

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Single-particle states in ^{81}Zn populated in single-neutron transfer reaction $^{80}\text{Zn}(d,p)$

January 5, 2011

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Abstract:

The aim of this proposal is to study at REX-ISOLDE the low-lying single-particle structure of ^{81}Zn via the $^{80}\text{Zn}(d,p)$ reaction in inverse kinematics. This experiment will provide valuable information on the neutron single-particle states neighbouring the $N=50$ shell gap in close proximity to ^{78}Ni . The reaction will be studied exploiting the capabilities of the Miniball and T-REX detector arrays. This proposal builds on the experience recently gained in experiment IS491, in which low-lying states of ^{79}Zn were successfully populated for the first time.

Requested shifts: 24 shifts (split into 1 run over 1 year)

1 Introduction

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 investigations opened up by the development of radioactive ion beams. These studies provide indispensable experimental data to map the evolution of effective single-particle energies (SPEs) as a function of isospin. Furthermore, they constitute the basis data for the modelling of the structural properties of regions with even larger N/Z ratios.

Direct single-nucleon transfer reactions, such as the (d,p) stripping reaction here proposed, are an ideal method to study single-particle properties of the isotopes of interest. From the angular distributions of the light ejectiles, which depend on the orbital angular momentum of the transferred nucleon, the l -value of the states populated in the reaction can be inferred. This information is particularly useful when previously unknown states are populated in the reaction, as it usually suffices to discriminate between the few possible spin assignments. Depending on the reaction and the Q -value matching, the population of either high- l or low- l states can be favoured. Most importantly, transfer reactions permit to establish the distribution of single-particle strengths among the various states populated, which makes them one of the most powerful tools to correctly determine effective SPEs.

In the past few years, a new setup, which couples the Miniball germanium detector array with an array of segmented silicon detectors (T-REX), was successfully employed for single and double nucleon transfer experiments at REX-ISOLDE [1, 2, 3]. It is the intention of this collaboration to make use once again of this powerful setup, to reach out into the “terra incognita” which lies beyond the $N=50$ shell gap, to study neutron single-particle states in the vicinity of ^{78}Ni .

This proposal builds on the experience gained in Isolde Experiment IS491, the last Miniball experiment of the 2010 experimental campaign. The experiment aimed at the population of excited states in ^{79}Zn to study neutron single-particle states in the $N=49$ isotone closest to ^{77}Ni . ^{79}Zn was produced via the $^{78}\text{Zn}(d,p)$ transfer reaction in inverse kinematics. Several excited states were populated in the reaction with sufficiently large yield to collect proton-gamma coincidences, and even a considerable amount of proton-gamma-gamma coincidences. It should be mentioned that no excited states were previously known in ^{79}Zn . This experiment fully exploited the exceptional advantages offered by the coincident measurement of gamma rays and charged particles, permitted by the Miniball/T-REX setup. Although the analysis is only at an early stage, the collected data should allow a clear determination of the spin and spectroscopic strengths of the populated states.

For ^{81}Zn , spectroscopic information is similarly scarce. No excited states have yet been observed. The ground-state spin is still debated and different assignments are being proposed, as it will be further discussed in the next section. By scaling the statistics of run IS491 to the available ^{80}Zn beam intensity, this proposal shows that REX-ISOLDE can be first in the observation of low-lying states in ^{81}Zn .

2 Science Case

SPEs offer a privileged viewpoint to discriminate between distinct theoretical pictures, thanks to their sensitivity to the properties and interplay of the various components of the nucleon-nucleon interaction. Their knowledge is crucial in the study of the considerable reorganization of shell structure which occurs away from the line of beta stability (*cf.* [4] and references therein).

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 [5], and subsequently also in the self-consistent Hamiltonian [6]. In general, refinement of the interaction has gone hand in hand with new experimental discoveries. It is worth noticing for example that only with the additional inclusion of a long-range Gaussian central term [7], the calculated proton SPEs reproduce correctly the inversion of the $f_{5/2}$ and $p_{3/2}$ orbit occurring at $N=45$, and observed in a g factor experiment at ISOLDE [8].

^{81}Zn , two protons and one neutron away from ^{78}Ni , is the lightest $N=51$ isotone for which excited-state spectroscopy is currently within experimental reach. It will require considerable years of beam developments before ^{79}Ni can be studied in similar experiments. The structure of ^{81}Zn is a critical piece of information to map how neutron effective single-particle energies in $N=51$ isotones evolve as a function of increasing isospin. Figure 1, taken from [9], shows the low-lying states of neighbouring $N=51$ isotones, highlighting in particular the behaviour of the $5/2^+$ and $1/2^+$ states.

The single-particle nature of the low-lying states of ^{83}Ge and ^{85}Se has been recently investigated via transfer reactions by Thomas *et al.* at Oak Ridge National Laboratory (ORNL) [9]. These experiments permitted to firmly assign the states' spins and parity. One notices in particular the dramatic drop in energy of the first excited $1/2^+$ state. Simply put, this effect can be 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 $f_{5/2}$. While the $s_{1/2}$ orbit is almost unaffected, the $d_{5/2}$ orbit is progressively less bound, resulting in a reduced energy difference between the corresponding states.

It is interesting to notice that the shell-model calculations presented in a related work by the same authors [10] cannot reproduce the lowering of the $1/2^+$ state energy in going from Se to Ge. Moreover, a simple linear extrapolation from the data suggests that an inversion of the $1/2^+$ and $5/2^+$ states could already be observed in ^{81}Zn , analogous to the inversion observed in ^{75}Cu .

As previously stated, conflicting assignments of the ground-state spin have been put forward. In the beta-decay study of ^{81}Ga , Verney *et al.* [11] suggest a $1/2^+$ assignment to the ^{81}Zn ground state from beta-feeding arguments. On the other hand, a similar experiment recently performed at Oak Ridge National Laboratory, found more evidence for a ground-state spin of $5/2^+$ [12, 13]. Figure 2 shows the calculated proton angular distributions in the laboratory frame for low-

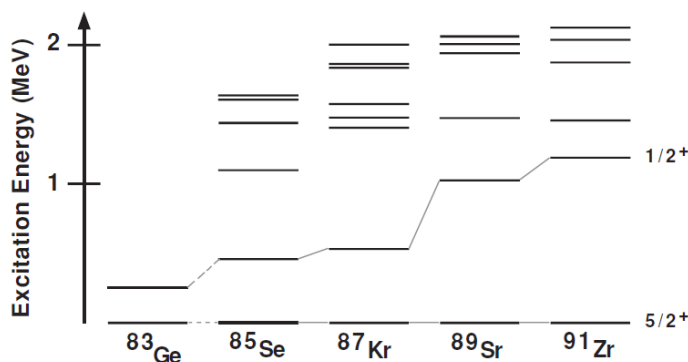


Figure 1: Even Z, $N=51$ systematics. From [9].

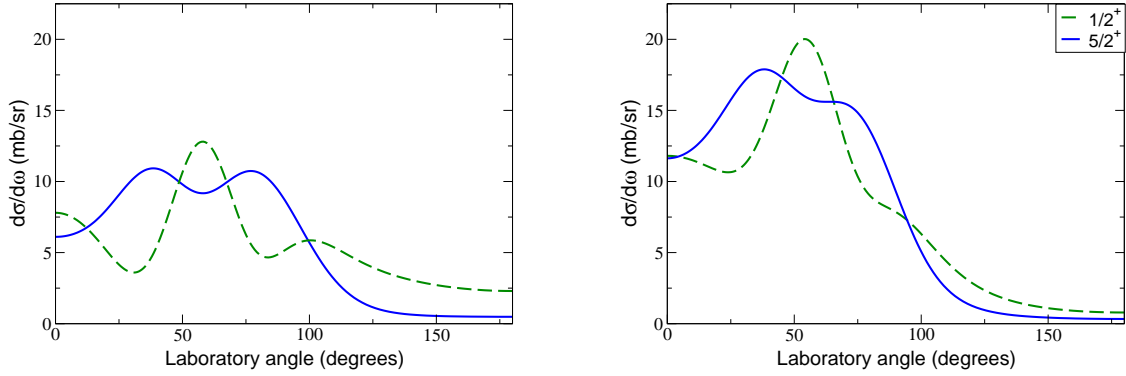


Figure 2: Calculated proton angular distributions corresponding to the population of low-lying $d_{5/2}$ and $s_{1/2}$ states in the $^{78}\text{Zn}(d,p)$ (left) $^{80}\text{Zn}(d,p)$ (right) reactions at 2.9 MeV/u, in inverse kinematics.

energy $5/2^+$ and $1/2^+$ states in ^{79}Zn (left) and ^{81}Zn (right) and populated via (d,p) transfer at 2.9 MeV/u. The calculations were performed using the codes TWOFNR [14] and DWUCK4 [15]. Optical model parameters were taken from Lohr and Haeberli [16] and Perey [17], but similar results could also be obtained with other optical model parameterizations. The calculated differential cross sections show that a beam energy of 2.9 MeV/u is in this case sufficient to distinguish between an $l=2$ and $l=0$ transfer. 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. The ground-state Q value (0.130 MeV) leads to well-matched conditions for low- l transfer. Assuming spectroscopic factors of 0.65, the total integrated cross section calculated for the $5/2^+$ and $1/2^+$ states in ^{81}Zn are, respectively, 71 and 69 mb.

The main challenge of this experiment lies in resolving the different states in ^{81}Zn , and in particular the ground state from the first excited state. The available beam intensity in fact will not permit the employment of a target sufficiently thin to fully exploit the energy resolution of the particle array. Even if that were the case, however, the intrinsic resolution of T-REX may be insufficient to resolve the two states. The selection of the proton emitted in the population of the first excited state can only be obtained by gating on the corresponding gamma-ray line detected in coincidence.

3 Experimental Method

The experimental setup comprises the T-REX silicon-detector array (described in full in reference [1]) coupled to the triple-cluster detectors of the Miniball gamma-ray spectrometer [18]. The T-REX currently consists of 8 planar $\Delta E - E$ telescopes around 90° and 1 Compact Disk (CD) DSSD detector at backward angles. The angular resolution of the array is approximately 5° . Each barrel ΔE detector is segmented into 16 strips perpendicular to the beam direction. The telescopes are used for particle discrimination. 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 covers angles from 147° to 172° . If available, two CDs of respective thicknesses of 0.5 and 1.5mm will be used at forward angles. They would cover forward angles from 8° to 30° , and their thickness would permit to fully stop the scattered protons. Mylar foils will be used as absorbers at forward angles to limit the counting rate caused by elastically scattered beam and carbon ions.

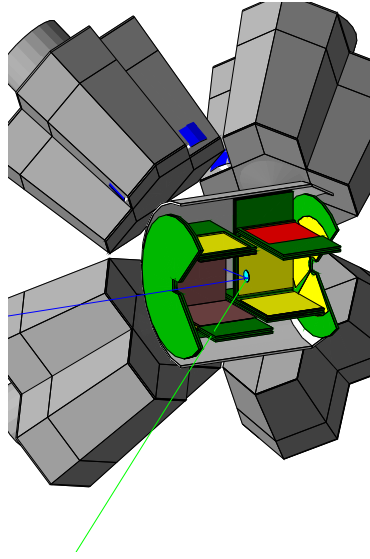


Figure 3: Schematic diagram of the Miniball/T-REX setup as modeled in the Geant4 simulation [1]

The main contribution to the proton energy resolution comes from the straggling in the target and the beam spot size (as well as, of course, the short distance between the target and the detector faces). For thin ($100 \mu\text{g}/\text{cm}^2$) C_2D_4 targets, an energy resolution of 400-500 keV can be achieved. For a thick ($\sim 1 \text{ mg}/\text{cm}^2$) target, however, the energy resolution is worsened to such an extent that the coincident detection of gamma rays becomes indispensable to measure proton angular distributions.

Whether or not it will be possible to collect prompt proton-gamma coincidences for the lowest excited state will strongly depend on the state's energy. The multipolarity of the de-exciting gamma-ray is in fact going to be E2, independent from the ordering of the lowest $1/2^+$ and $5/2^+$ states (assuming no other spin or parities are involved). For energies lower than ~ 270 keV, the state would be too long lived to allow for a sufficient number of coincident γ rays to be detected by Miniball, as can be seen in figure 4.

It is worth pointing out that shell model calculations by Padgett *et al.* [13] predict a first excited $1/2^+$ state energy of approximately 600 keV, i.e. *larger* in ^{81}Zn than in the neighbouring $N=51$ isotone, ^{83}Ge . Forcing the agreement with ^{83}Ge , the expectation is an energy of 360 keV [19], which would correspond to a state sufficiently short lived for this measurement.

In experiment IS469, which studied the $^{66}\text{Ni}(d,p)$ transfer reaction, some small modifications were introduced in the setup to observe delayed coincidences between protons and a known ^{67}Ni isomer lying in the microsecond range. The gamma rays were detected by a single-crystal germanium detector positioned at the beam dump. The setup permitted the periodic exchange of the aluminium foils were the activity was deposited. In this case, thanks to the short β half-life of all the isotopes involved in the decay chain of ^{80}Zn (respectively 0.54(2), 1.676(14), 29.5(4), and 15.2(2) seconds from ^{80}Zn to ^{80}As), the periodic exchange of foils would not be required. However, because of the short half lives and the larger gamma multiplicity of each decaying isotope in the chain, the rates on the beam dump detector would be approximately 2 orders of magnitude larger. For this reason this option lies at the limits of feasibility.

In addition, low-energy E2 transitions undergo large internal conversion; at 80 keV $\sim 60\%$ of the

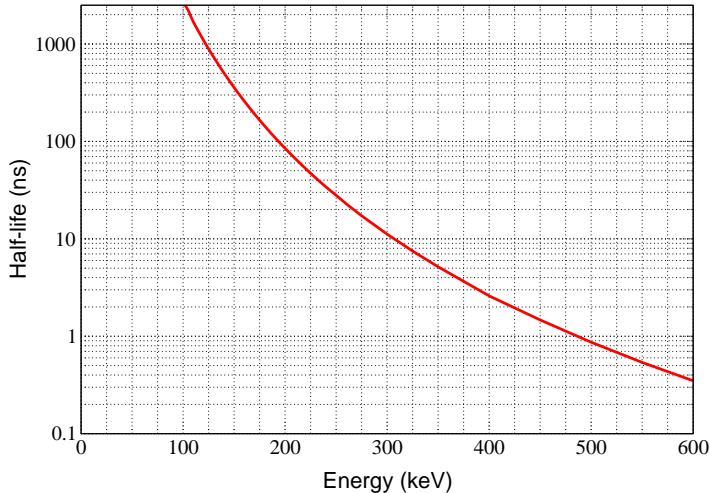


Figure 4: Half-life of E2 transitions for a nucleus of mass 81, plotted as a function of gamma-ray energy. A transition strength of 1 Weisskopf unit was assumed.

transitions are converted, reaching 90% at 50 keV. Indirect evidence about the presence of a low-lying transition – if this were to be indeed the case – may be obtained from the energies of higher-lying states which may decay to either of the first two states. Even if the possibility of resolving the first two states were not to be achieved, an upper limit on the energy of the state (and a lower limit on the lifetime) will be obtained. The information gained, useful in its own right, will also inform the choice of an alternative setup, if it were to prove necessary.

Figure 5 shows a gamma-ray spectrum of ^{79}Zn in coincidence with protons obtained using a thin target after 20 hours of beam time in Experiment IS491. For the Doppler correction it was assumed that the beam has no lateral straggling. The peak near ~ 1 MeV could only be seen with the RILIS lasers turned on, and therefore originates from ^{79}Zn . The analysis is still ongoing, but it seems likely that it corresponds to the first excited $5/2^+$ state. It has an area of 100 counts (and, consistently, about 500 counts after 100 hours of collection with laser ON), and it has been taken as a reference in the estimate of proton-gamma coincidences which one can expect in the $^{80}\text{Zn}(d,p)$ run.

In the ISOLDE database, the measured yield of ^{78}Zn and ^{80}Zn are, respectively:

- for protons directly on target, 4.3E6 and 1.4E5 at/ μC
- for protons on neutron converter, 4E5 and 3E4 at/ μC

In run IS491, the yield measurement gave only 1.5E6 at/ μC with protons on target and 3.3E5 at/ μC when shooting on the converter. The beam contaminants (^{78}Ga and ^{78}Rb) came in sufficiently small proportions (<30%), to make it unnecessary to use the neutron converter, which would have helped to reduce the gallium contamination. The amount of Ga contamination expected (more than 50%) in the ^{80}Zn beam requires the employment of the converter. Without any additional changes, the expected yield of ^{80}Zn (3E4 at/ μC) would be therefore 50 times smaller than the ^{78}Zn provided in run IS491.

A new development however is currently ongoing at ISOLDE (see [20]) towards the building of a modified neutron converter 3 to 10 times more efficient than the one currently used. A factor of 2 improvement has already been achieved, and a factor of 4 is likely [21]. Assuming an average

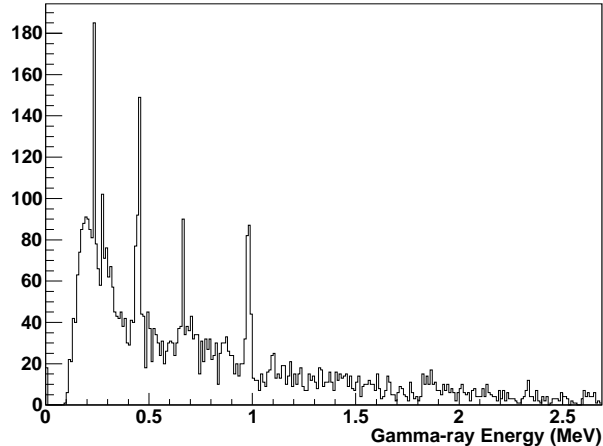


Figure 5: Doppler-corrected gamma-ray spectrum in coincidence with protons obtained in run IS491 after 20 hours of beamtime.

improvement by a factor of 4, the $^{78}\text{Zn}/^{80}\text{Zn}$ reduction factor drops from 50 to 12.5, resulting in $1.2\text{E}5$ at/ μC . It follows therefore that counting rates close to those measured in run IS491 with a thin target can be obtained in this new experiment using a thick, ~ 1 mg/ cm^2 target.

In the case of ^{80}Zn , a very large amount of ^{80}Rb contamination is expected. Rubidium contamination can however be reduced by 5 orders of magnitude with the employment of the quartz transfer line [22]. Its effect on the rate of radioactive zinc is disregardable and its inclusion in the target setup is mandatory and expressly required.

Ignoring for the moment the effects introduced by the lifetime, it is now possible to scale the area of the peak of Figure 5 to the characteristics specific of this new proposal. Assuming an energy of approximately 300 keV, the gamma detection efficiency almost doubles. Furthermore, the calculated cross section of the first excited state is 30% larger in the case of ^{80}Zn . Finally, in experiment IS491 we did not make use of the full available proton intensity (due to noise limitations which would not arise at these lower rates), using only 1.2 of the $1.5 \mu\text{A}$ available. For 100 hours of collection time one can expect therefore: $100 \times 4 \times 2 \times 1.30 \times (1.5/1.2) = 1300$ counts (~ 1000 if only a factor of 3 can be gained with the new converter). To this number the yet unknown reduction in coincidences caused by the state's lifetime needs to be subtracted.

Figure 6 shows the angular distributions extracted from simulated data for the $d_{5/2}$ and $s_{1/2}$ states in the $^{78}\text{Zn}(d,p)$ reaction, from protons selected by gating on a coincident gamma-ray transition. This figure shows that the discrimination achievable with only few hundred proton-gamma coincidences is sufficient to distinguish between the different values of l-transfer. The calculated proton angular distributions shown in Figure 2 are sufficiently similar to infer that this would also be true in the case of ^{81}Zn . Such results can be obtained with the current setup, provided that the lifetime of the state is not larger than about 10 ns.

Finally, it is also important to mention that for normalization purposes and to clearly disentangle ^{81}Zn lines from the contaminants, both laser ON and laser OFF runs will be required, at least in a ratio of 2:1. Furthermore, measurements of the beam composition using the ion chamber will need to be performed at least twice a day. These requirements are taken in consideration in the summary of requested shifts.

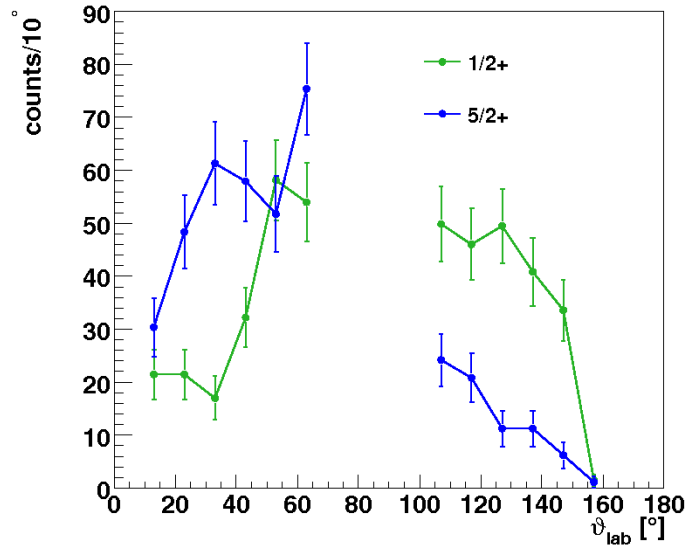


Figure 6: Expected number of counts per 10° angles for protons populating the $5/2^+$ or $1/2^+$ states, assuming that only a few hundred proton-gamma coincidences are detected, calculated for the $^{78}\text{Zn}(d,p)$ reaction. Only one of the two corresponding distributions in ^{81}Zn would be measured in coincidence with the gamma ray (the other corresponding to the ground state)

Summary of requested shifts:

Beam	Minimum Intensity	Target Material	Ion Source	Shifts
^{80}Zn	$1.5E5$ at/ μC	$\text{UC}_x/\text{graphite}$	RILIS	21 (+3)

The ^{80}Zn beam can be produced using a standard $\text{UC}_x/\text{graphite}$ target and laser ionized with RILIS. To reduce the amount of contaminants in the beam, both the neutron converter and the quartz transfer line are needed. In summary, we request 14 shifts with laser ON, 7 shifts with laser OFF and 3 shifts for beam setup, for **a total of 24 shifts of beam time**.

References

- [1] V. Bildstein *et al.*, Progr. in Part. and Nucl. Physics **59** (2007) 386.
- [2] K. Wimmer *et al.*, Phys. Rev. Lett. **105** (2010) 252501.

- [3] J. Diriken *et al.* EURORIB-2010 (Lamoura, France, June 2010).
- [4] O. Sorlin and M.-G. Porquet, *Prog. Part. Nucl. Phys.* **61** (2008) 602.
- [5] T. Otsuka *et al.*, *Phys. Rev. Lett.* **95** (2005) 232502.
- [6] T. Otsuka *et al.*, *Phys. Rev. Lett.* **97** (2006) 162501.
- [7] T. Otsuka *et al.*, *Phys. Rev. Lett.* **104** (2010) 012501.
- [8] K. T. Flanagan *et al.*, *Phys. Rev. Lett.* **103** (2009) 142501.
- [9] J. S. Thomas *et al.*, *Phys. Rev. C* **71** (2005) 021302.
- [10] J. S. Thomas *et al.*, *Phys. Rev. C* **76** (2007) 044302.
- [11] D. Verney *et al.*, *Phys. Rev. C* **76** (2007) 054312.
- [12] K. Jones, *Isolde Workshop and User Meeting 2010*, (Geneva, Switzerland, December 2010).
- [13] S. Padgett *et al.*, *Phys. Rev. C* **82** (2010) 064314.
- [14] University of Surrey modified version of the code TWOFNr of M. Igarashi, M. Toyama, and N. Kishida, private communication.
- [15] P. D. Kunz, University of Colorado, DWUCK4 Computer Program, Unpublished.
- [16] J. M. Lohr and W. Haeberli, *Nucl. Phys.* **A232** (1974) 381.
- [17] F. G. Perey, *Phys. Rev.* **131** (1963) 745.
- [18] J. Eberth *et al.*, *Eur. Phys. J.* **A20** (2004) 65.
- [19] S. Padgett, private communication.
- [20] T. Stora, *Isolde Workshop and User Meeting 2010*, (Geneva, Switzerland, December 2010).
- [21] T. Stora, private communication.
- [22] E. Bouquerel *et al.*, *NIM B* 266 (2008) 4298.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the	Availability	Design and manufacturing
MINIBALL + T-REX	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> To be used without any modification
[Part 1 of experiment/ equipment]	<input type="checkbox"/> Existing	<input type="checkbox"/> To be used without any modification <input type="checkbox"/> To be modified
	<input type="checkbox"/> New	<input type="checkbox"/> Standard equipment supplied by a manufacturer <input type="checkbox"/> CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	<input type="checkbox"/> Existing	<input type="checkbox"/> To be used without any modification <input type="checkbox"/> To be modified
	<input type="checkbox"/> New	<input type="checkbox"/> Standard equipment supplied by a manufacturer <input type="checkbox"/> CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL + T-REX installation.

Additional hazards:

No additional hazards.