ \to I_i^+)$ values, which can be measured via the γ-ray intensity of any depopulating transition to I_i^+. There are three such transitions, the cleanest of which is the 2.745-MeV decay to the ground state, which should have a minimum 4 counts in the background-free energy region above Compton background.

3.1.2 Transfer

DWBA calculations using the FRESCO code [38] 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 in this figure, although it may be that it is smaller for the negative parity states if their configurations are built upon the predicted particle-hole excitations. It is important to highlight that, due to the very good energy matching for $l = 2$ transfer at the HIE-ISOLDE energy of 5 MeV/u, the calculated cross section for the population of the $5/2^+$ state of 122 mb, is significantly larger than the previous experiment performed at 25 MeV/u [26]. Moreover, if there are two states, spin and parity considerations suggest that each of them should preferably decay to the $9/2^+$ ground state. Thus we will be able to conclude definitely on this point measuring the γ-rays in MINIBALL coincident with a proton in T-REX corresponding to an excitation energy window around 2.5 MeV. In addition, relative spectroscopic factors can be extracted as shown in previous work using the same setup [27]. To determine the proton count rate, a standard reduction factor of 0.6 for the spectroscopic factors has been taken into account (see [39, 40]) and the angular coverage of the T-REX barrel detectors assumed to be 40%; on-going simulations will refine this.
As discussed, it is necessary to observe the subsequent γ-ray decay of the excited states since they lie too close together to be resolved in the particle spectra. An average efficiency of 4% is assumed for the coincident detection of both the proton in T-REX and γ ray in MINIBALL. For the $5/2^+$ state, assumed to be at 2.5 MeV, this gives 840 counts over the backwards angles of T-REX for a 0.2 mg/cm^2-thick target in three days, enough to subdivide the data into angular segments by taking advantage of the position sensitivity of the barrel detectors.

3.2 ^{70}Ni: Coulex

According to the recent results [33] the yield of the primary beam of ^{70}Ni is 2×10^5 ions/μC. The purity of the beam is about 50%. A beam energy of 3.5 MeV/u is chosen to ensure that all scattering events meet the safe criterion and therefore all events in the CD, projectile or recoil, can be utilised. This simultaneously increases the angular range and removes the need to cleanly separate the two kinematic solutions, allowing for a thicker target to be used.
Two scenarios should be taken into consideration; in case that the lifetime of the 2^+ state in ^{70}Ni is $\tau = 1.5$ ps and $B(E2; 0_1^+ \to 2_1^+) = 0.086\ e^2\mathrm{b}^2$, we expect to have 200 counts/day with the 2.0 mg/cm^2-thick ^{196}Pt target in the laser ON mode, while in case of $\tau = 5.5$ ps and $B(E2; 0_1^+ \to 2_1^+) = 0.023\ e^2\mathrm{b}^2$ the predicted number is 60 counts/day. The present beam-time request assumes constant running in laser "ON/OFF" mode to precisely subtract Coulomb excitation of the beam contaminants. The rate estimates were made for ^{70}Ni-beam intensity of 10^4 pps at MINIBALL. Assuming, that the contamination is not greater than 50% we request 12 shifts of ^{70}Ni beam on the ^{196}Pt target and one shift for beam setup. Even with the relatively low statistics of couple of hundred counts, the experimental uncertainties should clearly discriminate between the two scenarios.

Summary of requested shifts: In total we are requesting **41 shifts** in this proposal. This breaks down as 30 (18+12) shifts for the Coulomb excitation of the ^{68,70}Ni beams plus 9 shifts for the one-neutron transfer studies with the ^{68}Ni beam. We will also require 1 shift for the each setup of beam (2).

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: MINIBALL + T-REX

Part of the	Availability	Design and manufacturing
MINIBALL + T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT Hazards named in the document relevant for the fixed MINIBALL + T-REX installation.