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Letter of Intent to the
ISOLDE and Neutron Time-of-Flight Experiments Committee
for experiments with HIE-ISOLDE

A HELIcal Orbit Spectrometer (HELIOS) for HIE-ISOLDE

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Abstract

The potential for a HELIcal Orbit Spectrometer at ISOLDE is discussed.

1. Introduction and Physics Case

Direct nuclear reactions have been traditionally used to determine a host of nuclear properties that are not easy to address using other reactions or decay processes. These range from basic level spectroscopy to single-particle, pairing, collective and cluster properties. Such reactions are important as they exhibit an inherent selectivity, connecting initial and final states in a single step by accessing a particular degree of freedom. The reaction mechanism is well studied and well understood, allowing a relatively transparent connection of experimental observables with underlying physics in a quantitative fashion. Single-nucleon transfer reactions have been critically important in establishing single-particle models in near stable nuclei; pair transfer has played a similar role in the understanding of pair correlations; inelastic scattering was necessary to probe collective modes not readily accessible via other methods; transfer of larger groups of nucleons has been used to characterize states with distinct cluster structures.

The exploration of nuclear structure away from the stability line is a major interest in contemporary nuclear physics and new facilities are being developed to produce beams of exotic nuclei as a tool for such research, in many cases with intensities that are useful for making direct nuclear reaction studies ($\gtrsim 10^4$pps). Direct reactions will play a critical role in the quantitative understanding of various issues in the development of nuclear structure in exotic systems that cannot be provided in other ways: elucidating the development of single-particle states with changing neutron excess; investigation of the development of pair correlations in exotic systems; probing new collective modes and exotic cluster states.

ISOLDE is an important facility in this respect due to wide range of beam species that have been developed over many years. The development of HIE-ISOLDE with the availability of higher beam energies, up to 10 MeV/u, provides an ideal opportunity to harness this facility for direct reaction measurements. The higher beam energies are important in several aspects. Firstly, it will allow studies of direct reactions on heavier beam species with improved yield. Higher energies also tend to reduce the influence of non-direct processes in the reaction mechanism, making quantities such as spectroscopic factors, which are extracted from measured cross sections on the basis of a single-step mechanism, more robust. In addition, the angular distributions of reaction products tend to become more distinctive of the angular momentum transferred in the reaction at higher beam energies, facilitating spin assignments of populated levels.

With radioactive ion beams, it is necessary to perform experiments in inverse kinematics using a light target. The centre of mass (CM) of the system has a much higher velocity in the laboratory frame compared to traditional approaches with light stable beams on stable targets. This results in a situation where the lab energies of the emitted light ions are small at the angles of interest, usually forward directions in the centre-of-mass system. Problems arise with particle identification using standard ΔE-E methods due to the low energies. Q-value resolution can be difficult because of the associated reduced energy dispersion, up to factors of five. Compounding this, at larger angles, the particle energy varies strongly with angle, which places severe demands on the angular resolution of the detectors. The HELIcal Orbit Spectrometer (HELIOS), recently developed at Argonne National Laboratory (ANL) [1], represents a new approach to measurements of light ions from nuclear reactions that avoids all the drawbacks of conventional approaches discussed above. HELIOS has been successfully commissioned [2] and used in experiments [3], demonstrating some considerable advantages in terms of resolution, acceptance and simplicity of operation. This Letter of Intent is presented as a description of the HELIOS concept and its requirements in order that the developments at HIE-ISOLDE will allow the use of such a spectrometer, should the opportunity arise in the future.

2. Experimental setup

The HELIOS spectrometer is based around large-bore high-field superconducting solenoid (field up to 3T), with its axis aligned with the beam, as shown systematically in Figure 1. The beam passes through a hollow array of position-sensitive silicon detectors before hitting the target near the centre of the spectrometer. Light-ions emitted in the reaction are transported via helical orbits back to the axis where they are detected in a position-sensitive silicon array. Silicon arrays can be operated forward or backward of the target, the choice being made on the kinematic characteristics of the reaction to be studied. Beam-like recoiling ions can be detected in coincidence, if needed, using a recoil detector at the end of the solenoid.

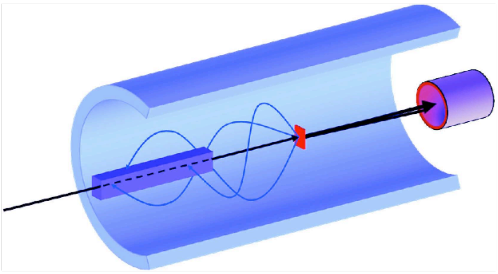

Fig. 1. A schematic illustration of the HELIOS concept. (Beam enters from the left.)

The ions return to the beam axis after a period equal to their cyclotron period $T_{CYC}(ns)=65.6\times A/qB$ where A is the mass in amu, the magnetic field B in Tesla and q is the charge state, so a measurement of the time-of-flight of the ion determines A/q. The other important experimental quantities are the ion energy E_{LAB} and the distance from the target z at which the particle is returned to the axis, measured in the Si array. The return distance z is determined by the component of the velocity parallel to the axis $v_P=z/T_{CYC}=V_{CM}+v_0\cos\theta_{CM}$, where V_{CM} is the velocity of the centre-of-mass system, v_0 and θ_{CM} are the velocity and emission angle of the particle in the centre-of-mass frame. The particle energy in the laboratory and CM frames are then related by a simple linear relationship: $E_{CM}=E_{LAB}+mV_{CM}^2/2-zmV_{CM}/T_{CYC}$.

The separation in laboratory energy between kinematic groups corresponding to different energy levels in the residual nucleus at a fixed z is equal to the spacing in the CM frame. This approach therefore removes the kinematic Q-value compression as well as the broadening across a detector opening angle, issues which limit conventional approaches of detectors at fixed angles. The energy resolution in the HELIOS concept is largely determined by the intrinsic energy and position performance of the position-sensitive Si array, although tempered by other effects such as beam energy spread, energy losses in the target and beam spot size. There are other advantages to the technique. The surface area of silicon needed is much smaller than a conventional array of the same solid-angle coverage, leading to fewer electronic channels, lower cost and easier operation. The magnetic field also eliminates a large class of backgrounds such as electrons and scattered beam particles.

As an example of the quality of data from recent experiments with heavy beams using the HELIOS device at ANL is shown in Figure 2, which demonstrates that superior Q-value resolution can be obtained with this device.

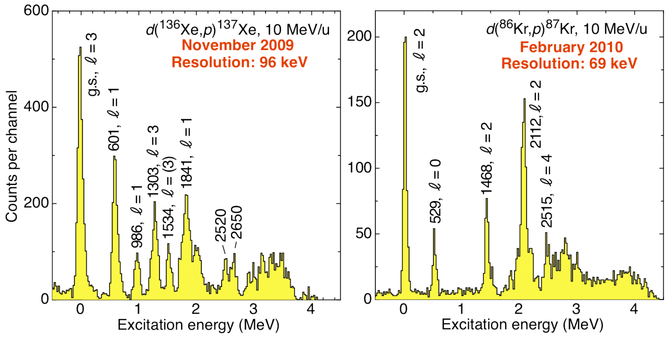

Fig. 2. Excitation energy spectrum from the d(^{86}Kr,p)and the d(^{136}Xe,p) reactions using the HELIOS spectrometer at Argonne National Laboratory.

3. Beam and infrastructure requirements

The performance of a HELIOS detector at ISOLDE is assessed with respect to the projected beam characteristics for the HIE-LINAC, available on the web page.

Ultimately, the Q value resolution of any device is set by the longitudinal emittance of the beam. For HELIOS, it is velocities that are important and the expected beam energy spread of 0.9% will impose a limit of ~90 keV to the energy resolution using a beam of A=100, for example. Other contributions to the energy resolution are lower than this component. Contributions to the Q-value resolution due to the silicon detector position and energy resolution are both of the order of 50 keV or lower. The transverse beam spot size maps to a spread in the return distance along the array and has a contribution to the energy resolution that depends on the lab scattering angle. A beam spot size of 5 mm diameter is estimated to contribute less than 90 keV between 30 and 150° in a worst-case scenario of a 10 MeV/u beam and a 3-T field. This estimate is consistent with experimental observations with the ANL-HELIOS where a radioactive boron beam, produced using in-flight methods with intrinsically poor emittance, was collimated by a 5-mm aperture [3]. Beam spots of 5-mm diameter can therefore be accommodated without compromise to the resolution, and, when combined with the need to transport the incoming beam through the upstream hollow Si array, set the beam acceptance of the device. The current ANL Si array has a beam acceptance of ~10 π.mm.mrad. The quoted normalized transverse beam emittance of better than 0.3π.mm.mrad for the HIE-LINAC, and the relativistic factor βγ~0.15 for 10MeV/u beams, implies that the actual beam emittance, 2π.mm.mrad, is sufficient to transport a HIE-ISOLDE accelerated beam into a HELIOS device without significant loss of intensity. Furthermore, the experience of transporting in-flight boron beams at ANL indicates that the strong magnetic field may help suppress small transverse excursions.

It is *essential* for particle identification to be able to measure the time of flight of the spiraling light ions. The identification does not present difficulties in terms of time resolution, where ~1 ns can be tolerated, as different *A/q* are generally separated by intervals of the ~20 ns, depending on the exact field used. However, the currently specified 10-ns repetition rate presents significant difficulties. The provision of a multi-harmonic pre-buncher device to clear 100-ns periods, without significant beam loss, would be required here and for many other experiments where time-of-flight is important.

A HELIOS-type spectrometer would occupy a total footprint of approximately 6.5 by 4m^2, including the size of the magnet and room for access.

Experience at Argonne suggests that liquid helium consumption is approximately 250 litres per month, although there are additional losses when the magnet is powered up or down. It may be advantageous to consider integrating this into the accelerator refrigeration system.

Potential developments could allow additional measurements of γ rays at the target position using $LaBr_3$ detectors with photodiode readout, similar to simultaneous MRI/PET technology in medical imaging.

4. Safety aspects

The main safety aspects are the presence of a strong magnetic field and operations with liquid helium. However, the solenoid magnet is similar, or could indeed be identical to, those used for MRI scanners in hospitals and therefore should not present insurmountable difficulties, particularly as correction coils are typically installed to minimize fringe fields.

5. References

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3. B. B. Back et al. Phys. Rev. Letts. 104, 132501 (2010)