CERN-INTC-2021-049 / INTC-I-235
27/09/2021

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

BEAM DEVELOPMENT FOR A STUDY OF THE EVOLUTION OF SINGLE-NEUTRON STATES OUTSIDE THE N=82 CORE USING ^{146}Gd, ^{148}Dy AND ^{150}Er(d,p).

September 27, 2021

S. J. Freeman[1,2], D. K. Sharp[2], R. Heinke[1], B. A. Marsh[1], K. Chrysalidis[1], L. P. Gaffney[3], B. P Kay[4], P.A. Butler[3], M. Labiche[5], I. Lazarus[5], R.D. Page[3], R. Raabe[6], F. Browne[1], D. Clarke[2] B. Olaizola[1], S. Bennett[2], P.T. MacGregor[2], A.G Smith[2], S. Reeve[2] and the ISS collaboration.

[1] *CERN, CH-1211 Geneva 23, Switzerland*
[2] *The University of Manchester, Manchester, M13 9PL, UK*
[3] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK*
[4] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[5] *STFC Daresbury Laboratory, Daresbury, WA4 4AD, UK*
[6] *KU Leuven, Belgium*

Spokespersons: D.K. Sharp (david.sharp@manchester.ac.uk), S.J. Freeman (sean.freeman@cern.ch)
ISOLDE contact persons: S. J. Freeman and R. Heinke

Abstract: A request for three shifts to measure yields, enhancement factors and contaminants for beams of ^{146}Gd, ^{148}Dy and ^{150}Er using the LIST method to assess viability of a future proposal to investigate the evolution of single-neutron orbitals outside $N = 82$.

Installation: Yield measurements with LIST source

1 Physics cases

Core to much of our understanding of nuclei is the description of nuclear structure in terms of the motion of single nucleons within the nuclear mean field. The properties of single-particle orbitals around the Fermi surface are key ingredients in the understanding of a large range of phenomena from excitations within a shell-model approach to the description of the collectivity of low-lying vibrational states. The evolution of single-particle structure when tracked over a range of neutron excess is an important strand in both current experimental and theoretical developments. A rich and complex behaviour is being revealed where relative single-particle energies change with neutron and proton number, altering the sequence of levels and modifying the gaps in the sequences, resulting in the demise of several of the magic numbers familiar in β-stable nuclei and the appearance of new ones in more exotic nuclei.

Care needs to be taken when comparing theoretical predictions with data; the energy of the lowest state of a given spin-parity is often a misleading estimate for the energy of the corresponding single-particle orbital if there is significant fragmentation of strength. Single-nucleon transfer reactions are a well understood probe of the single-particle strength distribution in nuclei via the comparison of measured cross sections, taken under specific experimental conditions, with DWBA calculations, which results in a quantity known as the spectroscopic factor. The absolute value of spectroscopic factors can often have questionable meaning as they can depend sensitively on parameter choices in the DWBA calculation. Moreover, comparison of data from isolated measurements on particular targets has problems from different approaches to the calculations but also from differences in the experimental approaches.

Recently, more systematic transfer studies have been made across chains of stable isotopes using common experimental approaches and consistent reaction modelling to reveal the underlying changes in single-particle structure, for example, [1, 2, 3, 4, 5, 6, 7]. Theoretical investigations (for summary, see Ref. [8]) have highlighted the importance of the tensor component of the nucleon-nucleon interaction in driving this evolution. Across a chain of nuclides, specific nucleon orbitals are filling, thus changing the overall effects of nucleon-nucleon interactions inducing shifts in orbital energies. The tensor interaction induces shifts that depend on the relative coupling of orbital and spin angular momentum in a particular orbital, which are needed to fully describe the evolving single-particle states in some systems.

Similar quantitative measurements are becoming possible for unstable species with the development of spectrometers, such as the ISOLDE Solenoidal Spectrometer, specifically designed for transfer-reaction studies in inverse kinematics using radioactive beams.

This letter of intent requests beam development for a subsequent proposal aiming to determine the energy centroids of low-lying strength corresponding to the nodeless $\nu h_{9/2}$ and $\nu i_{13/2}$ orbitals in ^{147}Gd, ^{149}Dy and ^{151}Er. These centroids have been established in the stable $N = 83$ isotones ($54 \leq Z \leq 62$) using the (d,p) [2, 9] and $(\alpha,{}^{3}\text{He})$ reactions

[3, 4]. Single-particle strength is fragmented into two fragments due to the mixing of single-particle excitations with weak-coupling states of the same quantum numbers [9, 10, 11, 12]. The relevant energy trends are summarised in Figure 1. From $Z = 54$ to 62, the difference in the $\nu h_{9/2}$ and $\nu i_{13/2}$ centroids was found to decrease from around 650 to less than 100 keV in agreement with theoretical predictions incorporating the tensor force [2, 3, 13] as shown in Figure 1(f). Such evolution is driven by a strong attractive tensor interaction between the $\nu i_{13/2}$ neutron and protons in the $\pi g_{7/2}$ orbital, which is filling with increasing Z; and a strong negative interaction between those protons and the $\nu h_{9/2}$ neutron. The energetic trajectories of the individual experimental centroids can be seen in Fig 1(c) and (d).

There is currently no quantitative information on the single-neutron nature of states in other $N = 83$ species beyond those accessible from neutron-adding reactions on stable nuclides. In the lighter $N = 83$ species, direct information on 13/2+ states is missing. But there is energetic information for Z>62, although spectroscopic factors have not been measured. The energy difference between the lowest $13/2^+$ and $9/2^-$ states are shown in Fig. 1(e), which shows a sudden change in the systematics beyond $Z = 62$ where the two states begin to diverge quite strongly in energy. In these heavier systems, the $\pi g_{7/2}$ orbital is expected to be fully occupied and additional protons occupy the $\pi h_{11/2}$ orbital, with significant consequences for the high-j neutron orbitals due to the strong radial overlap. Since the sense of the spin-orbit coupling is reversed in $\pi h_{11/2}$ compared to $\pi g_{7/2}$, the sign of the tensor interaction with neutrons reverses and the $\nu i_{13/2} - \nu h_{9/2}$ gap is expected to increase by some 0.16 MeV per additional $\pi h_{11/2}$ proton [14]. This reversal in energy trends *appears* to be seen in the evolution of the lowest $9/2^-$ and $13/2^+$ states in Figure 1(e).

However, strong conclusions need to be treated with extreme caution since the single-particle content of states beyond $Z = 62$ is not known. Indeed, the 3^- core excitation is expected to fall lowest in energy close to the $Z = 64$ subshell closure (see Fig. 1(d)), leading to significant mixing between the two $13/2^+$ states based on $\nu i_{13/2} \otimes 0^+_{\mathrm{CORE}}$ and $\nu f_{7/2} \otimes 3^-_{\mathrm{CORE}}$. The $\nu h_{9/2} \otimes 0^+_{\mathrm{CORE}}$ also mixes with $[\nu f_{7/2} \otimes 2^+_{\mathrm{CORE}}]_{9/2}$.

Determination of the spectroscopic factors are critical to unravel the underlying trends in single-particle energies. We propose to measure the relevant spectroscopic factors to make an experimental determination of the relevant centroids via transfer reactions using beams of ^{146}Gd, ^{148}Dy and ^{150}Er. The measurements with the first two beams are highest priority and would probe the region of maximal particle-vibration coupling and the turn around of the tensor driven trends, whilst a study with the Er beam would confirm the continuation of the trend as protons fill the $h_{11/2}$ orbital.

For such measurements, we would require beams at energies above 8 MeV/u at intensities greater than 10^5 pps to perform an experiment in a reasonable time. With such high-Z beams, it is difficult to deploy identification methods for beam-like particles recoiling from reactions, so beam contamination is an important issue. We therefore require either a high beam purity, or a method to associate populated states with a particular beam

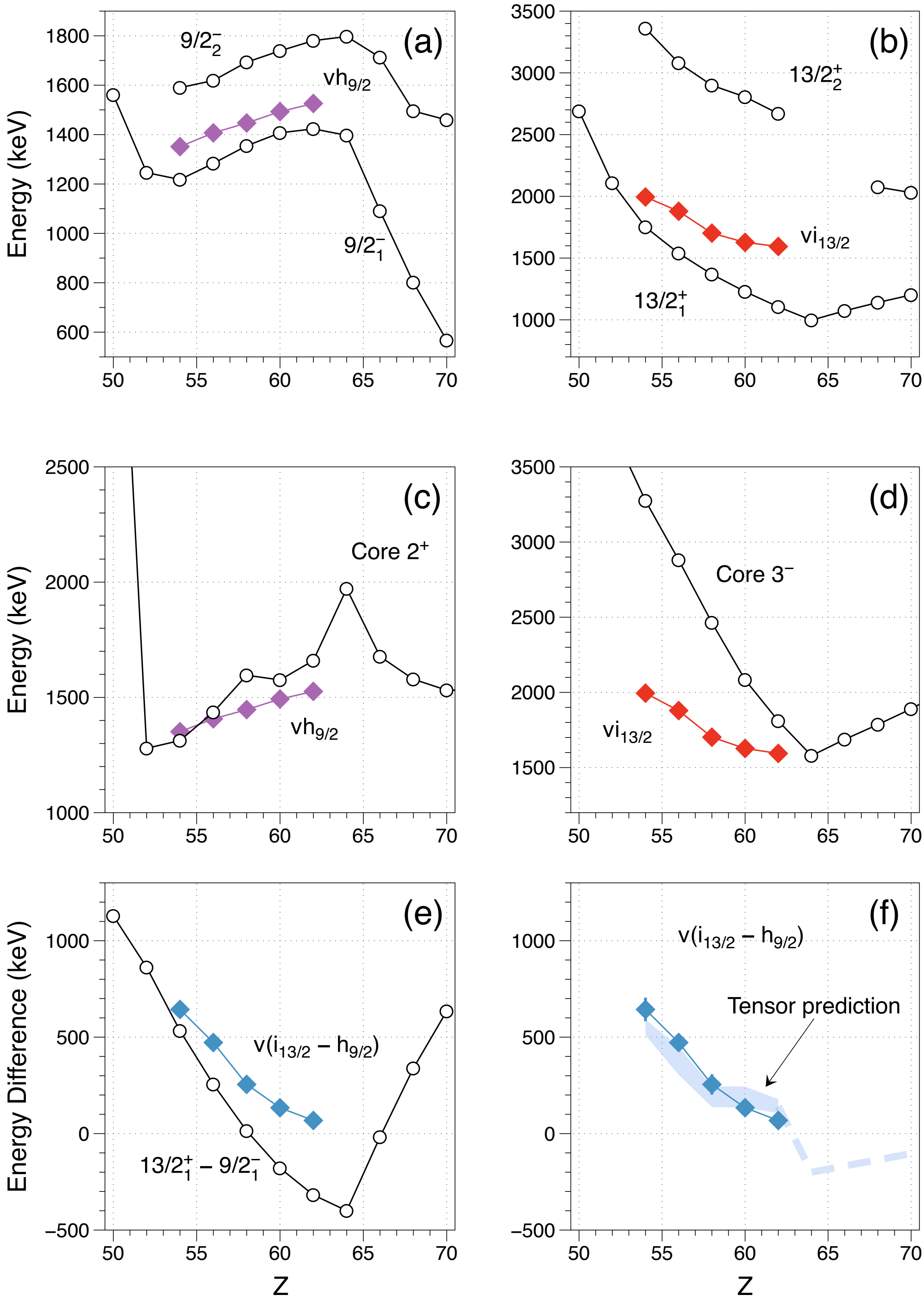

Figure 1: (a) Excitation energies for the lowest $9/2^-$ states (black) and associated single-particle centroid (purple) for $N = 83$ isotones.(b) Excitation energies for the lowest $13/2^+$ states (black) and associated single-particle centroid (red). (c) The excitation energy of the core 2^+ state compared to the $\nu h_{9/2}$ single-particle centroid. (d) The excitation energy of the core 3^- state compared to the $\nu i_{13/2}$ single-particle centroid. (e) The difference in the energies of the lowest $9/2^-$ and $13/2^+$ states compared to the difference between the single-particle centroids. (f) The difference between the single-particle ceontroids and calculations with the tensor interaction [2]. The dashed line extends the calculations for $Z > 62$ on the assumption of a good $Z = 64$ sub-shell gap beyond which the proton $h_{11/2}$ orbitals fills.

species, for example, something akin to laser-on/laser-off comparisons used with RILIS.

This letter of intent therefore requests time for the beam development using a LIST source. We first describe the experimental setup of a future proposal with ISS and then describe the aims of the currently requested beam development.

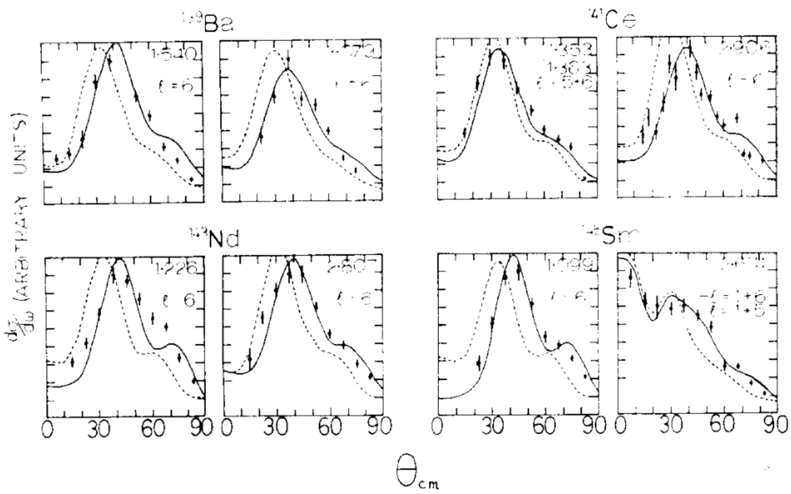

Figure 2: Angular distributions for $\ell = 6$ (d,p) transitions at deuteron energies of 19 MeV. The solid and dotted lines represent DWBA calculations for $\ell = 6$ and 5 transitions, respectively. This figure is taken from Ref.[9].

2 Experimental details

Reaction and beam energy – For the future experiment, we would propose to use the ISOLDE Solenoidal Spectrometer (ISS) to analyze protons from single-neutron adding (d,p) reactions at incident beam energies greater than 8 MeV/u to probe single-particle structure in ^{147}Gd, ^{149}Dy and ^{151}Er. There are advantages in performing the experiments at the highest energy available to maximise the cross-section for transfer to all states of interest, in particular high-j states, whilst also achieving distinct angular distributions that enable assignments to be made. Figure 2 shows some (d,p) measurements on stable $N = 82$ targets from Ref.[9] that show discrimination between $\ell = 5$ and 6 at 9.5 MeV/u; DWBA calculations show that similar discrimination persists down to at least 8 MeV/u. The beam development should establish what intensities are available, allowing the full feasibility of the experiment to be checked.

Experimental set-up – The transfer experiment will use the ISS configuration successfully employed in the recent study of $^{206}\text{Hg}(d,p)^{207}\text{Hg}$ [15]. We will use the new ISS on-axis silicon array, successfully commissioned in August and September 2021 shown in Figure 3; a ladder of multiple targets provides mitigation from target degradation by the heavy incident beam.

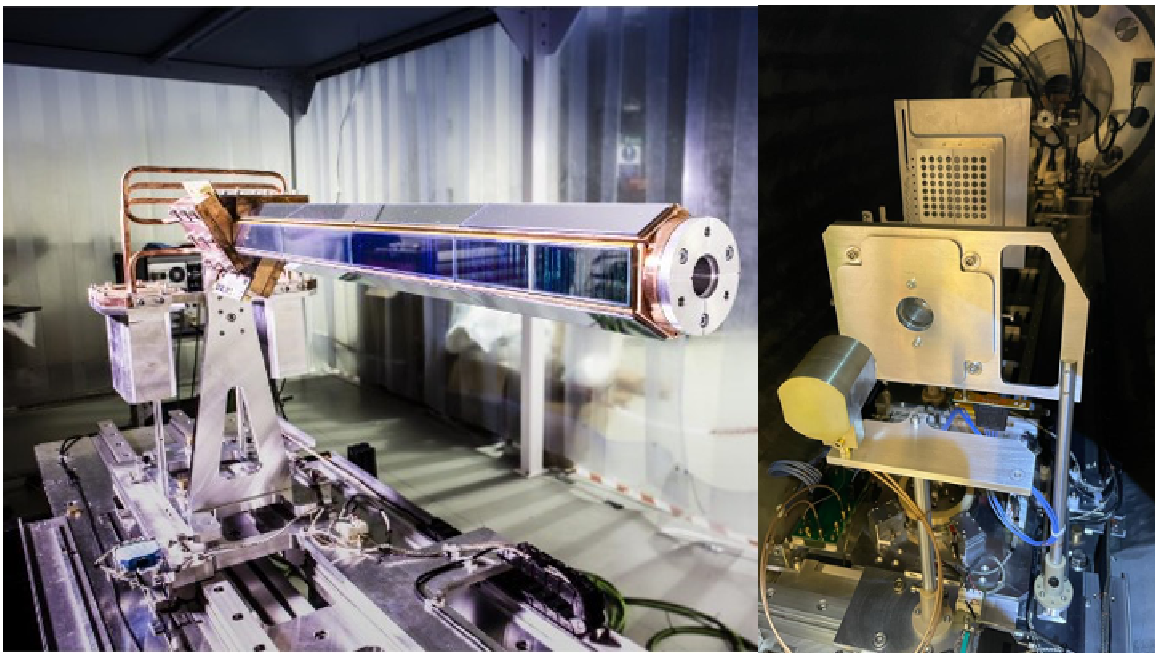

Figure 3: Left: The new on-axis silicon array for ISS. Right: Multiple-target ladder with Faraday cup and luminosity monitor in the foreground.

3 Beam development

The relevant rare-earth beams, ^{146}Gd, ^{148}Dy and ^{150}Er, have high production yields with a tantalum target, with measurements at the SC showing yields of the order of $10^8/\mu$Ci. Surface ionisation efficiencies of these elements are expected to be up to $\sim$10% and a method of controlling the associated contamination is needed.

Laser Ion Source and Trap (LIST) mode of operation [16, 17] has the potential to provide the necessary controls. Here, regions of surface ionisation and laser ionisation are separated by a repelling electrode, so that surface ionised ions are suppressed and neutral atoms entering the laser ionisation region can be selectively ionised via an appropriate laser ionisation scheme. Such schemes already exist for Gd, Dy and Er, although there is potential to improve on them.

Suppression factors of up to 10^6 have been obtained with LIST. The overall efficiency is low, but the high production yields provide compensation. Even if the suppression of contamination is not perfect, comparison of LIST-on to LIST-off transfer spectra could provide a route to associating populated states with specific beam species.

We therefore request **three shifts** in order to test the LIST method with Gd, Dy and Er, by measuring the LIST yields and suppression factors for the beams required for the physics case presented here and a full proposal will be submitted following a successful conclusion to these measurements.

References

[1] J. P. Schiffer, *et al.,* Phys. Rev. Lett. **92**, 162501 (2004).

[2] B. P. Kay, *et al.,* Phys. Lett. B **658**, 216 (2008).

[3] B. P. Kay, *et al.,* Phys. Rev. C **84**, 024325 (2011).

[4] R. Talwar, *et al.,* Phys. Rev. C **96**, 024310 (2017).

[5] D. K. Sharp, *et al.,* Phys. Rev. C **87**, 014312 (2013).

[6] D. K. Sharp, *et al., Submitted to Phys. Rev. C*

[7] A. M. Howard, *et al.,* Phys. Rev. C **101**, 0343309 (2020).

[8] Takaharu Otsuka, Alexandra Gade, Olivier Sorlin, Toshio Suzuki, and Yutaka Utsuno Rev. Mod. Phys **92**, 015002 (2020).

[9] W. Booth, S.Wilson and S.S. Ipson, Nuc. Phys. A **229**, 61 (1974).

[10] K. Heyde, M. Waroquier, H. Vincx, Phys. Lett. B 57 (1975) 429.

[11] L. Trache, A. Clauberg, C. Wesselborg, P. von Brentano, J. Wrzesinski, R. Broda, A. Berinde, V.E. Iacob, Phys. Rev. C 40 (1989) 1006.

[12] A.M. Oros, L. Trache, P. von Brentano, K. Heyde, G. Graw, Phys. Scr. T 56 (1995) 292.

[13] G. Coló, H. Sagawa, S. Fracasso, P.F. Bortignon, Phys. Lett. B 646 (2007) 227.

[14] T. Otsuka, private communication.

[15] T.L Tang et al. Phys. Rev. Letts. 124, 062502 (2020).

[16] D.A. Fink et al. Nuclear Inst. and Methods in Physics Research, B, Vol. 317, 15.12.2013, p. 417-421.

[17] D.A. Fink et al. Phys. Rev. X 5, 011018.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: Routine yield measurements

	Availability	Design and manufacturing
Routine Yield Measurements	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field			
Batteries			
Capacitors			
Ionizing radiation			
Target material			
Beam particle type	^{146}Gd,^{148}Dy,^{150}Er		
Beam intensity	$>1\times10^{5}$		
Beam energy	40-60 keV		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibrations source)		
• Sealed source			
• Isotope			
• Activity			

Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser	LIST ion source		
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			

Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above):