EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letter of Intent I-CERN-INTC-2010-032, INTC-I-100 and the endorsed proposal CERN-INTC-2011-002, INTC-P-290)

Spectroscopy of low-lying single-particle states in ^{81}Zn populated in the ^{80}Zn(d,p) reaction

October 2, 2012

R. Orlandi[1], R. Raabe[1], D. Mücher[2], A. Jungclaus[3], V. Bildstein[5], A. Blazhev[6], M. J. G. Borge[3,8], P. A. Butler[7], R. Chapman[4], G. de Angelis[10], J. Diriken[1], J. Elseviers[1], E. Farnea[11], F. Flavigny[1], L. M. Fraile[12], S. J. Freeman[9], H. O. U. Fynbo[13], L. Gaffney[7], R. Gernhäuser[2], A. Gottardo[10], T. Grahn[20], P. T. Greenlees[20], G. F. Grynier[19], R. Grzywacz[14], B. Hadinia[5], M. Huyse[1], A. Illana[3], D. G. Jenkins[15], J. Johansen[13], B. P. Kay[15], Th. Kröll[16], R. Krücken[2,22], S. M. Lenzi[11], V. Liberati[1], S. Lunardi[11], D. Mengoni[11], E. Nacher[3], D. R. Napoli[10], B. S. Nara Singh[15], K. Nowak[2], G. O'Neill[7], S. Padgett[21], S. D. Pain[17], J. Pakarinen[20], P. Rahkila[20], G. Randisi[2], E. Rapisarda[8], P. Reiter[6], T. Roger[19], E. Sahin[10], J. F. Smith[4], K. Spohr[4], T. Stora[8], O. Tengblad[3], J. S. Thomas[9], J.J. Valiente-Dobón[10], P. Van Duppen[1], M. von Schmid[16], D. Voulot[8], N. Warr[6], F. K. Wenander[8], K. Wimmer[18], the MINIBALL collaboration and the T-REX collaboration

[1] *IKS KU Leuven, Leuven, Belgium*
[2] *Technischen Universität München, München, Germany*
[3] *IEM - CSIC, Madrid, Spain*
[4] *University of the West of Scotland, Paisley, UK*
[5] *University of Guelph, Guelph, Canada*
[6] *Universität zu Köln, Köln, Germany*
[7] *University of Liverpool, Liverpool, UK*
[8] *CERN, Geneva, Switzerland*
[9] *University of Manchester, Manchester, UK*
[10] *Laboratori Nazionali di Legnaro dell'INFN, Legnaro (PD), Italy*
[11] *Università di Padova and INFN Sezione di Padova, Padova, Italy*
[12] *Universidad Complutense de Madrid, Madrid, Spain*
[13] *University of Aarhus, Aarhus, Denmark*
[14] *University of Tennessee, Knoxville, TN USA*
[15] *University of York, York, UK*
[16] *Technischen Universität Darmstadt Germany*
[17] *Oak Ridge National Laboratory, Oak Ridge, TN USA*

CERN-INTC-2012-051 / INTC-P-352
02/10/2012

[18]*Central Michigan University, Mount Pleasant, MI USA*
[19]*GANIL, Caen, France*
[20]*University of Jyväskylä and Helsinki Institute of Physics, Finland*
[21]*Lawrence Livermore National Laboratory, Livermore, CA, USA*
[22]*TRIUMF, Vancouver, Canada* [23]*University of Oslo, Oslo, Norway*

Spokesperson: Riccardo Orlandi Riccardo.Orlandi@fys.kuleuven.be
Co-Spokesperson: Riccardo Raabe Riccardo.Raabe@fys.kuleuven.be
Contact person: Elisa Rapisarda Elisa.Rapisarda@cern.ch

Abstract: The aim of this proposal is the study of single-particle states of ^{81}Zn via the ^{80}Zn(d,p) reaction in inverse kinematics. ^{81}Zn will be produced by means of a laser-ionized, 5.5 MeV/u HIE-Isolde ^{80}Zn beam impinging on a deuterated-polyethylene target. The protons and gamma rays emitted in the reaction will be studied using the Miniball + T-REX setup. This experiment will constitute the first spectroscopic study of ^{81}Zn, which is critically important to determine the energy and ordering of neutron single-particle orbits above the N=50 gap and the properties of ^{78}Ni.

Requested shifts: 39 shifts, split into 1 run over 1 year)

1 Physics Case

The study of the structural properties of nuclei neighbouring shell closures in unexplored regions of the nuclear chart is one of the most important avenues of investigation opened up by radioactive ion beams. For example, these studies provide essential experimental data to map the evolution of effective single-particle energies (ESPEs). ESPEs offer a privileged viewpoint to discriminate between distinct theoretical pictures being very sensitive to different terms of the nucleon-nucleon interaction.

In recent years, a considerable step forward in the description of shell-structure evolution was taken with the inclusion of the monopole component of the tensor interaction in the effective Hamiltonian and in the self-consistent Hamiltonian [1]. In general, refinement of the interaction has gone hand-in-hand with new experimental discoveries (see, for example, [2] and [3]).

^{81}Zn, two protons and one neutron away from ^{78}Ni, provides critical information to map how neutron ESPEs in N=51 isotones evolve as a function of increasing isospin. Furthermore, it is the lightest N=51 isotone for which excited-state spectroscopy is currently within experimental reach. It will require years of beam developments before ^{79}Ni can be studied in similar experiments.

Conflicting assignments have been put forward for its ground-state spin [4, 5], both based of beta-feeding arguments. Thanks to the available beam purity and the higher quality of data, the $5/2^+$ assignment proposed by Padgett *et al.* [5] rests on firmer ground. The spin and parity of the ground state should ultimately be confirmed or disproved by a laser-spectroscopy measurement already approved [6] but still to be scheduled at this facility. Besides the ground state, however, no other state has yet been observed in ^{81}Zn.

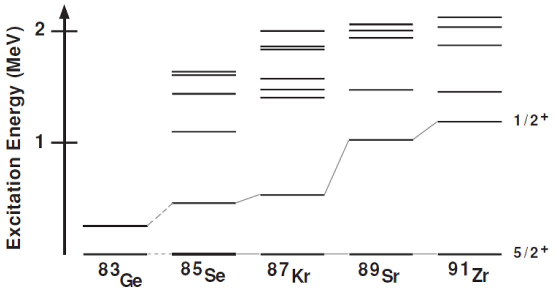

Figure 1: Even Z, N=51 systematics of first excited states. From [8].

In the proposed experiment, excited states in ^{81}Zn will be populated via the ^{80}Zn(d,p)^{81}Zn reaction, in inverse kinematics. The ground and first-excited states, in particular, are central to determine the ESPE of the $\nu 2d_{5/2}$ and $\nu 3s_{1/2}$ orbits above the N=50 gap. Population of higher-lying states, such as members of the $2^+ \otimes \nu d_{5/2}$ multiplet, analogous to those measured via beta-decay by Perru *et al.* [7] in ^{83}Ge, and in ^{85}Se, is also expected. The spin and parity of the first excited states in ^{83}Ge and ^{85}Se were firmly established as $1/2^+$ by Thomas *et al.* [8], using (d,p) transfer. These measurements confirmed the dramatic drop in energy of the first excited $1/2^+$ state in the N=51 isotones with increasing isospin, as shown in Figure 1. This effect is attributed to the progressive emptying of the proton orbits above Z=28, and in particular the $f_{5/2}$ orbit, which decreases the attraction due to the tensor force between neutrons in the $g_{9/2}$ and $d_{5/2}$ orbits and protons in the $f_{5/2}$. From the systematics, and relying on the ground-state assignment by Padgett *et al.*, it is expected that the $s_{1/2}$ state be the lowest lying above the $5/2^+$ ground state.
The current proposal shows that an intensity of $1 \cdot 10^5$ ^{80}Zn/μC at the ISOLDE target will suffice to clearly establish the character of the two states and to determine their (at least relative) spectroscopic factors. This beam intensity is expected from the employment of a new neutron converter [9], which will be tested later this year. Even if, however, the currently available ^{80}Zn yield ($3 \cdot 10^4$) were not to improve with the new converter, single-nucleon transfer will serve to populate low-l states in ^{81}Zn, in sufficient amounts to permit their study via gamma spectroscopy, as proven by the rich data collected by our group in the recent ^{66}Ni(d,p) and (t,p) measurements with the same setup [10]. The data collected would therefore still provide the first insights into the structure of the most neutron-rich N=51 isotone studied so far; and they would permit to establish at least the energy of the first ($s_{1/2}$) excited state, if sufficiently short lived to decay in view of Miniball.

2 Experimental Method

The ^{80}Zn beam will be produced using a UC$_\chi$ target and laser ionized using RILIS [11]. The yield expected with the new neutron converter is $1 \cdot 10^5$ at/μC [12]. Using the HIE-ISOLDE upgrade, the beam will be post-accelerated to 5.5MeV/u and transported to the Miniball target chamber, impinging on a 1mg/cm^2 deuterated polyethylene (C_2D_4) target. Assuming 5% efficiency for transmission, for a proton current of 1.5μA, the minimum expected ^{80}Zn beam intensity at Miniball is $7.5 \cdot 10^3$ pps.

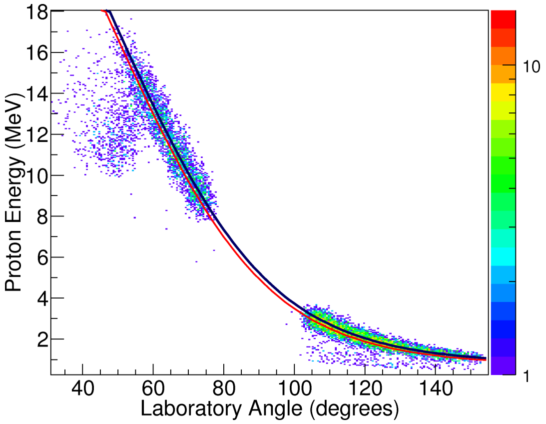

Figure 2: Energy versus lab angle for ^{81}Zn(d,p) protons for the ground and 300-keV states in ^{81}Zn. The corresponding kinematic curves are also shown.

The experimental setup will comprise the T-REX silicon-detector array (described in full in reference [13]) coupled to the Miniball spectrometer [14]. This coupling of arrays, which permits the coincident detection of protons and gamma rays, has been employed several times for single- and double-nucleon-transfer experiments at REX-ISOLDE [10, 13, 15]. For thin C_2D_4 targets ($\sim$100μg/cm^2) the expected resolution for this reaction is approximately 400-500 keV (assuming a beam-spot of 3mm). For a 1 mg/cm^2 target, the resolution worsens to $\sim$1000 keV. In the present case gamma selection is thus necessary to resolve the states of interest.

The differential cross-sections for the two lowest-lying states were obtained from DWBA calculations performed with five different optical model potential parameterizations [16], which yielded similar results. The average total production cross section is 68 mb for a $d_{5/2}$ ground state and 40 mb for the $s_{1/2}$. Assuming spectroscopic factors of 0.7, $7.5 \cdot 10^3$ pps, and a 1 mg/cm^2 C_2D_4 target, the expected reaction rates for each individual state are, respectively, 97.2 and 57.6 protons/hour. Figure 2 shows the amount of detected protons expected for these reaction channels after 7 days of beam-time. This figure was obtained from the analysis of data simulated using the Transfer Monte-Carlo code developed by V. Bildstein and K. Wimmer. The simulated proton emission is not isotropic but governed by the calculated differential cross-sections. The barrel detection efficiency deduced from the simulation is approximately 46% for the $5/2^+$ channel and 38% for the $1/2^+$.

Although the $1/2^+$-state energy has a minimal impact on the calculated cross section (less than 2% variation from 0 to 900 keV), it determines the amount of prompt proton-gamma coincidences which can be collected. If the energy is lower than 250-300 keV, the E2 multipolarity of the $1/2^+ \rightarrow 5/2^+$ transition would result in a lifetime too long to allow for a sufficient number of coincident γ rays to be detected by Miniball. It is worth pointing out that shell-model calculations by Padgett *et al.* [5] predict a first excited $1/2^+$ state energy of approximately 600 keV, i.e. actually *larger* in ^{81}Zn than in the neighbouring N=51 isotone, ^{83}Ge. If these calculations are at least correct in the *relative increase* of the $1/2^+$ energy in going from ^{83}Ge to ^{81}Zn, a first excited state of 360 keV - fast enough to be observed with Miniball - would be observed.

After 7 days of collection time, the number of useful detected protons is 7400 for the

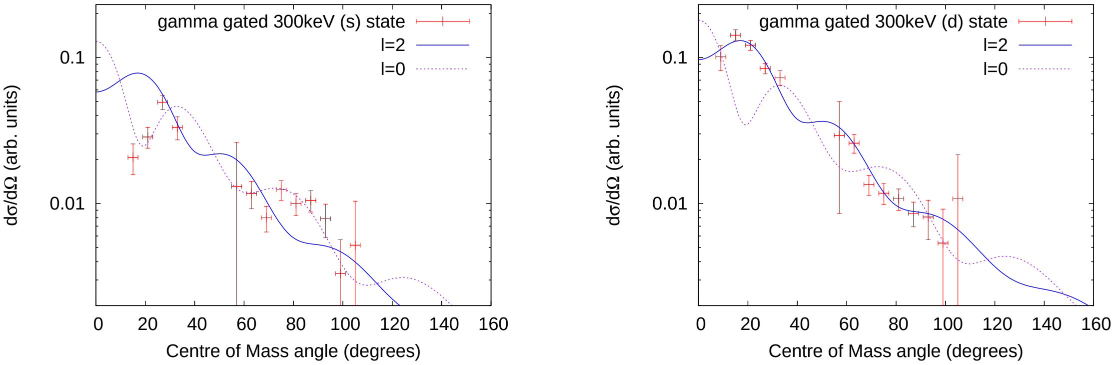

Figure 3: Proton angular distributions for the reaction populating the $s_{1/2}$ (left) or $d_{5/2}$ (right) state at 300 keV, deduced from simulated data corresponding to 7 days of beam-time. Angular distributions corresponding to angular momentum transfer l=0 and l=2 are also shown.

ground state and 3600 for the $1/2^+$. The Miniball photopeak efficiency varies from 13% at 250 keV to 8% at 600 keV. Assuming an average photopeak efficiency of 10%, approximately 350 proton-gamma coincidences would be detected for direct transfer to the $1/2^+$ state. Figure 3 (left) shows the quality of the proton angular distribution that would be obtained after 7 days of beam time. Since the state ordering has not yet been determined unambiguously, on the right hand side the corresponding plot for a $5/2^+$, 300-keV state (obtained with 750 proton-gamma coincidences) is shown.

Even if the lifetime of the first excited state proved to be too long ($>\sim$10ns) for the proposed gamma selection, gating only on the protons would still provide important information. Figure 4 (left) shows the combined proton angular distribution for both states, obtained after 7 days of beam time, which differs strongly from a pure l=0 or l=2 and, in conjunction with the absence of a low-gamma transition, stands as evidence that the ground and first excited states lie very close in energy. It would not give any indication about the ordering, but would constrain the lower limit of the lifetime (and upper energy limit) of the first excited state. On the right hand side of Figure 4 one can also see that the summed angular distribution would also provide some relatively coarse information of the relative ratio between s and d: it would for instance be sensitive if the SF of one of the states was 2 or 3 times as large as the other.

3 Final remarks on beam intensity and composition

It seems worth pointing out that proposal INTC-P-290, to study this reaction, submitted in January 2011, was already endorsed by the INTC, but deferred till after the test of the new neutron converter. The test of the new converter has been finally scheduled to take place before the end of the year [12]. Given the ongoing international efforts to produce and study ^{81}Zn in other facilities, we believe that a further delay based on the same considerations may not be timely.

In fact, even if the test with the new neutron converter will not show the expected increase

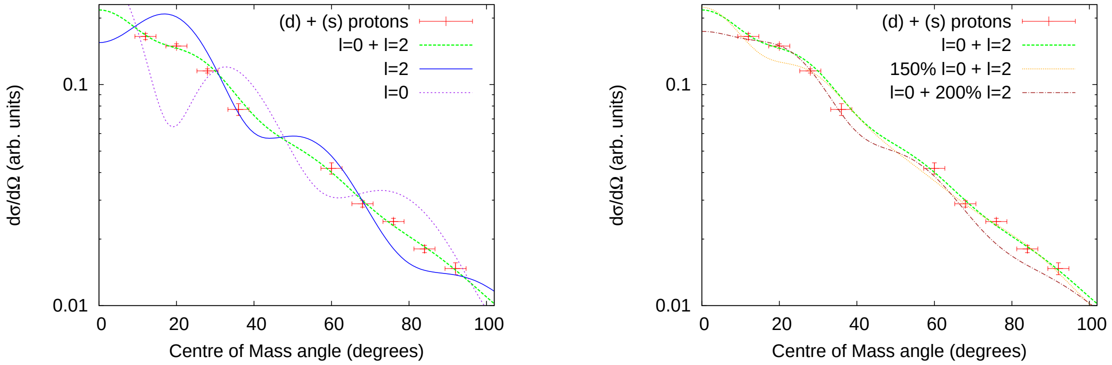

Figure 4: Summed angular distributions for the simulated l=0 and l=2 transfer, gated only on protons, compared to (Left) pure l=0 and l=2, (Right) summed l=0 and l=2 with relative total cross-sections differing from the calculations by the percentagesindicated in the legend.

in ^{80}Zn beam intensity, the experiment could still be carried out with the current available beam intensity, $3{\cdot}10^4$ at/μC, using the standard neutron converter and the quartz transfer line. The intensity at Miniball would drop to $2.3{\cdot}10^3$ pps, i.e. by about a factor of 4. Transfer protons would then simply be used to gate the gamma-ray spectrum. With a thicker target (2mg/cm^2), the production cross-section of the $1/2^+$ state would increase by 50%. Therefore the 350 coincidences would reduce to about 100, not sufficient to identify the l transfer, but enough to see such a low energy peak.
Furthermore, no additional gain would result from performing the experiment at even higher energies. At 10 MeV/u the cross sections of the $5/2^+$ and $1/2^+$ states would respectively drop by 60% and 80%, drastically reducing the number of proton-gamma coincidences necessary to disentangle their angular distributions.
Finally, either with the new neutron converter or with the old converter coupled to the quartz transfer line, the contamination of ^{80}Ga is expected to be similar in intensity to ^{80}Zn, making up approximately 50% of the total beam intensity. For such a large amount of contamination, 5 additional days without laser ionization need to be allocated to discriminate ^{81}Zn states from contaminant ones.

Summary of requested shifts: 21 shifts (beam ON) plus 15 shifts (beam OFF) of beam time plus 3 shifts for beam setup. 39 shifts in total.
Installation: MINIBALL + T-REX

References

[1] T. Otsuka *et al.*, Phys. Rev. Lett. **95** (2005) 232502; T. Otsuka *et al.*, Phys. Rev. Lett. **97** (2006) 162501.

[2] T. Otsuka *et al.*, Phys. Rev. Lett.**104** (2010) 012501.

[3] K. T. Flanagan *et al.*, Phys. Rev. Lett. **103** (2009) 142501.

[4] D. Verney *et al.*, Phys. Rev. C **76** (2007) 054312.

[5] S. Padgett *et al.*, Phys. Rev. C **82** (2010) 064314.

[6] B. Cheal, M. Bissel *el al.*, Proposal CERN-INTC-2011-016.
[7] O. Perru *el al.*, Eur. Phys. J. A 28, (2006) 307-312.
[8] J. S. Thomas *et al.*, Phys. Rev. C **71** (2005) 021302.
[9] T. Stora, *Isolde Workshop and User Meeting 2010*, (CERN, Geneva, Dec. 2010).
[10] J. Diriken, J. Elseviers, Priv. Comm.
[11] B. A. Marsh et al., Hyperfine Interactions Vol. 196, 129 (2010).
[12] T. Stora Priv. Comm.
[13] V. Bildstein *et al.*, Progr. in Part. and Nucl. Physics **59** (2007) 386.
[14] J. Eberth *et al.*, Eur. Phys. J. **A20** (2004) 65.
[15] K. Wimmer *et al.*, Phys. Rev. Lett. **105** (2010) 252501.
[16] J. M. Lohr and W. Haeberli, Nucl. Phys. A 232, 381 (1974).; F. D. Becchetti and G. W. Greenlees, Phys. Rev. 182,. 1190 (1969). ; R. L. Varner et al., Phys. Rep. 201, 57 (1991).; J. J. H. Menet et al., Phys. Rev. C 4, 1114 (1971).; J. J. H. Menet et al., Phys. Rev. C 4, 1114 (1971).
[17] K. Sieja, Priv. Comm.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

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.