Study of valence neutrons in $^{136}$Xe with HELIOS

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Abstract. The single-neutron adding $(d,p)$ reaction has been performed on $^{136}$Xe in inverse kinematics at 10 MeV/u. The position, time-of-flight, and energy of the outgoing protons were analyzed by the new helical orbit spectrometer, HELIOS, at Argonne National Laboratory. An excitation-energy resolution of $\leq 100$ keV was obtained in the outgoing proton spectra. The experimental setup is described, along with a technique of extracting absolute cross sections. Data are shown which illustrate the performance of the device. This measurement clearly demonstrates the potential of HELIOS for future heavy radioactive-beam studies.

1. Introduction

Single-nucleon transfer reactions are a powerful probe of nuclear structure; they allow us to extract key quantities, such as energies and spectroscopic factors, for shell-model and mean-field theories. Traditionally, these measurements have been performed in ‘conventional’ kinematics where a light stable ion beam impinges upon a stable, and typically heavier, target. To probe the structure of radioactive nuclei, further away from stability, requires that these reactions be performed in so-called inverse kinematics where a radioactive ion beam strikes a light stable target. For such reactions, the large center-of-mass (c.m.) velocities result in a strong angle sensitivity with respect to the energy of the outgoing ion, and a kinematic compression in the laboratory frame. These measurements typically result in low resolution, often of the order of hundreds of keV full-width at half maximum (FWHM). The new helical orbit spectrometer, HELIOS [1, 2], at Argonne National Laboratory (ANL) foregoes these complications by transporting the outgoing ions in a high-field, homogeneous solenoid. A schematic of the device is shown in Fig. 1. The ions follow helical trajectories before returning to the axis where their time-of-flight (the cyclotron period, which provides particle identification), energy and position are measured. The relationship between position and energy is linear, and the energy separation between outgoing ions is identical to that of the excitation energy in the residual nucleus. In this work we report on the measurement of the neutron-adding $(d,p)$ reaction on $^{136}$Xe using the HELIOS spectrometer to analyse outgoing protons. The underlying physics motivation is described below. A parallel motivation for this measurement...
was to assess the performance of the HELIOS spectrometer with beams of comparable mass to those expected from the CAlifornium Radioactive Isotope Breeder Upgrade (CARIBU) [3] at the Argonne Tandem Linear Accelerator System (ATLAS) at ANL—those in the vicinity of $^{132}$Sn. The HELIOS spectrometer has been successfully commissioned with light ions, both with a stable beam measurement of the $(d^{28}Si,p)^{29}Si$ reaction [2] and a radioactive beam produced using the in-flight method at the ATLAS accelerator [4] in the study of the $(d^{12}B,p)^{13}B$ reaction [5].

Measuring the $(d^{136}Xe,p)^{137}Xe$ reaction was motivated by recent exploration of the evolution of single-particle states outside the $N = 82$ isotones. Tracking the properties of single-particle states over a large range of neutron excess has been very instructive in demonstrating the influence of the tensor force in nuclear structure—the $N = 82$ isotones, along with the $Z = 50$ isotopes, present such opportunities. A study of the change in separation of the nodeless $h_{11/2}$ and $g_{7/2}$ proton orbitals across the stable even Sn isotopes [6] – approximately 2 MeV between $^{112}$Sn and $^{124}$Sn – formed a means of testing the suggestion by Otsuka et al. [7] that the evolution of effective single-particle energies can be described by the addition of a tensor term to the nuclear Hamiltonian. A subsequent systematic study of the nodeless $i_{13/2}$ and $h_{9/2}$ neutron orbitals outside the $N = 82$ isotones [8], using the $(\alpha,^3He)$ reaction, found a qualitatively similar effect, though it was confined to the four stable, metallic isotones, $56 \leq Z \leq 62$. Similar systematic studies had been performed previously via the $(d,p)$ reaction [9].

There is notably limited data available from neutron transfer on $^{136}Xe$, particularly for high-$\ell$ (5$h$ and 6$h$) transfer. There are two main reasons for this: first, $^{136}Xe$ is gaseous, and so previous measurements suffered from low resolution and contamination [10]. Though the work in Ref. [11] cites 45-keV FWHM resolution and low contamination, their analysis focussed on low-$\ell$ transfer which is well-matched in the $(d,p)$ reaction. The $(d,p)$ reaction has also been performed in inverse kinematics in an early test of the inverse reaction mode at GSI in the 1990s [12]. Common to all previous works is that they ran at beam energies between $\sim$5-7.5 MeV/u, too low to populate high-$j$ orbitals with significant cross sections. The work of

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**Figure 1.** (Left) An annotated schematic of the HELIOS spectrometer. Label (a) identifies the target assembly, (b) is an elongated Faraday cup designed to minimise back scatter of reaction products, and (c) a Si surface barrier detector used to monitor elastically-scattered ions from the target. (Right) Trajectories, projected on the $yz$ plane, of ions measured in this experiment. For the $^{12}C$ trajectory a charge state of 6$^+$ is assumed.
Ref. [8] found the $i_{13/2}$ and $h_{9/2}$ strength to be strongly fragmented for the $N = 82$ isotones, being shared between two states in each case. Recently, the lowest-lying $13/2^+$ state in $^{137}$Xe has been observed [13], but no previous identification has been made of a second state—the same is true for $9/2^-$ states. At 10 MeV/u, the cross section for $\ell = 5$ and 6 transfer is of the order of 1 mb/sr and the angular distributions are sufficiently forward peaked, $\sim$30 and 40$^\circ$ respectively, to enable this measurement in HELIOS. Under these conditions, the assumptions made in the DWBA are better met, allowing a more reliable comparison of results from $(d,p)$ and $(\alpha,^{3}\text{He})$.

2. Measurement
A beam of $^{136}$Xe at 10 MeV/u and with typical intensities of $10^7$ Xe ions per second ($\sim$50 pA) was delivered by ATLAS. Beam entered the HELIOS spectrometer along the $z$ axis where it impinged upon a deuterated polyethylene (CD$_2$) target. For this measurement the field was 2 T. In this configuration, the beam passes through a hollow tube with a inner diameter of 10 mm. Its outer extent forms a 23-mm square profile which supports an array of position-sensitive Si detectors (PSDs) covering a distance of $\sim$35 cm along the $z$ axis. The array comprises 24 PSDs, each of which has an active area of 9 mm by 50 mm. They are arranged such that six equally-spaced PSDs cover the length of the array on each of the four sides. The detectors are cooled; standard operation is at $\sim$0$^\circ$C. The PSDs are 700 $\pm$ 15-$\mu$m thick, sufficient to stop protons of $\lesssim$ 10 MeV which is comparable to the maximum proton energy accepted based on the geometry of the solenoid and the strength of the field. The solid angle coverage of the array for this measurement (currently a prototype) is 0.5 sr, which is a factor $\sim$3 less than the anticipated fully-furnished array.

The energy as a function of distance from target to the position of impact on the array is shown in Fig. 2—it has a characteristic linear relationship. Outgoing ions are dispersed by the magnetic field according to their energy, angle of emission, and their mass-to-charge ratio. The latter provides an automatic particle identification as it dictates the cyclotron period of the ion. For protons this is unique—for deuterons and $\alpha$ particles (and protons executing two cyclotron periods before impacting the array), this is ambiguous. The time-of-flight is measured with respect to the intrinsic radio-frequency of the ATLAS facility, with a typical resolution of about 8 ns. An example of this is also shown in Fig. 2. To cover the angular range necessary, from about 5 to 40$^\circ$, two different target-array distances were used for both beams. For the example shown in Fig. 2, these are denoted by red (373 mm separation between target and the centre of the first detector) and blue (171 mm).

To extract absolute cross sections, a measurement of elastically-scattered deuterons was made in the Rutherford regime. A 400-mm$^2$, 60-$\mu$m thick Si surface-barrier detector was placed on axis parallel to the $xy$ plane at a distance of 360-mm downstream of the target. At a beam energy of 5 MeV/u the scattering angle to the detector had a central value of 34.9$^\circ$ which is within $\pm$3% of Rutherford as determined by DWBA calculations using several optical-model parameters [14]. At 10 MeV/u, elastic scattering of deuterons deviates from Rutherford by $\sim$52% and so cannot be reliably used to deduce absolute cross sections directly. The reaction cross sections where normalised to the low-energy scattering data. The targets were found to deteriorate rapidly under beam irradiation. Elastically scattered C recoils were also accepted by the luminosity monitor and so both constituents of the target could be monitored simultaneously. Targets used had a nominal thickness of $\sim$125–175 $\mu$g/cm$^2$.

3. Results
In this report we focus on a preliminary analysis of the $d(^{136}\text{Xe},p)^{137}\text{Xe}$ data. The raw energy versus position data are corrected for their kinematic slope and projected onto the energy axis. This is done on a detector-by-detector basis. For each, a self-consistent energy calibration was
Figure 2. (Left) A composite plot of proton energy versus z for a subset of the data from the \(d(^{136}\text{Xe},p)^{137}\text{Xe}\) reaction. These data have been gated on events corresponding to the cyclotron period of a single proton orbit. Two different target-array positions were used and are denoted in red (Position I) and blue (Position II). The characteristic ‘U-shape’ is a consequence of the ADC threshold. (Right) An example of the timing between the beam RF structure and an event in the array – the cyclotron period – for a detector at the right of Position I. The three peaks correspond to (a) one proton orbit, (b) two proton orbits (ambiguous with deuterons and alpha particles), and (c) three protons orbits (ambiguous with tritons). Depending on their position in z, not all detectors accept events corresponding to multi-orbit protons.

performed as a sufficient number of states are known in \(^{137}\text{Xe}\). Data from a multi-line alpha-source provided verification of this calibration and a detector-to-detector efficiency correction. (The alpha source was placed at the target position with the same magnetic field as used for reaction measurement.) Groups of four detectors from each ‘position’ in z are summed together and define a natural angle bin. In total there are twelve angle bins from the combination of data from the two target-array settings (see Fig. 2). The central angle of each detector is determined from geometry and reaction kinematics. Protons emitted at laboratory angles closer to 90° can execute multiple orbits. Gating on the time peak corresponding to one proton cyclotron period (see Fig. 2) removes these events, though a background still remains from protons evaporated from fusion reactions between the beam and the target, \(^{136}\text{Xe}+^{12}\text{C} \rightarrow p + X\).

An example of an outgoing proton spectrum is shown in Fig. 3. A smooth background has been subtracted. An excitation-energy resolution of 96-keV FWHM was achieved. A total of 20 states were populated, 13 of which have been observed for the first time in the \((d,p)\) reaction. Though several states were poorly resolved, yields could be extracted using a number of techniques, such as line shape fitting with constrained positions and widths, the latter determined by fitting isolated states. In some instances, e.g. the 1534- and 1590-keV states, the behaviour as a function of angle, as well as a larger width, suggest a doublet, and it was fit accordingly. Extracted yields were normalised to the elastic scattering data taken at 5 MeV/u providing absolute cross sections with an estimated uncertainty of \(\sim 15\%\). Several angular distributions are shown in Fig. 3 for transfer of \(\ell = 1, 3, 5,\) and \(6\). In some instances, data could not be reliably extracted from all detectors and so not all distributions have twelve data points. This is a consequence of only 18 of the 24 detectors on the Si array functioning for this experiment, so at some positions, there were less than four detectors—not all positions had sufficient yield to determine cross sections at all angles. Angular distributions were not extracted for states at 2025, 2120, 2905, 2995, 3150, 3340, 3470, and 3610 keV, either due to these states not being resolvable at several angles or because of low statistics. DWBA calculations performed using the PTOLEMY code [15] with several sets of optical-model parameters from the literature [14].
Figure 3. (Top) Preliminary outgoing proton spectrum for the $d^{(136\text{Xe},p)}^{137}\text{Xe}$ reaction. States are labelled by their excitation energy and, where known, their $\ell$ value, spin and parity. Those marked with a $\Delta$ symbol have been identified for the first time in this work. The identification of the state at 1751 keV was guided by Ref [13]. (Bottom) Preliminary example proton angular distributions for $\ell = 1$, 3, 5, and 6 transfer following neutron adding to states in $^{137}\text{Xe}$ via the $(d,p)$ reaction. The black circles represent the data with statistical error bars whilst the curves are DWBA calculations made using the code PTOLEMY [15]. They are normalized to the data. States are labelled by their energy in keV and $\ell$ value; those in parentheses have been assigned in this work.

were normalized to the data to determine the $\ell$ transfer. Exploration in to the variation between the different parameters sets is ongoing.

Two states consistent with $\ell = 5$ transfer have been measured. The first, at 1218 keV, was previously reported in $\beta$ decay and in $(d,p)$, both tentatively [16]. The second, at 1590 keV, is deduced for the first time in this work. Based on results from the $(\alpha,^3\text{He})$ reaction on the stable $N = 82$ nuclei, one expects these two states to exhaust the $h_{9/2}$ strength [8]. Only one state consistent with $\ell = 6$ has been extracted from these data at 1751 keV. A previously unpublished assignment of $13/2^+$ to a state at this energy has been confirmed [13]. For previously known states at 0, 601, 986, 1218, 1303, 1534, and 1841 keV, good agreement is seen between this work and the literature [16]. This analysis is preliminary—further analysis will include a full spectroscopic analysis which incorporates a broader study of the $N = 82$ isotones.
4. Conclusions

Direct transfer reactions provide a unique probe of nuclear structure. As more facilities worldwide provide precise and clean radioactive ion beams, the study of reactions in inverse kinematics will become increasingly important. This exploration of the single-neutron adding reaction $d^{(136 \text{Xe}, \text{p})}$^{137}Xe clearly demonstrates the potential of the HELIOS concept for these types of measurements. Results from these data extend our knowledge of single-particle properties outside the $N = 82$ isotones.

A measurement of the $d^{(130 \text{Xe}, \text{p})}$^{131}Xe was also performed during the same experiment for its relevance to the nuclear matrix elements for the potential neutrinoless double beta decay of $^{130}$Te. In order to constrain uncertainties in the theoretically calculated matrix elements an experimental knowledge of the difference in the initial and final $0^+$ ground-state wave functions is essential. Members of this collaboration have performed a series of experiments to map out the occupancies of valence neutrons [17] and protons [18] for the $^{76}$Ge→$^{76}$Se system. Other measurements within the $^{130}$Te→$^{130}$Xe system are being planned using a cryogenic Xe target [19]. The analysis of these data are underway.

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