HELIOS – progress and possibilities

B P Kay[1], M Alcorta[2], B B Back[2], S I Baker[2], S Bedoor[3], T Bloxham[4], J A Clark[2], C M Deibel[2,6], S J Freeman[5], C R Hoffman[2], A M Howard[5], J C Lighthall[2,3], S T Marley[2,3], A J Mitchell[5], K E Rehm[2], J P Schiffer[2], D K Sharp[5], D V Shetty[3], J S Thomas[5], A H Wuosmaa[3], and S Zhu[2]

[1] Department of Physics, University of York, York YO10 5DD, United Kingdom
[2] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[3] Physics Department, Western Michigan University, Kalamazoo, MI 49008, USA
[4] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[5] Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom
[6] Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA

E-mail: `benjamin.kay@york.ac.uk`

Abstract. The helical orbit spectrometer, HELIOS, at Argonne National Laboratory has been developed to measure transfer reactions in inverse kinematics with good Q-value resolution. The technique is discussed alongside examples of measurements with medium-mass beams, the first exploration of reactions in the the forward hemisphere, and a future outlook.

1. Introduction

Direct single-nucleon adding and removing reactions, pair transfer, and inelastic scattering are powerful probes through which to study nuclear structure. From them, information such as single-particle energies, spectroscopic factors, pairing correlations and collective degrees of freedom can be extracted. These properties form the basis of our understanding of nuclear structure. These reaction techniques have been used in the stable-beam and -target domain for many years, with great success. The excellent resolution provided by magnetic spectrometers, such as Enge split-pole spectrometers and Q3Ds, was key to this success. However, the combinations of available beams and targets are to some extent now exhausted. What remains are precision tests and systematic studies. To extend our reach with direct reactions, one can look to radioactive ions beams, of which many current (proposed) facilities can now (will soon) provide at useful energies and intensities. In this regime, reactions such as those listed above, have to be performed in inverse kinematics, where the heavy radioactive ion beam impinges a light stable target.

The study of single-nucleon transfer reactions in inverse kinematics is well developed; the first example of such studies was by Kraus *et al.* in the early 1990s [1] with the (d,p) reaction induced by stable ^{132,136}Xe beams. Many radioactive-beam measurements have been made since with light- to medium-mass beams (for example, see Refs [2, 3, 4, 5]). Common to all these experiments is the placement of Si detectors at fixed angles in the laboratory, typically, but not exclusively, in a 'barrel' arrangement with a composite of position-sensitive detectors

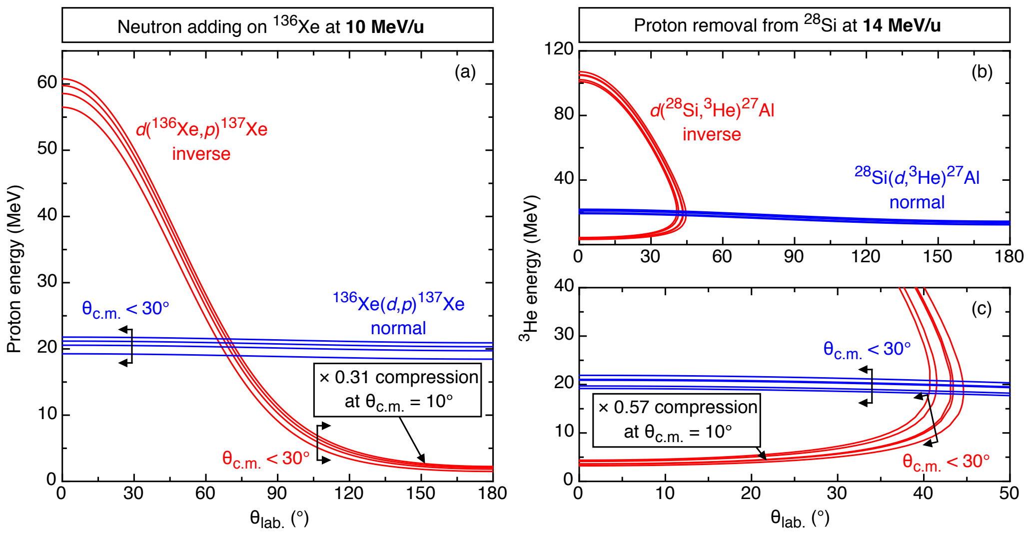

Figure 1. (Colour online) (a) Kinematic lines of proton energy versus $\theta_{\text{lab.}}$ for the $d(^{136}\text{Xe},p)$ reaction at 10 MeV/u following population of the 0, 601, 1218, and 2510-keV states in ^{137}Xe in both normal (blue) and inverse (red) kinematics. (b) Similar lines for ^{3}He ions following population of the 0, 884, 1015, 2212, and 2735-keV states in ^{27}Al via the $d(^{28}\text{Si},^{3}\text{He})$ reaction at 14 MeV/u, with (c) focussing on the forward centre-of-mass angles to emphasise the two-solution nature of negative Q value reactions in inverse kinematics.

surrounding the target and annular detectors up and downstream of the target. Such examples are TIARA [6], T-REX [7], ORRUBA [8], and SHARC [9]. Often these have been coupled with simultaneous γ-ray measurements. Common to all these measurements is the poor Q-value resolution inherent in the inverse kinematics regime. This makes such measurements challenging, often limiting the amount of useful information one can extract from the data. These challenges are discussed below, followed by a description of the technique exploited by HELIOS and how it ameliorates some of these problems.

2. The challenges of transfer reactions in inverse kinematics

The outgoing proton energy as a function of laboratory angle following the (d,p) reaction on ^{136}Xe at 10 MeV/u is shown in Fig. 1(a) for both the 'normal' and inverse kinematics regimes. The challenges associated with reactions in inverse kinematics are a consequence of the large centre-of-mass velocity of the scattering system. This has the following consequences:

- A strong proton-energy dependence with respect to laboratory angle referred to as kinematic shift. This demands a high angular granularity when measuring proton energy as a function of laboratory angle which is referred to as the *conventional* approach hereafter.
- A significant kinematic compression, or *differential* kinematic shift, at forward centre-of-mass angles (typically those of interest). This is effectively the degree to which the resolving power is diminished for a given laboratory-frame resolution. This cannot be recouped through higher angular granularity in a chosen detection system. The example shown in Fig. 1(a) has a compression factor of 0.31 at $\theta_{\text{c.m.}} = 10°$ implying two states separated by 1 MeV in the centre-of-mass frame are separated by only 310 keV in the laboratory frame. The excitation-energy resolution thus suffers by this factor.

- At forward centre-of-mass angles the proton energy is lowered due to the kinematic shift. This can provide a challenge to conventional ΔE–E telescopes for particle identification.

A further complication is added when the reaction has a negative Q value, such as (d,t) and $(d,{}^3\mathrm{He})$. This results in a double-valued kinematic solution about $\theta_{\mathrm{max.}}$ in the laboratory frame. In the example given in Fig. 1(b,c), the ^{3}He ion does not scatter beyond $\theta_{\mathrm{lab.}} = 44.6°$, the point where the centre-of-mass velocity exceeds the velocity of the ^{3}He ion (given by $\tan\theta_{\mathrm{max.}} = 1/\sqrt{(V/\bar{v})^2 - 1}$; V is the centre-of-mass velocity of the system and $\bar{v}$ is the velocity of the outgoing ion in the centre-of-mass frame [10]). Dealing with this can be particularly challenging for fixed laboratory-angle measurements. Note also that in the low-energy solution of the outgoing ion corresponding to population of the ground state is *lowest* in energy in the laboratory frame, with subsequent excited states appearing at higher energy unlike the positive Q value reactions.

3. The HELIOS approach

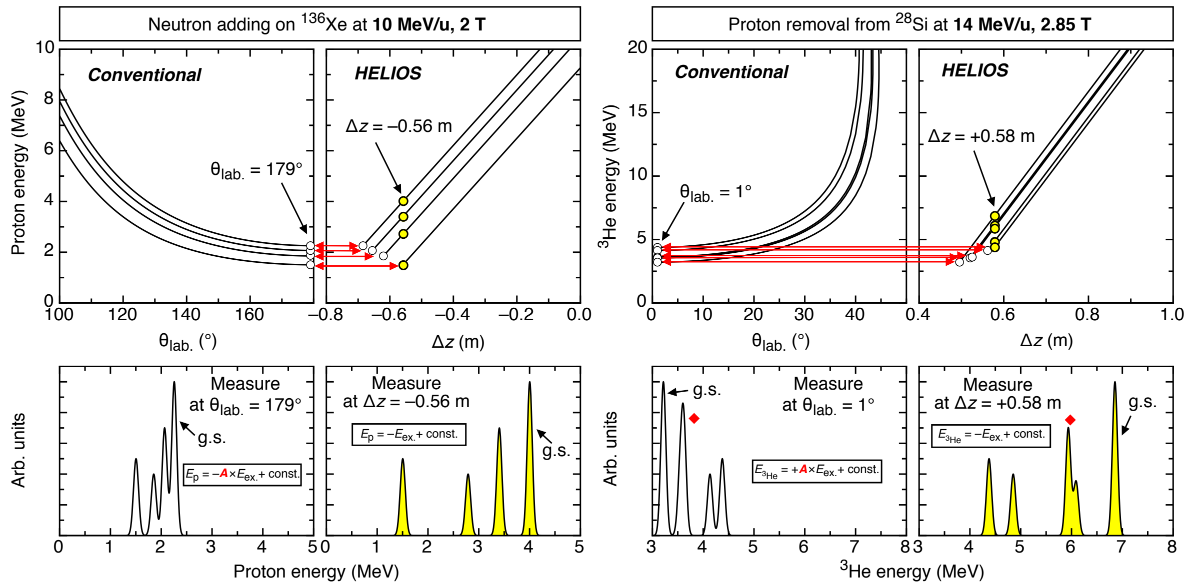

Figure 2. (Colour online) (Top) An illustration of how a solenoid translates the kinematical curves in energy versus $\theta_{\mathrm{lab.}}$ into energy versus Δz for positive Q-value $d({}^{136}\mathrm{Xe},p)$ reaction at 10 MeV/u and 2 T (left) and for the negative Q-value $d({}^{28}\mathrm{Si},{}^3\mathrm{He})$ reaction at 14 MeV/u and 2.85 T (right). (Bottom) The respective projections are for a corresponding fixed $\theta_{\mathrm{lab.}}$ and Δz. The striking feature is the absence of kinematic compression using the solenoidal technique. For these simulated projections, a 100-keV FWHM in the laboratory frame is assumed to account for intrinsic Si resolution and target effects in both cases.

The approach exploited by the HELIOS spectrometer [11, 12] avoids the complications associated with the conventional approach, that is, determining the energy of the outgoing ion as a function of the longitudinal velocity component. This is achieved by transporting the outgoing ions in the homogenous magnetic field of a superconducting solenoid. The outgoing ions describe helical trajectories, returning to the magnetic axis which is coincident with the beam axis, after one cyclotron period. Surrounding the axis is an array of position-sensitive Si detectors. These record the position the ion hits the array, its energy, and time with respect to the radio frequency structure of the beam. These three properties are sufficient to provide all the information needed, such as $\theta_{\mathrm{c.m.}}$, $E_{\mathrm{c.m.}}$, and m/q.

Figure 2 illustrates the advantages of this approach for typical positive- and negative-Q-value reactions. These are summarised as follows:

- There is no kinematic compression. The excitation energy in the laboratory frame is related to the centre-of-mass frame by only an additive constant. This results in a improvement in Q-value resolution by a factor of ∼2–4 (bottom panels of Fig. 2).
- The kinematic shift is linear in Δz and modest. For a typical (d,p) measurement at 2 T, this slope is <15 keV/mm in Δz. The position resolution of the present Si array is ∼1 mm.
- The characteristic cyclotron period of outgoing ions, which is independent of their energy, is used as particle identification. Ions with energies as low as ∼200 keV can be readily identified.
- For negative-Q-value reactions, the two solutions are 'unfolded' about $\theta_{\mathrm{max.}}$ into a simple sloping line in E versus Δz (top, right panel of Fig. 2).

It should be noted that if the same laboratory-frame resolution was to be achieved by both a conventional and HELIOS measurement (i.e. accounting for intrinsic Si resolution, beam and target effects, and angle versus Δz effects), the conventional approach would still have poorer Q-value resolution as a consequence of kinematic compression. This is intimately linked to resolving power.

The HELIOS spectrometer was commissioned in 2008 with the stable-beam $d(^{28}\mathrm{Si},p)$ reaction at 6 MeV/u with a 2-T field [12] achieving a Q-value resolution of ∼100 keV. It was followed by light radioactive-beam measurements of the $d(^{12}\mathrm{B},p)$ reaction at 6.24 Mev/u and 1.05 T [13]. Here a 73-μg/cm^2 thick CD_2 target was used and a resolution of ∼100 keV FWHM achieved. This can be readily compared to a study of the same reaction using a conventional Si detector arrangement where a Q-value resolution of ∼250 keV was obtained [14]. The $d(^{15}\mathrm{C},p)$ reaction was also studied, at 8.2 MeV/u and 2.85 T with the beam impinging a 110-μg/cm^2 thick CD_2 target yielding a Q-value resolution of 140 keV [15]. The radioactive beams were produced via the in-flight technique at the ATLAS accelerator [16]. In the near future, the CAlifornium Radioactive Isotope Breeder Upgrade (CARIBU) [17] at the ATLAS facilty will allow the acceleration of ^{252}Cf fission fragments. Of particular interest will be (d,p)-reaction studies with beams in the vicinity of ^{132}Sn. Consequently, we have tested the performance of HELIOS with stable beams in this mass region. We also initiated the first exploration of deuteron-induced negative Q-value reactions as part of the ongoing assessment of the capabilities of HELIOS.

4. (d,p) reactions with medium-mass beams

In early tests we performed the $d(^{86}\mathrm{Kr},p)^{87}\mathrm{Kr}$ [18] and $d(^{136}\mathrm{Xe},p)^{137}\mathrm{Xe}$ [19] reactions at 10 MeV/u in a 2-T field. For both, the aim was to determine the single-particle energies of high-j states, the $\nu g_{7/2}$ and $\nu h_{11/2}$ outside $N = 50$ in the case of ^{87}Kr, and the $\nu h_{9/2}$ and $\nu i_{13/2}$ outside $N = 82$ for ^{137}Xe. These complement simultaneous (previous) studies of the solid, stable $N = 51$ isotones [18] ($N = 83$ isotones [20]). The (d,p) reaction on these isotopes has been studied before, but using complex gas-cell targets. HELIOS provided an attractive alternative. The experimental details and results of these measurements can be found in Refs [18, 19]. By way of example, for the ^{136}Xe measurement, a schematic of the experimental set up can be seen in Fig. 3(a). Here, an on-axis Faraday cup in combination with a Si detector were used to determine the luminosity and monitoring target thickness in order to extract absolute cross sections. To cover the required angular range, two different target-array distances were used as can be seen in Fig. 3(b). A typical excitation-energy spectrum is shown in Fig. 3(c) demonstrating a resolution of ∼100 keV.

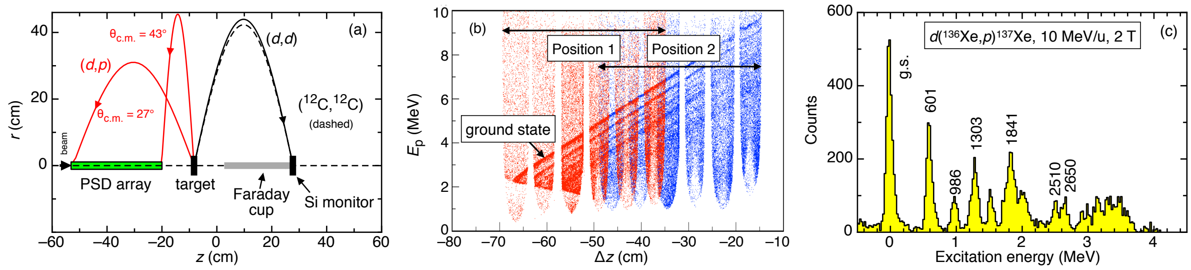

Figure 3. (Colour online) (a) Schematic of the set up for the $d(^{136}\text{Xe},p)$ measurement at 10 MeV/u and 2 T. Sample trajectories are given in the r–z plane. (b) Proton energy versus Δz spectrum gated on the respective proton-energy-versus-RF-time spectra. (c) Excitation-energy spectrum for states in ^{137}Xe. The complete results of this measurement can be found in Ref. [19].

5. Deuteron-induced negative-Q-value reactions

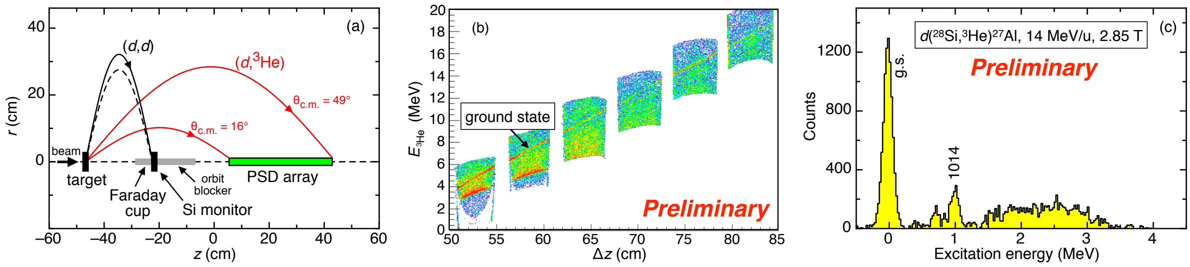

Figure 4. (Colour online) (a) Schematic of the set up for the $d(^{28}\text{Si},^{3}\text{He})$ measurement at 14 MeV/u and 2.85 T. Sample trajectories are given in the r–z plane. (b) Preliminary ^{3}He energy versus Δz spectrum resulting from energy-specific gates applied to the respective ^{3}He-energy-versus-RF-time spectra. (c) Preliminary excitation-energy spectrum for states in ^{27}Al.

To test the performance of HELIOS with the array placed downstream of the target, the stable-beam $d(^{28}\text{Si},^{3}\text{He})$ and $d(^{28}\text{Si},t)$ reactions were studied at 14 MeV/u at a maximum field strength of 2.85 T. The analysis of these data is still in progress. The following discussion focusses on the $(d,^{3}\text{He})$ measurement. A schematic of the experimental set up, a ^{3}He versus Δz spectrum, and an excitation-energy spectrum of ^{27}Al are shown in Fig. 4. A 250-μg/cm^2 target was used to enhance the yield due to the lower cross section of the $(d,^{3}\text{He})$ reaction compared to the (d,p) reaction. As a consequence, a resolution of only ∼170 keV was achieved. The main obstacles here are the significant proton and α-particle backgrounds from fusion-evaporation reactions of the beam and target. However, the excellent timing resolution allows one to gate on ^{3}He ions with little contribution from the tails of the dominant proton and α particles peaks. A preliminary analysis indicates both measurements were successful, which opens up the possibility of using these reactions to explore exotic nuclei through in-flight produced radioactive beams at the ATLAS facility.

6. Conclusions and future outlook

HELIOS proves to be a powerful and flexible instrument for studying transfer reactions in inverse kinematics as has been demonstrated in early experiments with light in-flight produced radioactive beams [13, 15], medium-mass beams [18, 19], and deuteron-induced negative-Q-value

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reactions. An excitation-energy resolution of <100 keV has been demonstrated for beams up to mass 136. The key to this improvement in resolution over conventional methods is the removal of kinematic compression by the mapping of $\theta_{\text{lab.}}$ onto a target-array distance Δz by means of a solenoidal field.

Shortly a gas-cell target will be available for the study of such reactions as charge-exchange via (^{3}He,t), and proton-adding via e.g. (^{3}He,d) and (α,t), the latter being of interest for populating high-j single-proton states in, e.g. ^{133}Sb. Also of interest are (α,p) reactions to constrain astrophysical reaction rates and complement the work of Ref. [21]. Further developments include a new modular, multi-configuration array designed to maximise solid-angle coverage and provide flexibility when additional recoil detectors are required. A Bragg chamber and PPAC, developed by the University of Manchester, is due to be commissioned. This will offer another recoil detection and identification technique, particularly useful for low-intensity CARIBU beams.

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