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A Proposal to the INTC Committee

Probing the N=50 shell gap near ^{78}Ni

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Abstract: An experiment is proposed to study the properties of low-lying states close to the N=50 shell gap by single nucleon transfer. The d(^{78}Zn,p)^{79}Zn reaction will be studied using the T-REX silicon-detector array coupled to the MINIBALL gamma-ray spectrometer. A ^{78}Zn beam intensity of 5×10^4 pps is expected. The isotope ^{79}Zn, with Z=30 and N=49, lies two protons above and one neutron below the double-shell closure at ^{78}Ni. Determination of the single-particle structure of low-lying states in ^{79}Zn will provide valuable information about the persistence of the N=50 shell gap in this neutron-rich region. In particular the behaviour of the $g_{9/2}$ and $d_{5/2}$ orbitals will be investigated. In total, 27 shifts of beam time are requested. This experiment is envisaged to be the first of a series of measurements on progressively more neutron-rich Zn isotopes.

1 Physics Case

Single-particle motion in a mean-field potential constitutes one of the fundamental concepts of the current understanding of nuclei. The correct predictions of the occurrence of magic numbers, interpreted as the signature of energy gaps corresponding to closed-shell configurations of neutrons and protons, and of the properties of nuclei lying close to these numbers, was essential to the development of the nuclear shell model. Recent studies of exotic nuclei have indicated that the familiar textbook magic numbers are not as enduring as once thought and can change or disappear in nuclei far from stability. This evidence poses new challenges to descriptive theoretical models.

Nuclei on the neutron-rich side of the stability line are under particularly intense scrutiny in the study of the evolution of magic numbers. Two main factors are believed to affect the relative energies of single-particle excitations in neutron-rich systems. First, near the dripline, and for a neutron separation energy smaller than about 2 MeV, the softer neutron binding potential will lead to a reduced spin-orbit splitting [1]. With the exception of the lightest nuclei, however, the neutron-rich nuclei which can be currently produced are too far from the dripline to exhibit a significant softening of the nuclear potential. Second, the density dependence of the residual interaction, and in particular of its tensor component [2, 3], affects the relative energy spacings of single-particle orbits. The tensor interaction, which acts throughout the whole nuclear chart, is stronger between nucleons in specific single-particle orbits. This dependence on the orbits being filled implies that major structural differences can be observed away from the stability line.

Changes in shell structure due to the tensor interaction have been recently discussed in different mass regions [3, 4, 5, 6, 7]. The magic numbers at N=20 and 28 seem to disappear with increasing isospin while new magic numbers at N=14, 16 and 32 emerge. In this context, experimental studies of hitherto inaccessible exotic nuclei around "traditional" major shell gaps are particularly interesting; a comparison with theoretical calculations can reveal the onset of changes in the accepted nuclear shell structure, and would permit and refine the inclusion of the tensor component in effective shell-model interactions (see, for example, [8]). The spectroscopic investigation proposed in this work will focus on one such nucleus, ^{79}Zn, which lies two protons above and one neutron below the Z=28 and N=50 shell gaps.

While the tensor interaction is particularly strong between protons and neutrons in spin-flip partner orbitals, a recent generalization predicts a similar behaviour for orbitals with different orbital angular momenta [3]; an attraction is expected between orbitals with anti-parallel spin configuration and a repulsion between orbitals with parallel spin configuration. This generalization is particularly relevant to the N=50 shell gap and ^{79}Zn; shell-model calculations which take into account the effect of the tensor force predict a weakening of the shell gap near $^{78}_{28}$Ni$_{50}$. This effect has been reported to be due to the attraction between neutrons in either $g_{9/2}$ or $d_{5/2}$ orbitals and protons in $f_{5/2}$ orbitals, and the repulsion between the $g_{7/2}$ neutrons and the $f_{5/2}$ protons [9, 10]. Furthermore, in the β-decay of odd-mass Ni isotopes a strong monopole shift of the $\pi 1f_{5/2}$ level in Cu isotopes is observed when the $\nu 1g_{9/2}$ shell above N=40 is being filled [11, 12, 13, 14].

Conversely, in-beam experiments on $N \simeq 50$ Ge and Se isotopes [15] and isomer studies following fragmentation [16, 17, 18, 19] give evidence for the persistence of the N = 50 shell gap. Furthermore, a recent Physical Review Letter by Hakala *et al.* [20] suggests an increase in the strength of the N=50 shell gap on the basis of finite-range liquid-drop model calculations. Those calculations are found to best reproduce the measured two-neutron separation energies over a range of $N = 50$ isotones from $Z = 40$ down to $Z = 31$. These calculations predict the shell gap to be approximately 700 keV *larger* in Zn than in Ge, increasing by a further MeV in ^{78}Ni. The measurement here proposed would yield a clear determination of whether in ^{79}Zn the gap size is indeed increased or reduced.

While $_{30}$Zn isotopes form in their own terms an interesting set of nuclei in which to study the evolution of neutron single-particle structure, the special interest on ^{79}Zn is enhanced by its vicinity to ^{78}Ni, whose single-particle (hole) structure cannot at the present time be experimentally accessed. Accelerated radioactive nuclear beams of ^{78}Ni of the required intensity for low-energy nucleon transfer studies are not yet available. It is also worth mentioning that a strong N=50 gap below ^{78}Ni bears significant implications for astrophysics. The gap size in fact influences the path of the astrophysical r-process [21], determining which N=50 isotopes constitute waiting-point nuclei.

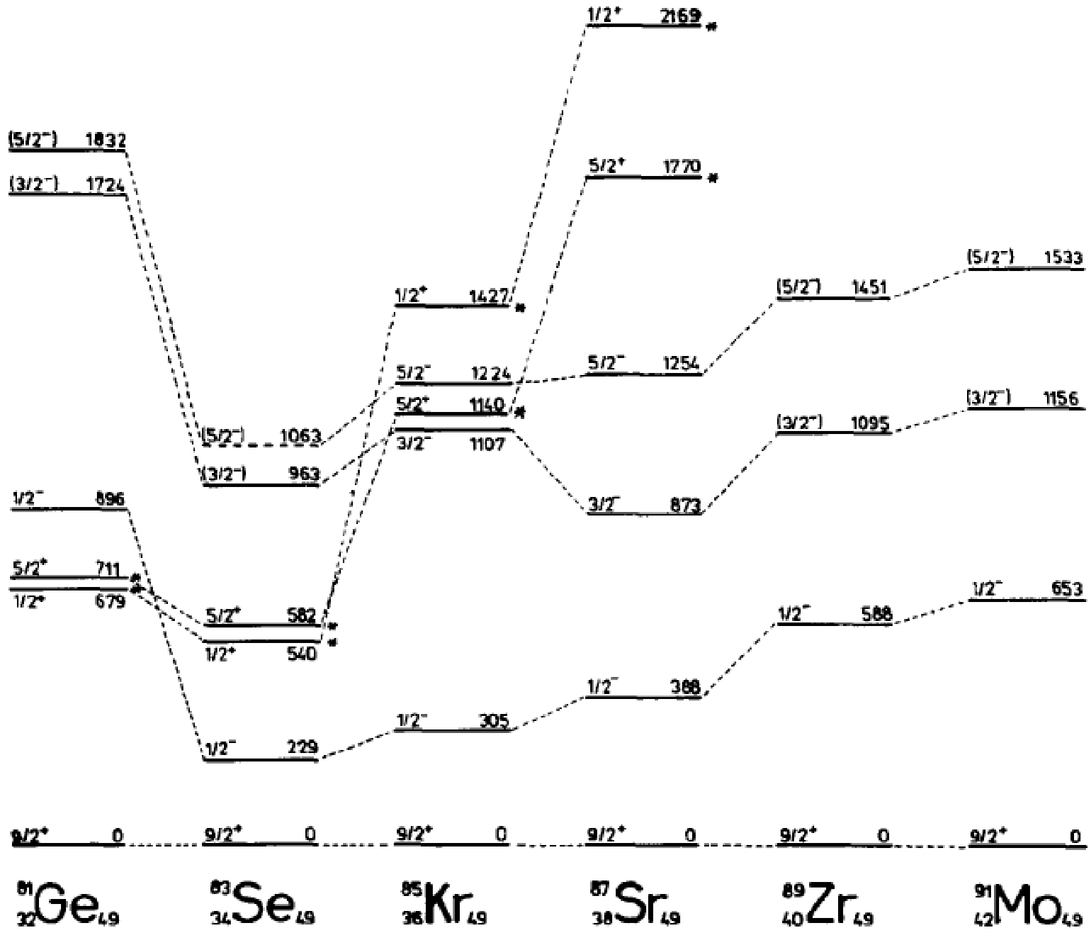

Figure 1: Systematics of low-lying excited states in the odd mass N=49 isotones (partial level schemes from Hoff *et al.* [22])

In general, an indication of the size of the shell gap can be obtained from the comparison of selected excited states, observed in gamma-spectroscopy experiments, with shell model calculations [23]. This method, however, relies on model-dependent theoretical estimates of the single-particle contents of the excited states. States observed in gamma-ray spectroscopy measurements of neutron-rich nuclei are often assigned to single-particle states on the basis of weak arguments. To quantify the distribution of single-particle strength in neutron-rich nuclei, it is necessary to perform direct single-nucleon transfer reactions. Hence, we propose to study the single-neutron structure of ^{79}Zn via the ^{78}Zn(d, p) reactions at 3MeV/u in inverse kinematics at the REX-ISOLDE facility.

Nucleus	$t_{1/2}\,(5/2^+_{\mathrm{I}})$	B(E2) (w.u.)
$^{85}_{36}$Kr$_{49}$	3.5^{+28}_{-14} ps [24]	4(2)
$^{83}_{34}$Se$_{49}$	$\simeq$3 ns [25]	$\simeq$0.13
$^{81}_{32}$Ge$_{49}$	3.9(2) ns [22]	0.038(2)

Table 1: Measured half-lives of the lowest-lying $5/2^+$ states in some neutron-rich even Z, N=49 isotones, and corresponding B(E2) strengths in Weisskopf units.

2 The Experiment

So far, knowledge on the structure of ^{79}Zn is limited to a few ground-state properties. The lifetime of the ground state was measured at ISOLDE [26] but, as yet, its spin and parity have not been firmly established, although a $9/2^+$ assignment can be assumed. No information is available on the expected $5/2^+$ and $1/2^+$ lower excited states. These states will be populated via the d(^{78}Zn,p)^{79}Zn single-nucleon stripping reaction, in inverse kinematics, and will yield valuable information on the evolution of the $d_{5/2}$ and $s_{1/2}$ neutron orbits in the vicinity of ^{78}Ni. With the proposed reaction mechanism, the states will be distinguished and identified from the determination of the orbital angular momentum quantum number of the transferred neutron. Figure 1 shows the low-lying states of odd-mass N=49 isotones, from Z=32 to Z=42, observed in β-decay [22]. $5/2^+$ and $1/2^+$ states can be seen low in the spectrum in the vicinity of ^{79}Zn.

Population of the excited states of ^{79}Zn via the (d,p) reaction will permit a reliable experimental determination of their single-particle character, through the determination of spectroscopic factors. It is well known that the cross sections for such nucleon-transfer reactions, performed at near Coulomb barrier energies, are sensitive to the amplitude of the asymptotic neutron wavefunction and are, to a good approximation, insensitive to the shape of the neutron wavefunction within the bound-state potential [27]. The transfer cross section is a measure of the product of the spectroscopic factor and the square of the amplitude of the asymptotic neutron wavefunction in the localized region of transfer. The optical-model parametrization of nuclear distortion effects in the entrance and exit channels does not have a strong effect on the relative spectroscopic factors.

Table 1 shows the half-lives of the $5/2^+$ states in neighbouring heavier even-Z isotones, and the corresponding B(E2) strengths in Weisskopf units. The systematic

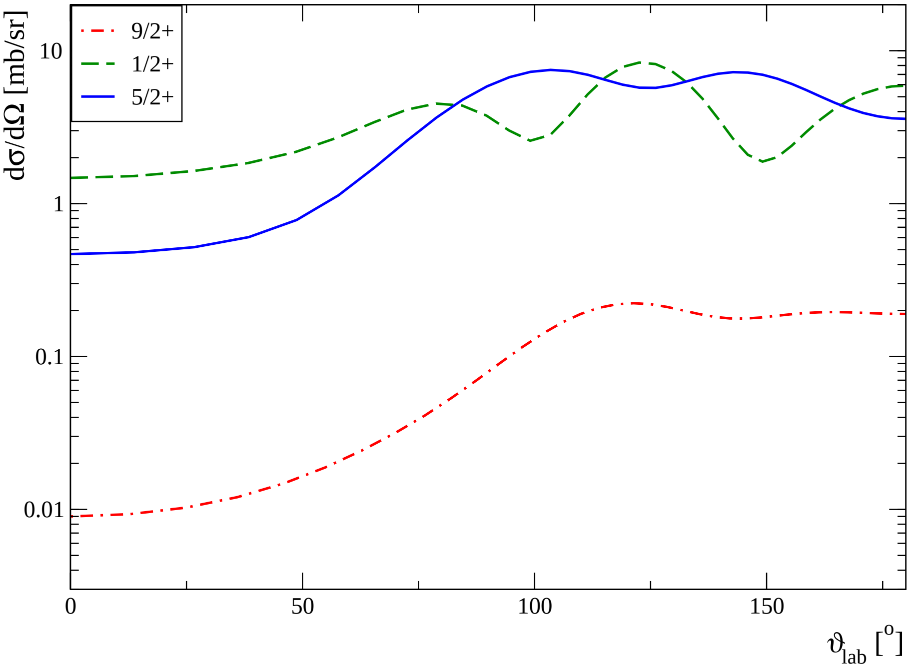

Figure 2: Differential cross sections for the population of states in ^{79}Zn versus the centre-of-mass angle for d(^{78}Zn,p)^{79}Zn at 3 MeV/u, in inverse kinematics, from DWBA calculations.

trend suggests that the half-life of the $5/2^+$ state in ^{79}Zn is also likely to lie in the nanosecond range. If so, the state will be sufficiently short-lived to enable the coincident detection of protons and gamma rays. If the half-life is less than approximately 5 ns, at least half of the gamma decays will occur in view of the MINIBALL germanium detectors (reducing to one third for a 10 ns half life). Combined with the assessment of its single-particle character, the excitation energy of the $5/2^+$ state will give a clear indication of whether the gap between the $d_{5/2}$ and $g_{9/2}$ orbitals is reduced or not in ^{79}Zn. The likely long half-life of the $1/2^+$ state (seconds) will instead imply that its gamma-ray decay will not be observed in coincidence with protons. The energy of this state will need to be determined solely via proton detection.

The ground-state Q-value of 1.924MeV leads to well-matched conditions for low-l transfer, resulting in approximately 100 mb total cross section for the expected $5/2^+$ and $1/2^+$ excited states. The theoretical differential cross-sections in the laboratory frame are plotted in Figure 2, assuming a spectroscopic factor of 0.65 for each of the excited $5/2^+$ and $1/2^+$ states, and of 0.1 for the $9/2^+$ ground state.

For the DWBA calculations, performed with the code DWUCK4 [28], optical model parameters were taken from Lohr and Haeberli [29] and Koning and De-

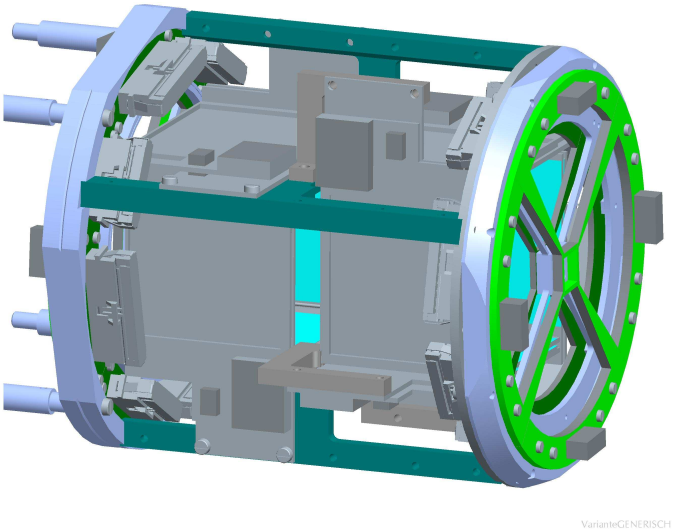

Figure 3: Schematic representation of the T-REX silicon detector array.

laroche [30], but similar results could be obtained with other proton optical model parametrizations by Perey [31] and by Becchetti and Greenlees [32]. For the neutron bound state, a Woods-Saxon potential with diffuseness parameter 0.65 fm and bound state radius parameter $r_0 = 1.25$ fm was adopted. Figure 2 shows that the calculated differential cross sections for the populations of the ^{79}Zn states differ sufficiently to clearly distinguish the different l-values involved in the nucleon-transfer process.

Beams of neutron-rich Zn isotopes have previously been used at REX-ISOLDE for Coulomb-excitation measurements [33]. Using the RILIS facility, relatively pure beams of Zn can be delivered with suitable intensities for single-nucleon transfer studies to be undertaken for Zn isotopes up to A=80. Further experiments will be informed by the result of this first study; at the present time we envisage extending the proposed inverse-kinematics (d, p) reaction studies to other neutron-rich Zn beams, and in particular, to ^{80}Zn.

2.1 Experimental Method

The proposed experiment will use the recently built T-REX silicon-detector array [34], together with the MINIBALL [35] gamma-ray spectrometer. The silicon-detector array is described in full in Reference [34]. In brief, it consists of a barrel of eight planar detectors around 90° and a Compact Disk (CD) DSSD detector at backward

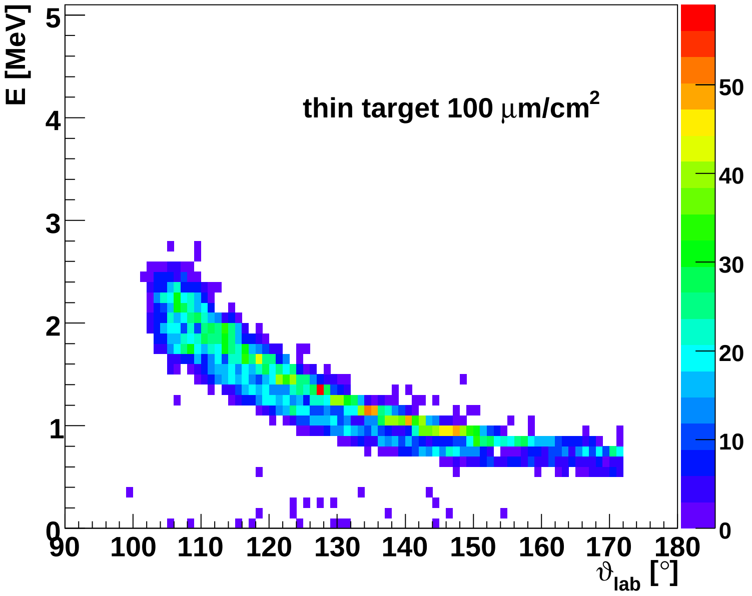

Figure 4: Results of Monte-Carlo calculations, for protons emitted in the reaction d(^{78}Zn,p)^{79}Zn, detected at backward angles with the silicon-detector array. The statistics correspond to 21 shifts of beam time, assuming a ^{78}Zn beam intensity of 5×10^4 pps, using a 100 μg/cm^2 C_2D_4 target.

angles. A schematic figure of the array is shown in Figure 3. The barrel detectors are ΔE-E telescopes both at forward and at backward angles. The ΔE detectors are 140 μm thick, and the E detectors are 1 mm thick. The 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 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 contribution to the proton energy resolution comes from the straggling in the target.

To obtain spectroscopic information for the states of ^{79}Zn, the protons ejected from the transfer reaction will be detected either in singles or in coincidence with gamma rays. Since the population of the ground and $1/2^+$ state will not be accompanied by prompt gamma-ray emission, for these states the measurement will be based only on proton singles.

The discrimination between different proton groups has been simulated with the aid of GEANT4 [36] Monte-Carlo calculations. Figure 4 shows the results of the GEANT4 simulations for the statistics corresponding to 21 shifts of collection time. The results of DWBA calculations were also input to the simulation. Simulations

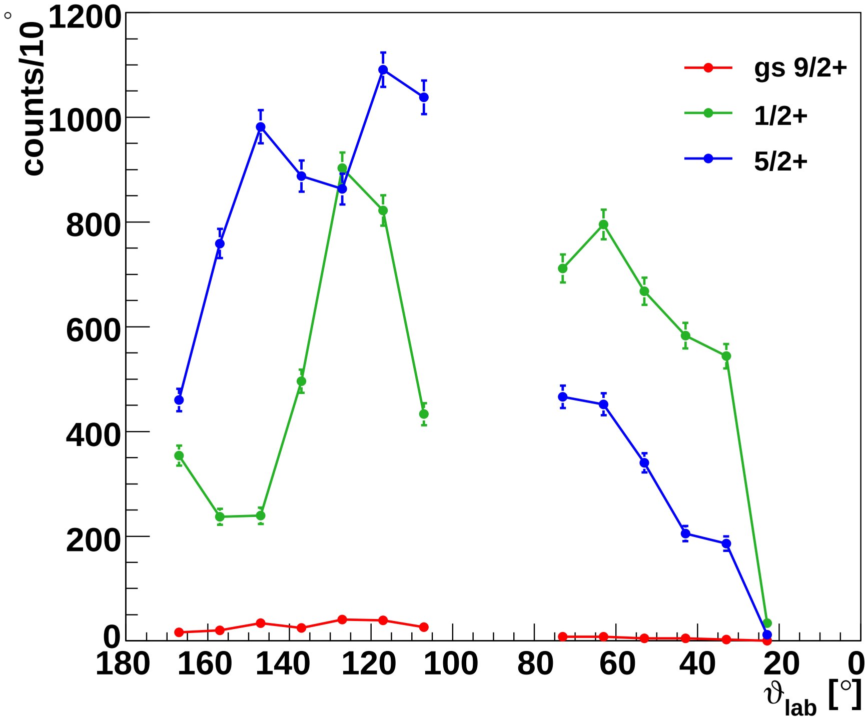

Figure 5: Calculated proton angular distributions (per 10° angle) for the ground state (gs), and the excited $1/2^+$ and $5/2^+$. The counts are estimated for 21 shifts of beam time and a 100 μg/cm^2 C_2D_4 target.

reveal that a thin, 100 μg/cm^2 deuterated polyethylene (C_2D_4) target will permit to resolve ^{79}Zn states with an energy difference of at least 500 keV. Figure 5 exhibits the expected number of counts per 10° bins, assuming 21 shifts of beam time at 5 10^4 pps, assuming spectroscopic factors of 0.65 for the two excited states.

Were the excited states to lie closer than 500 keV (a possibility which 3 initial shifts of beam time will be sufficient to unveil), a thick, 1mg/cm^2 target will subsequently be employed, to enhance the number of particle-gamma coincidences. If the lifetime of the $5/2^+$ state is smaller than approximately 10 ns, the acquired coincident data will suffice to assess the single particle nature of the $5/2^+$ state. For protons detected in coincidence with a de-exciting gamma ray ($E_\gamma = 1$MeV, $t_{1/2} = 5$ ns), the statistics expected for 21 shifts of beam time with beam impinging on the thick target are shown in Figure 6. The state's excitation energy, together with a further determination of the transition multipolarity, will be provided by the detected gamma ray. The information thus gained on the $5/2^+$ state will also permit the deconvolution of the $5/2^+$ and $1/2^+$ superimposed proton angular distributions.

It should be noted that, even in the unlikely absence of gamma-ray coincidences,

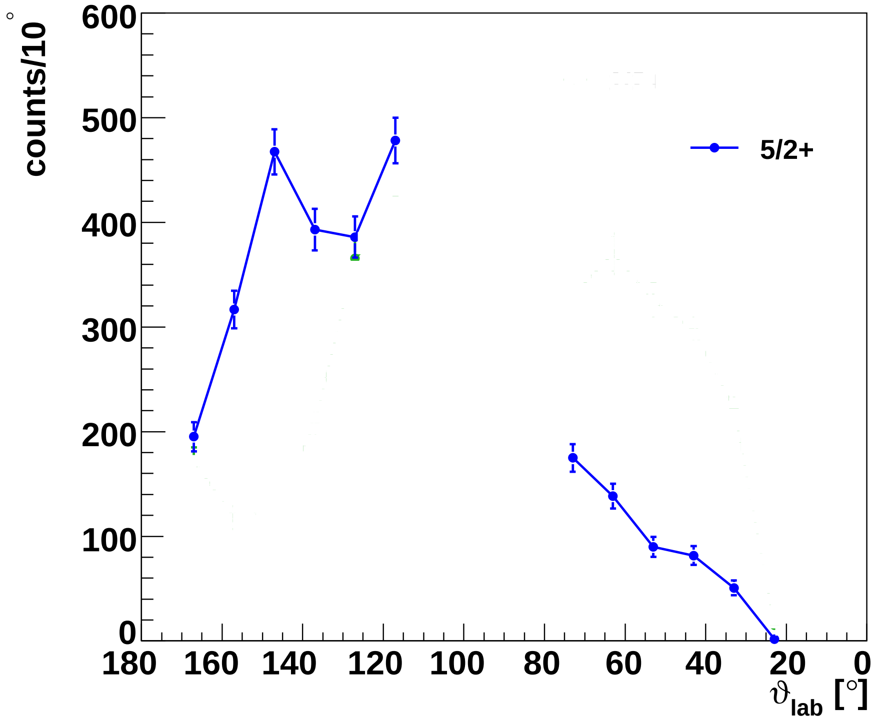

Figure 6: Expected number of counts per 10° angle, for the protons corresponding to the population of the $5/2^+$ state in ^{79}Zn, obtained for 21 shifts of beam time, and a C_2D_4 target thickness of 1mg/cm^2, assuming a gamma-ray efficiency equivalent to the detection of a 1MeV gamma ray, and a $5/2^+$-state half-life of 5 ns.

the energy resolution of the silicon detector will be sufficient to indicate whether the energy gap between $g_{9/2}$ and $d_{5/2}$ is reduced or increased compared to neighbouring ^{81}Ge.

The expected beam contamination corresponds to approximately 35% of ^{78}Ga [33]. Thanks to the larger Q-value for the (d,p) reaction on on ^{78}Ga [4.65(1) MeV — cf. 1.92(27) MeV on ^{78}Zn], the contaminant scattered protons will be clearly discriminated from their different kinematic signature. Further discrimination will be permitted by the selection of coincident gamma-rays with the MINIBALL array. Finally, the beam composition will be further assessed by placing an additional Ge detector to detect induced radioactivity on the beam dump and, if required, by a few hours of “Laser ON/OFF” runs.

3 Beam Time Request

The ^{78}Zn isotope can be produced using the standard UC$_\chi$/graphite target and ionised with RILIS. The expected yield of ^{78}Zn in-target production is $3.9{\cdot}10^5$ per μCi, with the neutron converter employed to suppress ^{78}Rb contamination [37]. A TANTALUM cavity will be used to reduce the Ga contamination. The ^{78}Zn beam intensity at the MINIBALL target is expected to be approximately 5×10^4 pps, considering a 5% efficiency for REX. The order of magnitude increase in beam intensity compared to experiment IS412, run in 2004 [33], is due to the particularly bad REX transport efficiency (approximately 0.5%) which affected the previous experiment.

The past measurement yields also an estimate of the percentage of gallium contamination to be expected, approximately 35%. For the beam time estimate, reaction cross sections of 1.3mb, 50mb, 50mb were assumed respectively for single particle transfer events populating the $9/2^+$, $1/2^+$ and $5/2^+$ states, obtained from DWBA calculations. An efficiency of 55% was assumed for the particle detectors. In order to accumulate enough statistics, 24 shifts of beam time with a ^{78}Zn beam are required, (where the 3 initial shifts will be used to determine the most appropriate target thickness). Three additional shifts are requested for beam preparation. In total, **27 shifts of beam time are requested**.

Beam	Minimum Intensity	Target Material	Ion Source	Shifts
^{78}Zn	5×10^4 pps	UC$_\chi$/graphite	RILIS	24 (+3)

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