Recent Experimental Results from HELIOS

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Abstract. The renewed emphasis on nuclear structure far from stability, studied with nucleon-transfer reactions that utilize radioactive beams, has led to many new and exciting results. Accompanying these developments are, however many technical challenges that confront studies of transfer reactions in inverse kinematics. Amongst these are the identification of reaction products and the resolution of states in the residual nuclei. A new device, HELIOS (the HELical Orbit Spectrometer) has been constructed to solve many of the problems encountered with such reactions. The device uses a uniform magnetic field produced by a large, superconducting solenoid to transport light reaction products from the target to a linear array of position-sensitive silicon detectors. In operation since August of 2008, HELIOS has been used to study a variety of \((d,p)\) reactions with beams of stable and unstable ions with masses ranging from \(A=11\) to 136.

1. Introduction

Nucleon-transfer reactions were first used to determine the spins and parities of nuclear states over 60 years ago [1][2]. During the intervening decades, studies of nucleon transfer have contributed an immense amount to our understanding of atomic nuclei. With their selectivity, and the relative simplicity of interpreting their results, not to mention the relative ease of carrying out the measurements, reactions such as \((d,p)\) have been used to build up much of what we know about nuclei, including the energies of states, the occupancies of nuclear orbitals, and the nature of the nucleon-nucleon residual interaction.

More recently, the ability to study similar properties far from the valley of stability through the use of beams of radioactive nuclei has been developed. The very same measurements and nuclear properties are proving to be even more interesting with values of \(N/Z\) very different from those with nuclei close to stability. Properties thought to be well understood, such as the ordering of shell-model orbitals, the nature of single-particle states, even the values of the “magic numbers” that inspired the development of the shell model itself are not what appear in textbooks. This renewed emphasis on the fundamental properties of nuclear states that can be studied with nucleon-transfer reactions has led to great strides in our understanding of nuclear structure far from stability. But it has not been easy.

In this modern era, we often work not with stable, heavy targets and light energetic beams such as \(^2\text{H}\), but rather energetic heavy, radioactive beams that bombard light gaseous or plastic targets that contain isotopes of hydrogen or helium in a regime known as “inverse kinematics” (as opposed to “normal kinematics”). Whereas before, the reaction products of interest, typically light ions such as protons, deuterons, tritons, and alpha particles emerged from the reaction with high energies and laboratory angles close to those in the center-of-mass system, with inverse kinematics the situation is more complicated. Due to the large center-of-mass motion associated with the energetic heavy beam,
the transformation from center-of-mass frame to laboratory frame produces light ions that have small energies in the laboratory, often making them difficult to detect and identify. Another unfortunate consequence is that it becomes more difficult to resolve excitations in the residual nuclei of interest due to an effect that has come to be known as “kinematic compression” where the center-of-mass to laboratory transformation causes the energy separation between kinematic groups in the laboratory to be much less than that in the center-of-mass frame, thereby reducing the resolution and the ability to separate closely-spaced levels [4][5].

In the case of neutron-stripping reactions such as (d,p), inverse kinematics have been used for some years. Reactions with 40Ca beams were studied as far back as the 1970’s [6] to make gamma-ray lifetime measurements, but for particle spectroscopy early examples are found from the 1990’s with stable (136Xe, Ref. [7]) and unstable (66Ni, Ref [8]) beams. After the year 2000, there has been a proliferation of measurements of stripping reactions in inverse kinematics, for example, with light ISOL beams [9][10], heavy stable [11] and light unstable beams [12] performed using segmented arrays of silicon detectors or the detection of gamma rays from the decay of states populated in transfer reactions. All of those measurements highlight, however, the technical challenges of working in the inverse-kinematic environment and have prompted the desire to develop a completely new and different experimental approach. Such a new approach is embodied by a device called HELIOS (the HELIcal Orbit Spectrometer), now in operation at the ATLAS accelerator facility at Argonne National Laboratory.

2. HELIOS: the HELIcal Orbit Spectrometer

2.1. The HELIOS concept

This use of a solenoidal geometry for inverse-kinematic reactions was first suggested as part of the discussion of instrumentation for a new radioactive-beam facility in the US [3]. HELIOS exploits a technique that connects the center-of-mass frame and the laboratory frame more directly than any other method [4][5]. In HELIOS, the experiment is immersed in a strong, homogeneous magnetic field oriented parallel to the direction of the beam. Light-charged particles, such as protons that might be emitted from a (d,p) reaction, instead of travelling straight lines follow helical trajectories as shown in figure 1 until they eventually return to the beam axis where they can be detected using a thin pencil-shaped array of position-sensitive silicon detectors. These detectors measure the energy \(E\) and flight time \(T\) of the light particles, as well as the distance \(z\) along the beam axis between the target and the point at which the particles return to that axis. The helical cyclotron motion of the particles ensures that their flight time \(T\) is equal to the cyclotron period \(T_{CYC}\) which in turn is defined solely in terms of the particle’s mass \(m\), charge \(q\), and the magnetic field \(B\), as \(T_{CYC} = 2\pi m/Bq\). The flight time then determines the mass-to-charge ratio \(m/q\) for light-charged particles, thereby in most cases providing a simple method of particle identification.

Also, for a given transition to some final state in the residual nucleus, the cosine of the center-of-mass angle \(\theta_{CM}\) is directly proportional to \(z\), and the center-of-mass energy \(E_{CM}\) is related to the laboratory energy \(E_{lab}\) by the simple linear relation \(E_{CM} = E_{lab} + A - B \times z\), where \(A\) and \(B\) are constants determined by \(T_{CYC}\), the masses of the nuclei, and the bombarding energy. Therefore, as a function of \(z\), the laboratory energies for particles from different excited states in the residual nucleus are always separated by the same amount which is equal to the center-of-mass energy difference, very close to the difference in excitation energy (see figure 2). Furthermore, the coefficient \(B\) is typically quite small, (typically 10-20 keV/mm) so that the contribution to the energy resolution from the kinematic shift \(dE_{lab}/dz\) is less than the intrinsic resolution of the detector, and is frequently much less than the kinematic shift with laboratory angle \(dE_{lab}/d\theta_{lab}\) that is seen in a measurement using a more standard technique (see figure 2). These properties together permit greater resolving power for excitations in the residual nucleus than might be achievable using other methods.
2.2. HELIOS implementation

The first implementation of this approach is the HELIOS device currently in operation at the ATLAS facility at Argonne National Laboratory. The technical details of HELIOS are presented in [13]. Briefly, the magnetic field is produced by a large, superconducting magnet taken from a retired magnetic-resonance imaging (MRI) device, with a bore diameter of 0.9 m and a length of 2.35 m. The maximum magnetic field in the center of the magnet is 2.85 T, and the field is uniform to approximately 0.1% within a sphere of 0.9 m diameter centered in the middle of the solenoid bore. The detector array contains 24 position-sensitive silicon detectors in a square configuration approximately 35 cm long with a 2 cm cross section. A moveable fan holds up to nine different targets that can be rotated into the beam axis by remote control, and the linear position of the targets can also be changed from outside the vacuum vessel without opening the chamber. Recolliding beam-like ions can be detected using recoil detectors placed at the downstream end of the solenoid; for
experiments with light beams (A<20) recoils are detected in an array of silicon $\Delta E$-$E$ telescopes. A computer rendering of HELIOS as configured for $(d,p)$ reactions appears in figure 3. Figure 4 shows a photograph of HELIOS as currently installed at Argonne National Laboratory. The inserts to Figure 4 show the square silicon-detector array (left insert) and the recoil-detector array (right insert).

Figure 3. Schematic representation of HELIOS.

Figure 4. HELIOS, at the ATLAS facility at Argonne National Laboratory. The inserts show the silicon-detector array (left) and the silicon recoil-detector telescope array (right).
3. Commissioning of HELIOS

The first demonstration of the operating properties of HELIOS was carried out by studying the $^{28}\text{Si}(d,p)^{29}\text{Si}$ reaction in inverse kinematics at a bombarding energy of 6 MeV/u. Recoiling $^{29}\text{Si}$ ions were not detected in this first demonstration experiment. Figure 5 contains a summary of data from this first measurement. The insert illustrates a time-of-flight spectrum where the time difference is between the time-of-arrival of a particle in the silicon array and the RF signal generated by the ATLAS accelerator. Two peaks are apparent, for particles with $m/q=1$ (filled) and 2. The $m/q=2$ peak actually corresponds to protons that execute two cyclotron orbits before returning to the beam axis. After imposing a selection on $m/q=1$, the two-dimensional histogram shows a correlation between energy and position measured in the silicon array. Several diagonal groups are observed, each of which corresponds to a different state in $^{29}\text{Si}$ known to be strongly populated in the $(d,p)$ reaction.

The transformation from laboratory energy to excitation energy in the residual nucleus is accomplished by a simple projection of these diagonal loci onto a perpendicular plane, which is equivalent to removing the linear dependence of the laboratory energy on $z$. The resulting excitation-energy spectrum obtained for the $^{28}\text{Si}(d,p)^{29}\text{Si}$ reaction appears in figure 6. The excitation-energy resolution attained in this first demonstration experiment ranged from approximately 80 keV FWHM for the best performing detectors, to 120 keV FWHM, with the value for all data from all detectors combined being approximately 100 keV FWHM. The targets had areal densities of 80 $\mu$g/cm$^2$, and the contributions to the resolution from energy loss of the beam, and straggling of protons in the target were less than 20 keV in this case. The resolving power of this approach is seen from the clean separation of the excited states at 6.19 and 6.38 MeV. Details of this commissioning experiment are presented in [13].

![Figure 5](image.png)

**Figure 5.** Energy-versus-position correlation for protons emitted in the $^{28}\text{Si}(d,p)^{29}\text{Si}$ reaction measured using HELIOS. The insert shows a time-of-flight particle-identification spectrum.
4. Recent physics measurements with HELIOS

HELIOS has been used to study a number of neutron-stripping reactions in inverse kinematics. These involve both stable and radioactive beams, and cover a wide range of masses. Several recent measurements are described below.

4.1. Exotic behaviour in $^{16}\text{C}$ and the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction

A study of the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction has been motivated by claims of exotic behavior observed in the low-lying positive-parity states in $^{16}\text{C}$. In particular, the results of measurements of the electromagnetic transition rates and other inelastic-scattering data for $^{16}\text{C}$ suggested an “anomalous” picture where the two valence neutrons are “decoupled” from the $^{14}\text{C}$ core [14][15]. A strongly suppressed B(E2) in comparison to expectations for this mass region was reported in [14], but that value was in contradiction with a later measurement in [16]; both of those results were in conflict with yet another measurement reported in [17]. One approach that probes the wave functions of the relevant states in $^{16}\text{C}$ in a complementary fashion is to populate the low-lying positive-parity levels in $^{16}\text{C}$ through neutron stripping with the $(d,p)$ reaction. As the ground state of $^{15}\text{C}$ is a good $1s_{1/2}$ single-particle state, the levels in $^{16}\text{C}$ populated with $(d,p)$ will be those with significant $1s_{1/2}$ content. The data, in particular the relative spectroscopic factors, provide information about the configuration mixing expected in this nucleus. Different calculations (e.g. [18][19]) of the structure of $^{16}\text{C}$ make different predictions about that mixing, and these predictions can be compared to the results for the stripping reaction.

We have studied the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction in HELIOS using a secondary $^{15}\text{C}$ beam produced at the In-Flight production facility at the ATLAS accelerator facility at Argonne National Laboratory [20]. The $^{15}\text{C}$ beam was produced by bombarding a cryogenic D$_2$ gas cell with an intense $^{14}\text{C}$ primary beam with an energy of 133 MeV. The secondary $^{15}\text{C}$ beam had an energy of 123 MeV, and an intensity between 1 and $2 \times 10^6$ particles per second measured in a silicon surface-barrier telescope mounted at the downstream end of HELIOS. The $^{15}\text{C}$ beam bombarded a deuterated polyethylene [(CD)$_2$] foil target with an areal density of 110 µg/cm$^2$. The proton energy-position correlation and $^{16}\text{C}$ excitation-energy spectrum from the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction measured in HELIOS appear in Figure 7 [21]. Here, the protons were detected in coincidence with $^{16}\text{C}$ ions detected and identified with the forward-angle recoil-detector array. The four peaks correspond to the $0^+, 2^+, 0^+_2$, and an unresolved doublet of $2^+_{3/2} \gamma 1^+$, excitations in $^{16}\text{C}$. For this, and other measurements with In-Flight radioactive beams, the
secondary-beam production method introduces another contribution to the excitation-energy resolution; typically, for gas-cell production that additional amount is on the order 50 keV or less, but for solid production targets (See Sec. 4.3. below) it can be as much as 100 keV. Figure 8 shows angular distributions (left) and extracted relative spectroscopic factors (right). The curves represent distorted-wave Born-approximation (DWBA) calculations using several different optical-model parameter sets. The relative spectroscopic factors are plotted in comparison to those predicted by shell-model calculations performed using the WBP interaction [22], and the normalization of the experimental values was fixed by requiring that the sum of the 0^+ (L=0) spectroscopic factors to add to 2.0. The uncertainties reflect the spread in relative cross sections from the different optical-model parameter sets. The agreement between theory and experiment is excellent, indicating that the shell model can well explain the configuration mixing in the 0^+ states in 16C. In addition, the shell-model wave functions have been used to calculate the B(E2) for the problematic 2^+_1→0^+_1 transition in 16C, and this value is in good agreement with the value obtained by the Berkeley group from a lifetime measurement [16]. These observations suggest that the structure of 16C is not particularly anomalous, and the properties are well understood in terms of well-accepted shell-model interactions [21].

4.2. The 19O(d,p)20O reaction and (sd)^4 states in 20O

In order to better understand the multi-neutron excitations in the sd shell away from stability, HELIOS has been used to study the 19O(d,p)20O neutron-stripping reaction. In 19O(d,p)20O, below 7 MeV excitation energy in 20O, only contributions from neutrons transferred to the 0d_5/2 and 1s_1/2 orbitals are expected. These transfers populate states with J^π=0^+, 2^+ and 4^+ for 0d_5/2 neutrons, and J^π=2^+ and 3^+ for 1s_1/2 neutrons, respectively. The expected 3^+ state had not been previously observed in 20O, although a candidate for a corresponding state in 18O has already been suggested [23]. The spectroscopic factors for neutron stripping may be compared to the predictions of different shell-model interactions in this
region, and can also be used to deduce empirical values for the diagonal elements of the neutron-neutron residual interaction for this value of $N/Z$ [24].

Figure 8. (Left panel) Proton angular distributions for the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction. The curves represent DWBA calculations with several different optical-model potential sets. The right panel illustrates the deduced relative spectroscopic factors with uncertainties arising from the normalization between calculation and experiment. An upper limit of 20% for the $2^+\rightarrow 2^+/3^+/1$ doublet is used (from [21]).

The radioactive $^{19}\text{O}$ beam was produced via the $^{18}\text{O}(d,p)^{19}\text{O}$ reaction in a manner similar to that described for $^{15}\text{C}$, with energy 125.6 MeV and an intensity between 2 and $4\times10^5$ particles per second. Protons recoiling $^{20}\text{O}$ nuclei were detected in the HELIOS silicon array, and forward-angle recoil detectors, respectively. Targets used in this study had areal densities of 260 $\mu$g/cm$^2$. A monitor detector was also positioned between the target and the recoil array to detect elastically scattered deuterons to measure the absolute luminosity (product of beam intensity times target thickness), and this information was used to provide absolute normalization information for the angular distributions that carried an uncertainty of approximately 20%. The relative uncertainties between different transitions were on the order of a few percent.

Figure 9 shows the energy-position correlation spectrum for this reaction (left panel), and the right panel illustrates the corresponding excitation-energy spectrum. The expected $0^+$, $2^+$, $3^+$, and $4^+$ transitions are all present; the $3^+_1$ state at 5.23 MeV was previously unreported.

Angular distributions for the observed states in $^{20}\text{O}$ appear in Figure 10, where the left column shows known $L=2$ transitions, and the right panel shows pure $L=0$ as well as one mixed $L=0$ and 2 transition (from [24]). The curves represent the results of DWBA calculations with for the appropriate angular-momentum transfers; in the case of the 1.67 MeV $2^+$ excited state the fit to the sum of $L=0$ and 2 is also shown. The resulting relative spectroscopic factors, expressed as shell-model occupancies, appear in the right panel. The uncertainties here are statistical and for the relative values are approximately 10% for each transition. The spectroscopic factors are in very good agreement with the predictions of shell-model calculations using three different interactions. More details concerning this measurement are given in [24].
4.3. The structure of the halo nucleus $^{14}$B from the $^{14}$B(d,p)$^{15}$B reaction

The nucleus $^{14}$B is the lightest $N=9$ isotope that is still particle bound in its ground state. The neutron binding energy is only 0.969 MeV, and expectations based on the inversion of the $1s_{1/2}$ and $0d_{5/2}$ orbitals observed in $^{15}$C as compared to $^{15}$O, as well as the results of knockout reactions [27] strongly suggest that the wave function for the $2^-$ ground state is largely dominated by a $1s_{1/2}$ neutron configuration, making it an obvious one-neutron halo candidate. The $^{14}$B level spectrum is not well known; most information comes from a heavy-ion charge exchange study, and the similarity of levels in $^{12}$B populated with the same reaction to the results for $^{14}$B [25]. The sd-neutron states of interest

Figure 9. (Left panel) Energy-position correlation spectrum for protons from the $^{19}$O(d,p)$^{20}$O reaction. (Right panel) $^{20}$O excitation-energy spectrum (from [24]).

Figure 10. (Left panel) Proton angular distributions from the $^{15}$O(d,p)$^{20}$O reaction. (Right panel) Orbital vacancies $G_+$ from spectroscopic $(d,p)$ spectroscopic factors deduced from the angular distributions shown on the left (from [24]).
should have negative parity, formed by the coupling of a $0p_{3/2}$ proton hole with either a $1s_{1/2}$ neutron producing $J^e=2^-$ and $1^-$, or a $0d_{5/2}$ neutron making $J^e=(1,2,3,4)^-$. Some configuration mixing is also expected for the $2^-$ and $1^-$ states (the $0d_{5/2}$ orbital is expected to be unimportant at low excitation energies). Information about these excitations can be obtained from the $^{13}\text{B}(d,p)^{14}\text{B}$ neutron-transfer reaction.

We have studied this reaction using the techniques described above. This measurement was more challenging due to the difficulty in producing a $^{13}\text{B}$ beam; at ATLAS the only way to produce an intense enough beam of $^{13}\text{B}$ is by proton pickup from $^{14}\text{C}$, and all such reactions have very negative Q values near -15 MeV. We chose the $^{9}\text{Be}^{(14}\text{C},p)^{10}\text{B}$ reaction due to the increased center-of-mass energy afforded by the less inverse nature of that reaction as compared to $(d,^3\text{He})$. The energy of the $^{13}\text{B}$ was 15.7 MeV/nucleon, and the intensity ranged between 2 and $4 \times 10^4$ particles per second. At this writing, the data are still being analyzed, but preliminary results indicate that four narrow states at low energy are populated, corresponding to the four lowest negative-parity states reported in compilations. Figure 11 shows a preliminary excitation-energy spectrum from the $^{13}\text{B}(d,p)^{14}\text{B}$ reaction. The $2^-$ ground state and $1^-$ first-excited state appear from events where the protons are detected in coincidence with identified $^{14}\text{B}$ ions (filled histogram) and above the neutron-emission threshold in $^{14}\text{B}$ the $3^-$ (1.38 MeV) and $4^-$ (2.08) MeV levels are also present. The reported broad $2^-$ state at 1.86 MeV \cite{26} is not observed, however it is expected to be populated with a cross section similar to that of the ground state so that it would be buried under the much stronger $3^-$ and $4^-$ states. At higher excitation energies, even pure $0d_{5/2}$ states become broad and disentangling the spectrum of broad levels becomes more complicated. That work remains in progress.

![Figure 11. Preliminary $^{14}\text{B}$ excitation-energy spectrum from the $^{13}\text{B}(d,p)^{14}\text{B}$ reaction. The filled (solid) histogram corresponds to events with protons detected in coincidence with $^{14}\text{B}$.](image)

Preliminary angular distributions for the four narrow states appear in Figure 12, with curves obtained from DWBA calculations carried out with optical-model parameters that describe the elastic scattering of protons and deuterons at 30 MeV from $^{12,13}\text{C}$. The ground state shows mixed $L=0$ and 2 character, while the first-excited $1^-$ state seems to be essentially pure $L=0$ with a very small $L=2$ component. The $3^-$ and $4^-$ angular distributions are consistent with pure $L=2$ transitions as expected. The corresponding relative spectroscopic factors extracted from a comparison of the data and the DWBA calculations also appears in Figure 12, plotted with the predicted values from shell-model calculations done using the WBP interaction \cite{28}. Although the excitation energies and level
ordering are not in precise agreement with experiment, the calculated spectroscopic factors agree well with the preliminary experimental values. The uncertainties are dominated primarily by the fitting uncertainty, and the normalization is determined by fixing the spectroscopic factor for the $3^-$ transition to 1.0. That normalization is chosen on the basis of the shell-model calculations which suggest a less than 5% contribution to that state from $0d_{3/2}$ configurations. These preliminary results support the contention that the ground and first-excited states of $^{14}$B are excellent one-neutron halo excitations, as had been suggested earlier from studies of neutron knockout from $^{13}$B [27], and as might have been expected from the neutron binding energies.

Figure 12. (Left panel) Preliminary angular distributions from the $^{14}$B($d,p)^{13}$B reaction. The curves are DWBA calculations as described in the text; for the $2^-$ and $1^-$ states the solid lines correspond to the sum of $L=0$ (dashed) and $L=2$ (dot-dashed) contributions. For the $3^-$ and $4^-$ states the curves represent pure $L=2$ transitions. (Right panel) theoretical (top) and experimental (bottom) spectroscopic factors. The position of the unobserved broad $2^-$ state is indicated in the bottom panel by the open symbol.

4.4. The $^{136}$Xe($d,p)^{137}$Xe reaction – towards $^{132}$Sn($d,p)^{133}$Sn

One of the earliest motivations for constructing HELIOS was to study the single-particle behaviour of heavier nuclei near closed shells, and one obvious candidate is the doubly-closed-shell nucleus $^{132}$Sn that has attracted intense recent interest. Data for the $^{132}$Sn($d,p)^{133}$Sn reaction have been reported [29],[30]. The low bombarding energy of that measurement (4.5 MeV/nucleon) precluded any information being obtained about high-$j$ orbitals. $^{132}$Sn beams at energies above the Coulomb barrier are not yet available from ATLAS, however they are expected soon from the CARIBU (CALifornium Rare Isotope Breeder Upgrade) device [31] being commissioned at that facility. HELIOS has been used to study reactions with another N=82 beam, $^{136}$Xe. The $^{136}$Xe($d,p)^{137}$Xe reaction has also been studied previously in inverse kinematics[7], however results were shown only for the lowest 3 levels. In order to examine the trends of single-neutron states for N=83 isotones, we have studied the $^{136}$Xe($d,p)^{137}$Xe reaction in HELIOS. These data demonstrate that the HELIOS approach works well
for heavy, as well as light beams, and that HELIOS is well situated for use with $^{132}$Sn beams when they become available at ATLAS.

Figure 13 shows data from the $^{136}$Xe($d,p$)$^{137}$Xe reaction obtained with HELIOS, at a bombarding energy of 10 MeV/nucleon so as to enhance the population of higher angular-momentum orbitals. These data were obtained without recoil detection; even so the kinematic loci appear clearly over a background produced by fusion-evaporation reactions on the $^{12}$C in the 80 $\mu$g/cm$^2$ thick (CD$_2$)$_n$ target. The corresponding excitation-energy spectrum appears as the bottom panel in Figure 13. Despite the high density of states many levels are clearly resolved.

Figure 13. (Top panel) Energy-versus-position correlation spectrum for the $^{136}$Xe($d,p$)$^{137}$Xe reaction at 10 MeV/u and 2 T. (Bottom panel) Excitation-energy spectrum for the $^{136}$Xe($d,p$)$^{137}$Xe reaction. The spin assignments are based on the analysis of angular-distribution data shown in Figure 14 (From [32]).

Angular distributions for several states populated in the $^{136}$Xe($d,p$)$^{137}$Xe reaction appear in Figure 14, with curves from DWBA calculations described in [32]. Several transitions with angular-momentum transfers of $L=1$, 3, 5, and 6 are identified. The deduced spectroscopic factors were used to determine the $h_{9/2}$ and $i_{13/2}$ single-particle excitation energies as shown in the right panel of Figure 14. The results follow the trends of higher-$Z$ $N=83$ isotones, and in particular the splitting between the $i_{13/2}$ and $h_{9/2}$ orbitals are in agreement with expectations based on our current understanding of the influence of the tensor force in this region. Details of these results may be found in [32].
Figure 14. (Left panel) Angular distributions from the $^{136}$Xe$(d,p)^{137}$Xe reaction. (Right panel) single-particle excitation energies and orbital splittings deduced for different N=83 isotones. Results from the current measurement are shown as the open symbols (from [32]).

5. Summary
The results obtained from HELIOS since August 2008 have shown that this new approach to the study of reactions in very inverse kinematics is viable, and can provide high-quality data that might be difficult to obtain using other methods. In addition to the results described here, HELIOS has been used to study alpha-particle transfer with ($^6$Li,$d$) reactions, and reactions that produce light reaction products emitted in the forward hemisphere such as ($d$, $^3$He) and ($d$, $t$). A number of technical additions are in progress, including gas detectors for heavy recoils, and a cryogenic gas target for reactions on $^{3,4}$He. It is anticipated that reaction studies with fission-fragment beams from CARIBU will soon commence, extending the reach of the device towards the $^{132}$Sn region. Finally, other implementations of this technique are now under consideration at laboratories around the world. We anticipate that this new approach to reactions in inverse kinematics will remain a powerful scientific tool for some years to come.

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