EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE proposal INTC-P-495)

Single-particle proton states in ^{69}Cu

May 31st, 2017

O. Poleshchuk[1], R. Raabe[1], M. Babo[1], P.A. Butler[2], S. Ceruti[1], H. De Witte[1],
B. Fernandez-Dominguez[3], F. Flavigny[4], S. Franchoo[4], S.J. Freeman[5], L. Gaffney[6], G.F. Grinyer[7],
M. Labiche[8], A.T. Laffoley[9], T. Marchi[1], R.D. Page[2], A.A. Raj[1], M. Renaud[1], F. Renzi[1], T. Roger[9],
D.K. Sharp[5], J.A. Swartz[10], J. Yang[1, 11]

[1]KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium

[2]Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK

[3]Universidade de Santiago de Compostela, 15706 Santiago de Compostela, Spain

[4]Institut de Physique Nucléaire Orsay, CNRS/IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay, France

[5]School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, UK

[6]ISOLDE, CERN, CH-1211 Geneva 23, Switzerland

[7]Department of Physics, University of Regina, Regina, SK S4S 0A2, Canada

[8]STFC Daresbury Laboratory, Daresbury, WA4 4AD Warrington, UK

[9]Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France

[10]Aarhus University, Department of Physics and Astronomy, DK-8000 Aarhus C, Denmark

[11]Physique Nucleaire Théorique, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium

Spokespersons: O. Poleshchuk, R. Raabe
(oleksii.poleshchuk@kuleuven.be, riccardo.raabe@kuleuven.be)
Local contact: L. Gaffney (liam.gaffney@cern.ch)

Abstract: We propose to probe single-particle proton states in the ^{69}Cu isotope with a stable beam of ^{70}Zn via the ^{70}Zn(d,^{3}He)^{69}Cu transfer reaction. The proton orbitals in this Cu isotope should experience no tensor force from the $\nu 1g_{9/2}$ neutron orbital, thus setting the initial position in the evolution of the proton $1f_{7/2}$-$1f_{5/2}$ spin-orbit partners along the Cu isotopic chain towards more neutron-rich isotopes. The cross sections for excited states, the spins of the states and the spectroscopic factors will be measured for the states populated by the transfer reaction. Our main aim is the measurement of the $\pi 1f_{7/2}$ strength in ^{69}Cu which was not previously observed. We will employ the SpecMAT active target and benchmark its performances by comparing with existing results.

Requested shifts: ^{70}Zn at 10 MeV/u, 5 days
Beamline: 2nd beamline, ISOLDE Solenoidal Spectrometer (ISS)

Introduction

Magic numbers established in the isotopes along the valley of stability might change when moving away from stability towards isotopes with extreme neutron to proton ratios. To study the evolution of such shell closures it is necessary to collect information along nuclide chains. A sequence of experiments directed to the systematic study of the evolution of the $1f_{7/2}$-$1f_{5/2}$ spin-orbit partners in $^{71-75}$Cu has been proposed to the INTC by our group [1]. The present LoI exploits the newly-opened opportunity to use a stable beam, by re-setting the previous proposal to start with the isotope ^{69}Cu.

The measurement will be used for the commissioning of the SpecMAT active target, by comparing with the results already obtained in Refs. [2] and [3]. We also aim to identify (part of) the missing $f_{7/2}$ strength in ^{69}Cu, which would provide the first experimental information about the size of the Z=28 closure in ^{69}Cu.

Physics case

The experimentally-observed lowering of the first excited states in odd $^{69-73}$Cu isotopes [4] and further inversion between the first excited state and the ground state in ^{75}Cu [5] has triggered high attention to the region of neutron-rich Cu and Ni isotopes. This observation was later explained by the combination of tensor and central forces in the nucleon-nucleon interaction [6]. Furthermore, a prediction was made of a reduction of the gap between the $\pi 1f_{7/2}$-$\pi 1f_{5/2}$ spin-orbit partners with the systematic filling of the $\nu 1g_{9/2}$ orbital. Recently, attempts have been made at the experimental investigation of the evolution of single-particle states in exotic neutron-rich Cu isotopes as a function of neutron number by using nuclear reactions [3, 7, 8]. The most recent experiments were performed at MSU involving a knockout reaction on a Be target with Zn beams [8]. The results of these experiments are expected to be available at the end of 2017.

We propose to use a stable beam of ^{70}Zn to populate single-particle states in ^{69}Cu isotopes using the (d,^{3}He) transfer reaction, which is a different method to the one used at MSU [8]. The average energy of the observed $7/2^{-}$ states weighted by their strengths in this experiment will indicate the position of the $\pi 1f_{7/2}$ orbital. Other (d,^{3}He) transfer-reaction experiments were used for the identification of shell structure in ^{69}Cu [2, 3]. Nevertheless, particularly $7/2^{-}$ states beyond 4 MeV were not observed. Consequently, the calculation of the $\pi 1f_{7/2}$ orbital position from those data relies strongly on theoretical models. An improved empirical determination of the position of this orbital is the main goal of our measurement.

Experimental method

The (d,^{3}He) transfer reaction in inverse kinematics will be used to populate single-particle states in ^{69}Cu. Based on the kinematic calculations, we expect to observe ^{3}He nuclei in forward angles of up to 44 degrees in the laboratory reference frame for the population of the ground state, and smaller angles for excited states. A magnetic field parallel to the beam will bend the trajectories of the particles emitted in the reaction in accordance to their mass and energy. By knowing the lab-angle, the energy of the particle and the strength of the magnetic field we can estimate the maximum radius of particle trajectories. The size of the SpecMAT chamber limits the detection of particles to radii of up to 85-90 mm, corresponding to ^{3}He ejectiles at angles of approximately up to 42 deg in the lab, thus covering most of the range for the reactions of interest.

In addition to the detection of the emitted light ions, coincident gamma-ray spectroscopy will be used to improve the energy resolution of the populated states and to study their decay patterns.

Experimental setup

SpecMAT is an active target i.e. a time projection chamber (TPC) where the detection gas is at the same time the target of the reaction of interest which is also surrounded by an array of scintillation detectors for gamma-ray spectroscopy. The design goal of the array is a resolution of 4% (26 keV FWHM at 662 keV) with a total photopeak efficiency of 7% at 1 MeV.

The TPC will be filled with deuterium gas and used for recording the tracks of charged particles emitted in the reaction. This is made possible by the following mechanism: Charged particles ionise the gas molecules along their path. Electrons produced during the ionisation will be guided by an applied homogenous electric field and collected on a pixelated pad plane [9]. While the two-dimensional distribution of electrons will be directly extracted from the position of fired pads, the third dimension will be reconstructed based on the electron drift time in the gas. The TPC and scintillator–array ensemble will be placed inside the ISS solenoidal magnet. A magnetic field collinear with the beam path will bend the trajectories of charged particles emitted in the reaction, providing an additional means of identification through the measurement of their curvature. The 3-dimensional tracks will provide full information about the particle, its energy and its lab-angle.

The instrument has a high luminosity and is primarily designed for detailed spectroscopy using weak beams of exotic nuclei. However, because of its geometry, it can potentially withstand higher beam intensities, up to 10^6 particles per second (pps).

Beam requirements

Beam intensity of ^{70}Zn at 10 MeV/u should not exceed 10^6 pps at the entrance of the chamber to avoid saturation of the charge sensitive pixelated pad plane and distortion of the electric field inside the TPC. Total cross sections for low-lying states populated in ^{69}Cu via the (d,^{3}He) reaction were extracted from angular distributions presented in [3] and are shown in Table 1. The 30-cm long gas chamber, filled with D_2 at 1 atm, gives 5 mg/cm^2 of target thickness. Even for the lowest cross section we may thus expect yields in the order of 100 events/h. The number of actual detected events strongly depends on the kinematics (particles emitted too close to the beam direction cannot be observed). If we require gamma-ray coincidence, we estimate rates of the order of 50 events per shift. With 4-5 days of beam time (12-15 shifts) we will thus be able to access the $7/2^-$ strength in those states above 4 MeV, probably even more weakly-populated, which were not previously observed.

Table 1 Total cross sections for population of low lying states in ^{69}Cu via the (d,^{3}He) reaction based on the experiment of Morfouace et. al. [3]

Isotope	State	Energy, MeV	Estimated total cross-section, mb
^{69}Cu	g.s. $3/2^-$	0	0.82
	$5/2^-$	1.23	0.04
	$7/2^-$	1.71	0.19
	$7/2^-$	1.87	0.03
	$7/2^-$	3.35	0.11
	$7/2^-$	3.7	0.05
	$7/2^-$	3.94	0.03

References:

1. O. Poleshchuk, *et. al.,* CERN-INTC-2017-012/INTC-P-495
2. B. Zeidman and J. A. Nolen, Phys. Rev. C 18, 2122 (1978)

3. P. Morfouace, *et. al.,* Phys. Rev. C, 93, 064308 (2016)
4. S. Franchoo, *et al.,* Phys. Rev. C, 64, 054308 (2001)
5. K.T. Flanagan, *et al,.* Phys. Rev. Lett., 103, 142501 (2009)
6. T. Otsuka, *et al.,* Phys. Rev. Lett., 104, 012501 (2010)
7. P. Morfouace, *et. al.,* Phys. Let. B 751, 306 (2015)
8. J. Belarge *et. al.,* DNP16 Meeting, http://absimage.aps.org/image/DNP16/MWS_DNP16-2016-000212.pdf
9. Y. Giomataris, *et. al.,* Nucl. Instrum. Methods Phys. Res. A 376, 29 (1996)

Appendix 1

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
	☐ Existing	☐ To be used without any modification
SpecMAT active target time projection chamber	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
ISOLDE Solenoidal Spectrometer (ISS)	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

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	*SpecMAT*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	1 [Bar], 22 [l]		
Vacuum			
Temperature	293 [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	Field cage: Up to 10 [kV], Pad plane: Up to 1 [kV]		
Static electricity			
Magnetic field	3 [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	Deuterium (D_2) gas		
Beam particle type (e, p, ions, etc)	ions		
Beam intensity	Up to $5 \cdot 10^6$ pps		
Beam energy	10MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		

• Open source	☒		
• Sealed source	☒ [ISO standard]		
• Isotope	Standard alpha and gamma calibration sources		
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	D_2, 22 [l]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	D_2, 22 [l]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

… kW