HELIOS: A new concept for studies of light-ion reactions with radioactive beams

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Much of the detailed knowledge about the structure of nuclei near the line of beta stability was obtained in studies of transfer and inelastic scattering reactions using light-ion beams and stable or long-lived targets. As radioactive beams are becoming available at a number of facilities around the world, including the CARIBU facility at Argonne, such studies can now be extended to nuclei away from the line of β-stability, vastly expanding the range of accessible isotopes. To achieve this goal, measurements have to be done in inverse kinematics, resulting in a conventional detection scheme in large-area detectors and a loss of the effective experimental resolution. The HELIOS spectrometer is based on a new concept, that is especially well suited for such studies by reducing the resolution problem, providing ready particle identification, and high detection efficiency with moderate Si detector area. In this talk, I will discuss the HELIOS concept and present results from the first series of experiments.

1. A little history

With the introduction of the Nuclear Shell Model by Mayer and Jensen [1], it has been a central theme in Nuclear Physics to study single-particle orbits in excited nuclei throughout the nuclear chart. During the following decades, much experimental work at laboratories and universities throughout the world resulted in detailed information on the single-particle structure, strength, spin-parity assignments of excited states in both spherical nuclei at or near the closed shells and the deformed nuclei that fall in-between them.

Concurrently, a rapid development of experimental facilities and techniques took place at many research centers. With the introduction of commercial Van de Graaff Tandem accelerators of ever increasing terminal voltage, precision beams of light particles became available and the development and proliferation of high-resolution magnetic (Bruekner, Enge Split-Pole, Elbek, Multigap, and Q3D) spectrometers meant that the tools needed to carry out experiments with the high energy resolution needed to study and resolve the excitations in nuclei across the periodic table were also in place. In addition, the discovery of direct nuclear reactions by Butler [2], its elaboration in terms of the Distorted Wave Born Approximation [3, 4], and the significance of spectroscopic overlaps by French and Macfarlane [5] established elegant connections between the theoretical concepts and the experimental observables. The extension of the understanding of single-particle structure to deformed nuclei by S.G. Nilsson [6] gave a more complete picture of all accessible nuclei.

The availability of separated isotopic material of high enrichment from the Stable Isotopes Division at Oak Ridge National Laboratory and the development of techniques to fabricate thin targets allowed researchers to measure excitation spectra with an energy resolution of down to 3-5 keV, in the early days using

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photographic films as the recording medium. Although the literature contains information on virtually all nuclei that can be reached with light charged particle reactions on stable or long-lived targets, the record is not always complete and/or the data analysis method for a series of isotopes in a region was not sufficiently uniform to study systematic trends of *e.g.* the single-particle strength distribution. Recent systematic measurements were thus carried out in the Sn region and in N=82 nuclei [7, 8].

During the 1970s there was a strong shift of interest toward research using heavy-ion beams and the more traditional, detailed nuclear spectroscopic studies using light-ion induced reactions tended to be abandoned by researchers in this field. At present there are only a couple laboratories where such studies can be continued.

2. Opportunities with radioactive beams

Over the last decade, radioactive heavy-ion beams, away from the line of β-stability, have begun to be available for studies of nuclear structure. In many cases, projectile fragmentation beams can be used for such studies via nucleon knock-out reactions to obtain information about particle orbits below the Fermi surface. To conduct detailed studies of single particle states above the Fermi surface, beams at energies comparable to the Coulomb barrier are needed. Such beams can be provided as secondary beams produced in flight [9] or as re-accelerated beams of ions extracted from a primary ^{252}Cf fission source at the CARIBU facility at Argonne [10] or from production targets bombarded with high-intensity primary beams at HIE-ISOLDE at CERN [11], the HRIBF facility at Oak Ridge National Laboratory [12], at TRIUMF [13], and several other institutions. In the near future, relatively intense, re-accelerated precision beams of the latter type will be provided at several new facilities, namely Spiral-2 at Ganil and FRIB at Michigan State University will also start operating.

Many of these new beams of radioactive nuclei will have sufficient intensity to allow studies of their single-particle structure via transfer reactions with light targets. The scientific thrust into these areas is driven by a desire to probe the predictive power of present nuclear structure models, search for changes in the single particle structure when the N/Z ratio is substantially different from that at the line of β-stability and when the Fermi levels for protons and neutrons are severely unbalanced. Another aspect is the relevance of this information for Nuclear Astrophysics. The rapid neutron-capture r-process is, for example, strongly affected by the structure of neutron-rich nuclei near the N=82 shell. Of course, measurements of ground state properties of such neutron-rich nuclei (masses and half-lives, etc.) requires only a low production rate and can therefore be extended far into the neutron-rich region, and maybe even out to the r-process path in some areas.

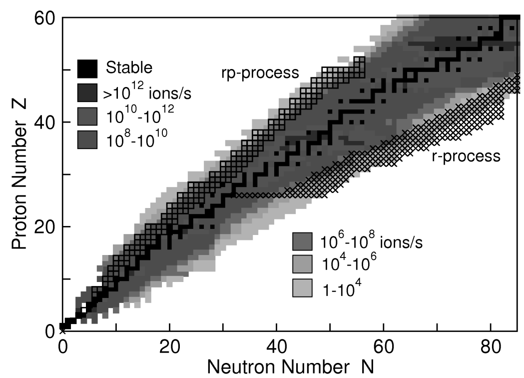

FIG. 1: This figure shows the intensities of re-accelerated beams that can be expected with 400 kW 200 MeV/u primary beams such as the planned FRIB facility. The map also indicates the expected location of the rp and r-processes.

By their nature, studies that require interactions with nuclei in a thin target, Coulomb excitation and transfer reaction studies, and which can provide detailed information about the excited states in such nuclei, require higher beam intensities, around 10^3 to 10^4 ions/s to be feasible. As shown in Fig. 1 the region of the nuclear chart where beam intensities of sufficient magnitude are projected for a fa-

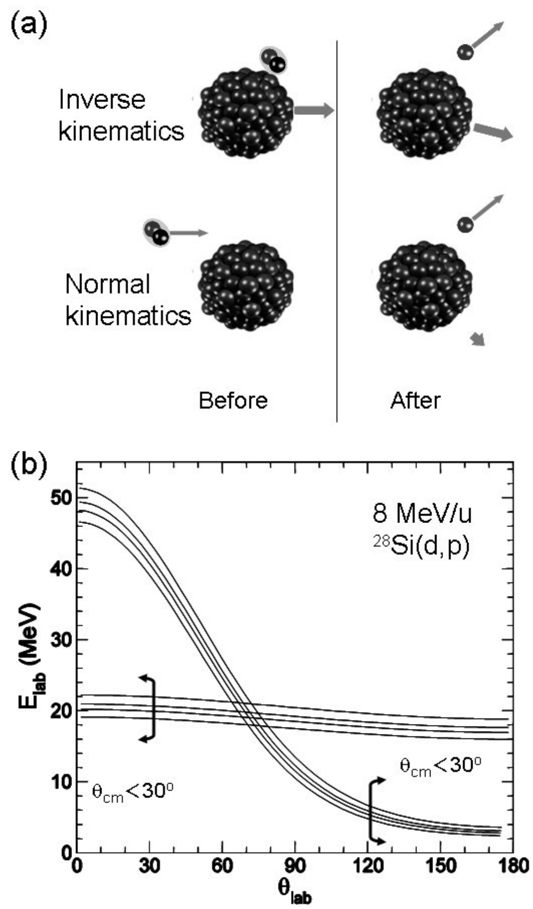

FIG. 2: Panel a: Illustration of "inverse" and "normal" kinematics reactions involving a simple neutron transfer. Panel b: Kinematic curves are shown for both "normal" and "inverse" kinematics for the ^{28}Si(d,p) reaction with a beam energy of 8 MeV/u in both cases.

cility such as FRIB [15], is very substantial. The beam intensity at existing [9, 12, 13] facilities as well as those that will start operation before FRIB [11, 16] will already allow for studies of less exotic nuclei as exemplified in a recent measurement of the single-neutron strength outside the doubly magic ^{132}Sn by Jones *et al.* [18].

3. Reactions in inverse kinematics

In order to take advantage of the many new exotic nuclei that are becoming available as re-accelerated beams, it is necessary to conduct experiments in inverse kinematics, *i.e.* where the radioactive, heavy beam is incident onto a light target. This situation changes the experimental situation dramatically, because of the large center-of-mass velocity of the scattering system, which is similar to that of the beam. An example of the kinematic curves is given in Fig. 2 for the reaction d(^{28}Si,p)^{29}Si as compared with the "normal" kinematics for ^{28}Si(d,p)^{29}Si. In normal kinematics, the energy of the outgoing proton corresponding to the ground state and the three lowest excited states in ^{29}Si, varies only little as a function of angle in the laboratory frame of reference. In contrast, a strong variation with angle, exceeding a factor of ten, is seen for inverse kinematics, which places severe demands on the detection: 1) for the angles corresponding to forward scattering in the center-of-mass system, $\theta_{c.m.} < 30°$, that are of interest for angular momentum transfer determination, protons have only very low energies in the laboratory, which render the standard ΔE-E technique of particle identification very problematic, 2) the energy interval between the various excitations in the ^{29}Si nucleus is strongly reduced, by a factor ∼2.4 relative to that observed in "normal" kinematics. These properties of the inverse kinematics situation severely limit the number of nuclei that can be studied. Although it has been demonstrated that systems with widely spaced excited states, many light systems and nuclei near shell closures, can be explored with normal detector systems [17, 18] it is clear that higher Q-value resolution is needed for nuclei in most of the new territory that is being made available with radioactive beam facilities, and that new techniques are required. This has led to the development at Argonne of a new type of spectrometer, the Helical Orbit Spectrometer, that circumvents the main difficulties with inverse kinematics, listed above. In the following section I'll describe the principle of the HELIOS concept and discuss its imple-

TABLE I: Cyclotron periods of light charged particles in a magnetic field of strength B=2 Tesla.

Particle	T_{cyc} (ns)
p	32.8
d,α	65.6
t	98.4
^{3}He	49.2

mentation.

4. The HELIOS Spectrometer

The concept of HELIOS is based on the fact that charged particles follow helical trajectories in a homogeneous magnetic field. If the magnetic field is aligned with the beam axis, see Fig. 3, the particles will return to the axis, provided that the magnetic field is strong enough to avoid collisions with the vacuum envelope of the magnet. The flight time until it returns to the axis is the cyclotron period, $T_{cyc} = 2\pi m/qeB$, where m/q is the charge to mass ratio of the particle and B is the magnetic field strength. Since the flight time scales with m/q of the particle one obtains automatic particle identification for a range of light charged particles, such as protons, tritons, and ^{3}He. Deuterons and α-particles have the same flight-time, but in many cases they will not overlap. Cyclotron periods corresponding to a typical magnetic field strength of 2 T, given in Table I, are long enough that particle identification can be achieved rather comfortably with reasonable time resolution.

Particles emitted in the backward hemisphere return to the axis upstream of the target whereas forward emitted particles return downstream. Position-sensitive Si detector arrays may be placed at either location to register the time-of arrival, t, energy, E, and longitudinal position, z, where the particle strikes the detector. The upstream array must be hollow to allow the beam to reach the target, whereas this requirement does not necessarily apply for a downstream array. However, in many cases it is advantageous to detect, in

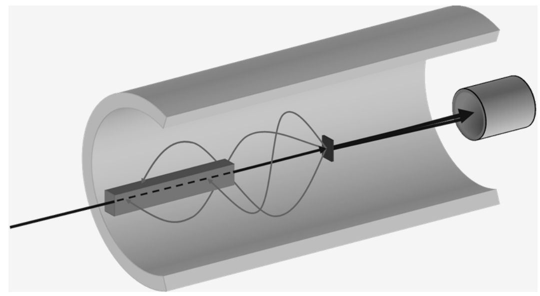

FIG. 3: Schematic illustration of the HELIOS concept. Beam enters from the left through a hollow tube that is supporting position sensitive Si detectors on the outside. Particles emitted from the target follow helical trajectories in the co-axial solenoidal magnetic field and return to the beam axis, some of them being intercepted by the Si detector array. Recoils may be detected in a detector located at very forward angles.

coincidence, the heavy beam-like recoils in detectors positioned at small angles, so even in these cases a hollow array is called for.

There is a simple relation between E, z, and the center-of-mass energy of the particle, E_{cm}, namely

$$E_{c.m.} = E + \frac{m}{2}V_{cm}^2 - \frac{V_{cm}qeB}{2\pi}z, \qquad (1)$$

where V_{cm} is the laboratory velocity of the center-of-mass system, a quantity that is known for the reaction. It is important to note that, unlike the situation in a normal setup, the coefficient in front of E is unity, which means that the measured level spacing is the same as what would be observed in the center-of-mass system. This feature effectively removes the detrimental effects of the inverse kinematics situation. The kinematic loci for different excitations in the nucleus are therefore straight lines for which the particle energy increases with z (positive downstream) with a slope that scales with $V_{cm}qB$ as illustrated for the d(^{28}Si,p) reaction at 6 MeV/u in Fig. 4.

The fact that no kinematic compression occurs when the particles are transported in a magnetic field arises because particles corresponding to different states emitted at the

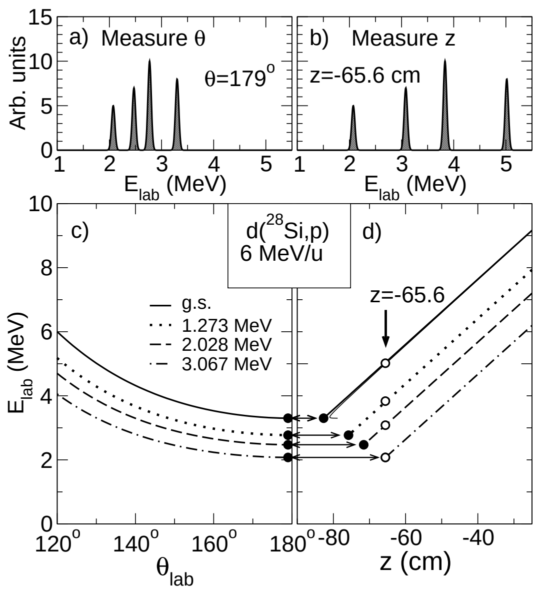

FIG. 4: Illustration of the improved Q-value resolution of the HELIOS concept exemplified by the d(^{28}Si,p) reaction populating the ground state and the first three excited states in ^{29}Si. The ^{28}Si beam energy is 6 MeV/u, and the assumed combined effects of target thickness and intrinsic energy resolution is $\Delta E = 75$ keV FWHM, for which the upper panels show simulated energy spectra for the emitted protons if measured either at a fixed angle θ=179° (panel a) or a fixed z-position, z=-65.6 cm (panel b). Panels c and d, demonstrate that particles corresponding to different excitations emitted at a particular angle are intercepted by the Si detector at different z-positions when transported in a 2T, co-axial, homogenous field (solid points). By performing the energy measurement at a specific z-position instead (open circles) the level spacing corresponding to that in the center-of-mass system is restored. The thin curve in panel d for the g.s. gives the 'hook' effect by intercepting the particles at a realistic radial distance of 1.4 cm.

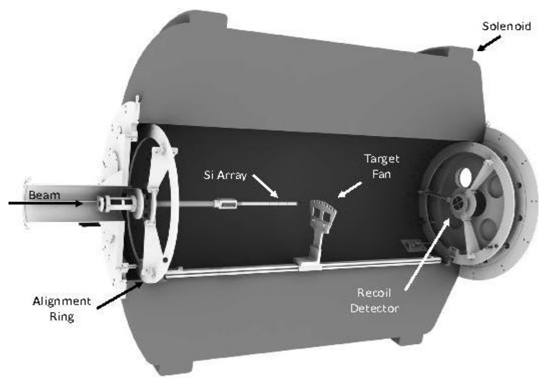

FIG. 5: Computer aided design rendering of the HELIOS spectrometer identifying the beam entrance, the Si detector array that is mounted onto an alignment ring, the target "fan" as well as of the recoil Si detector telescope.

same laboratory angle returns to the beam axis (or the detector array) at different distances z from the target as shown in Fig. 4.

A spectrometer based on this concept has recently been built at the ATLAS facility at Argonne National Laboratory. The main component is a large bore superconducting solenoid that was obtained from a decommissioned Magnetic Resonance Imaging scanner. This solenoid is able to generate a homogeneous magnetic field region over a cylindrical volume of diameter 90 cm and 100 cm in length. The strength of the magnetic field can be set up to 2.85 Tesla. The solenoid is mounted such that the magnetic field axis is coaxial with the beam. Fortunately, the end flanges, which were designed to support various RF and field gradient coils used for the MRI scanning, were such that they could be fitted with large vacuum covers that allowed the whole inside bore of the magnet to be evacuated by pumping through the 20 cm diam. beam-pipe. Support structures inside the magnet allow for the mounting of the hollow Si detector array at backward angles and a target "fan", both of which can slide longitudinally to allow for optimal coverage of the interesting region of particle emission, see Fig. 5. The design also allows for mounting of various detectors to register the coincident heavy recoils, shown here as a Si detector telescope. Another recoil detector system consisting of an x-y position sensitive PPAC backed by a co-axial Bragg curve spectrometer has been built, but this system has yet to be commissioned.

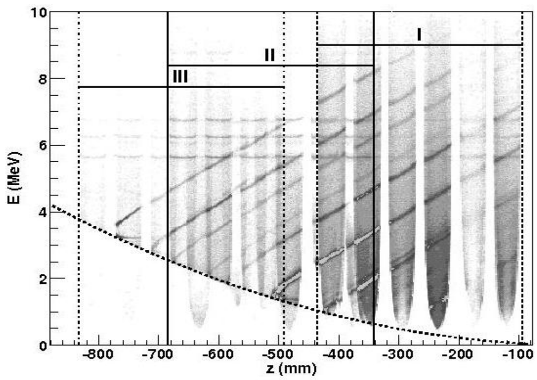

FIG. 6: Two-dimensional map of proton energy vs. the position of impact relative to the target position. The sloping lines on the map show the kinematic loci corresponding to the ground state and several excited states in ^{29}Si, whereas the horizontal lines correspond to alpha particles from a ^{228}Th source used for calibration purposes.

5. Commissioning experiment

After completion, the HELIOS spectrometer was commissioned in August 2008 by measuring the d(^{28}Si,p) reaction leading to states in ^{29}Si with strong single-particle (neutron) components. A two-dimensional map of the proton energy measured in the Si detector array as a function of position z is shown in Fig 6. As expected, one observes that the kinematic loci corresponding to the ground state and excited states in ^{29}Si fall on parallel, almost linear curves. Because of the finite transverse dimension of the Si detector array, particle trajectories are intercepted before reaching the axis. This leads to a nonlinear effect for trajectories corresponding to emission angle close to the beam axis.

Because of the limited longitudinal extent of the Si-detector array, $\sim$35 cm, this map is a composite of three different settings (indicated by roman numerals) of the distance from the target to the array. Also notice the deviation from a line at the lower end of the kinematic curves mentioned abbove.

Because of the properties of the spectrometer, discussed in Sect. 4, the Q-value resolution of 80 keV observed in this experiment has contributions only from target thickness effects, beam spot size and the intrinsic Si detector energy and position resolution; see Ref. [20] for further details.

6. Initial physics experiments

Encouraged by the positive results of the commissioning experiment, we have subsequently embarked on a series of physics measurements utilizing this device with both stable and radioactive beams produced by the inflight technique at ATLAS.

A. ^{12}B(d,p)

The first example is a study of the d(^{12}B,p) reaction populating excited states in ^{13}B in an attempt to separate two positive-parity states at E_{exc} = 3.48 and 3.68 MeV, which it had not been possible to separate in an earlier attempt with normal detectors [21]. In this experiment [22], the radioactive ^{12}B beam was produced via a (d,p) reaction of the 81 MeV primary ^{11}B beam with an intensity of 50 pnA in a cryogenic deuterium gas cell which resulted in a secondary ^{12}B beam of approximately 10^5 ions/s at 75 MeV. The ^{12}B ions were focused and separated from the primary beam using various beam-line elements [9] and brought into the HELIOS spectrometer to react with a 73 μg/cm^2-thick CD_2 target. A Si detector telescope covering the forward angular range θ=0.5°-2.8° consisting of 80 μm thick ΔE and 500 μm thick E detectors was used to measure ^{13}B recoils in coincidence with the protons from the (d,p) reaction that were detected in the Si detector array positioned upstream of the target. The primary ^{11}B beam was also used, at a reduced intensity, to measure the ^{11}B(d,p) reaction to excited states in ^{12}B at E_{exc}=2.62 and 3.39 MeV, which correspond to proton energies close to those for the ^{13}B doublet over the entire angular range. This measurement provided reference angular distributions used to normalize those measured for the ^{13}B doublet and allowed us to determine the angular momentum transfer and spectroscopic factor for the two members of the E_{exc}=3.48 and 3.68 MeV doublet, see Fig. 7.

From these measurements it is clear that the 3.48 MeV member of the ^{13}B doublet is pop-

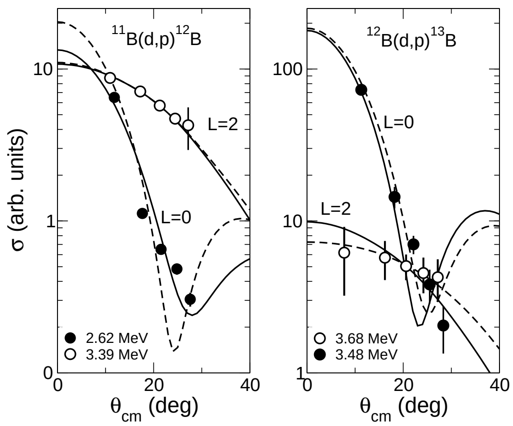

FIG. 7: The angular distributions for the ^{11}B(d,p)^{12}B reaction to the two states at E_{exc}= 2.62 and 3.39 MeV populated via L=0 and L=2 transfer are shown in the left panel. The known L=2 transition to the E_{exc}= 3.39 MeV state was used for normalization of the angular dependence of the detection efficiency. The solid circles are the HELIOS data for the L=2 transition to the 3.39-MeV state and the open circles are the L=0, 2.62-MeV state. The solid lines and the dashed lines are DWBA calculations with two different sets of parameters. On the right, the data for the ^{12}B(d,p)^{13}B doublet at 3.48 and 3.68 MeV are shown with the same normalization. The conventions on the symbols and curves are the same as on the left-hand side.

ulated by L=0 transfer since it is very similar in shape to that of the 2.62 MeV ^{12}B state, while the much weaker 3.68 MeV member appears to be reached by L=2 transfer. From these results and an analysis of the relative spectroscopic factors of the two states it appears that the E_{exc}= 3.48 MeV and 3.68 MeV states in ^{13}B correspond to the expected $1/2^+$ and $5/2^+$ states in this nucleus, respectively. However, with this assignment, the spectroscopic factor for the $5/2^+$ state is significantly weaker than predicted by theory.

B. ^{15}C(d,p)

Recent results on electromagnetic transition rates between states in ^{16}C have let to the speculation that this nucleus has an exotic structure. A measurement of the B(E2) value for the $2^+_1 \rightarrow 0^+$ transition [24] using the Coulomb-nuclear interference method in ^{208}Pb+^{16}C scattering thus obtained a B(E2) of 0.28±0.06 W.U. leading to the suggestion that the 2^+_1 state is a pure valence neutron excitation. In addition, a direct lifetime measurement of the $2^+_1 \rightarrow 0^+$ transition using a recoil-shadow technique [25] obtained a result that corresponds to a B(E2)-value of 0.26 W.U. in agreement with the scattering result. In contrast with these results, a more recent measurement of the lifetime of the 2^+ state using a fusion reaction to populate states in the ^{16}C system obtains a result which corresponds to B(E2)-value of 1.73±0.30 W.U. [26], consistent with theoretical expectations for even-even closed shell systems in this area and which does not require "exotic" interpretation of the structure of the 2^+_1 state in ^{16}C. With this background, it was felt that it might be advantageous to use a different experimental technique to explore the structure of the ^{16}C system.

Using an intense, 100 pnA ^{14}C beam of energy 133 MeV, a secondary ^{15}C beam was generated via the (d,p) reaction in a cryogenic gas cell in the ATLAS In-flight radioactive beam setup [9]. With this method we obtained a 123 MeV^{15}C-beam with intensity in the 1-2×10^6 ions/s. This beam was transported to the HELIOS spectrometer impinging on a 110μg/cm^2 CD_2 target. The detection of protons and coincident ^{16}C recoils was carried out in a manner similar to the ^{12}B(d,p) experiment described above (see Ref. [23] for details).

The resulting angular distributions for scattering into the lowest excitations in ^{16}C are displayed in Fig. 8 along with DWBA calculations using four different Optical Model potentials. These comparisons lend strong support to the previously tentative assignment of 0^+ to the third excited state at E_{exc}=3.017 MeV, since it is seen to be populated via an L=0 transfer, as is the ground state. From the relative spectroscopic factors for the lowest-lying states one finds excellent agreement with shell-model calculations [27], which also correctly account for the latest measurement of the B(E2;$2^+_1 \rightarrow 0^+$) transition matrix element [26]. Our ^{15}C(d,p) results thus lends strong support to a standard Shell model description of this nucleus and appears to be at variance with an "exotic" picture of its structure.

7. HELIOS Upgrades

Since its commissioning in 2008, the HELIOS spectrometer has performed a number of (d,p) neutron transfer experiments with both stable and radioactive beams in addition to the two examples discussed here. However, in order to take full advantage of the capabilities of the spectrometer, several additional upgrades are required. Thus, the addition of a gas target will allow for studies with ^{3}He and α induced reactions, which will significantly broaden the scope of the HELIOS scientific program. Such a target system, using LN_2 to cool and increase the density of the He-gas, has been designed and is presently being manufactured. It is expected to be available for use in early 2011. Also, the Si-detector telescope used in the examples described above will not allow for detection and identification of heavier recoils, as will be needed for studies involving neutron-rich radioactive beams that will soon become available from the CARIBU [10] injector to ATLAS. In its place, a new recoil detector system consisting of an x-y position sensitive PPAC detector backed by an axial Bragg Curve spectrometer has been constructed at Manchester University and will soon be available for use in experiments. Finally, the hollow Si-detector array used to date was assembled from existing position-sensitive detectors of varying quality. Since the angle and longitudinal efficiency of this array is not optimized, a new Si detector system is under development, see Fig. 9. It is a modular system that allows for mounting standard five-detector modules in different configurations onto liquid-cooled Al frames to suit the different requirements of a wide range of possible experiments. Indi-

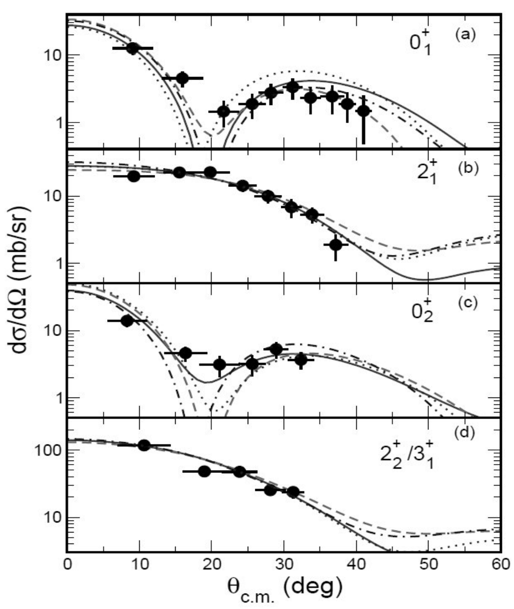

FIG. 8: The angular distributions for the ^{15}C(d,p)^{16}C reaction to the 0^+ ground state (panel a), the first excited 2^+ state (panel b), the second excited 0^+ state (panel c), and the unresolved $2^+/3^+$ doublet (panel d) are shown along with DWBA calculations using four different Optical model potentials. The error on the cross sections are statistical only and do not include contributions from systematic uncertainties (see Ref. [23] for details).

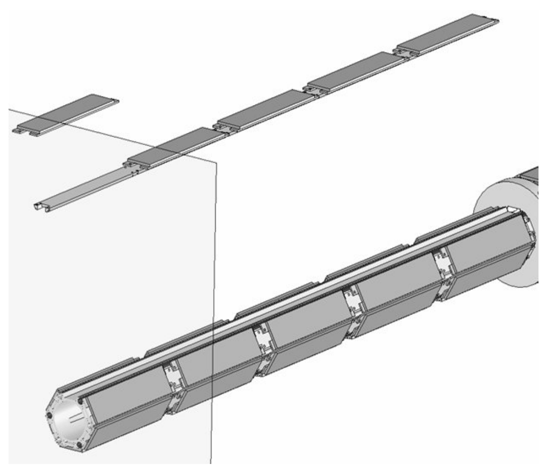

FIG. 9: Computer aided design rendering of the new Si-detector system showing the mounting of detector modules onto a liquid cooled, hollow Al frame, a five detector module as well as a single Si detector, which can be removed and replaced if necessary.

vidual Si wafers can be removed and replaced such that degraded detectors will not compromise the operation of the spectrometer. Aside from extending the overall acceptance of the spectrometer, these new modules can be mounted either upstream and/or downstream of the target as required for the different experiments. With these new upgrades, HELIOS will become a very versatile and efficient spectrometer that will allow us to take full advantage of both existing and new radioactive beam capabilities at ATLAS to study light-ion transfer reactions over a wide range of the nuclear chart.

8. Summary

Historically, the study of light-ion transfer reactions has provided extensive nuclear structure information on nuclei close to the line of β-stability, where such studies can be carried out with stable or long-lived targets in normal kinematics. However, to obtain similar information for the wide range of nuclear species that has or will become available in radioactive beam facilities, such studies must be carried out in inverse kinematics, which leads to severe limitations in terms of Q-value resolution when normal techniques are applied. In this talk I have shown that the HELIOS concept, in which light charged particles are transported in a homogenous magnetic field to a hollow Si detector array located on the beam axis, resolves this particular problem and also allows for both high detection efficiency and easy particle identification. The Argonne HELIOS spectrometer was commissioned in August 2008 and the advantages of this technique was successfully demonstrated. Since then, we have performed a number of studies of (d,p) reactions in inverse kinematics. I have briefly discussed the d(^{28}Si,p)^{29}Si commissioning experiment as well as two published studies involving radioactive beams produced in-flight at the ATLAS facility. In the d(^{12}B,p)^{13}B study, the improved Q-value resolution was crucial for separating two excited positive-parity states and study their structure. The d(^{15}C,p)^{16}C experiment was the first study of this reaction and it helped validate the theoretical understanding of this nucleus in terms of the modern shell model. In addition, I have described several future upgrades of the spectrometer, which will allow for additional improvements in detection efficiency and reliability with a new Si detector system, allow for the use of gaseous targets, and enable coincident recoil detection in heavier systems with the addition of a new recoil detector system.

Acknowledgments

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