HELIOS: New Results and Future Developments

Benjamin P. Kay, Physics Division, Argonne National Laboratory
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HELIOS: a new approach to studying transfer reactions in inverse kinematics*
(and potential for the use of a HELIOS-like spectrometer at HIE-ISOLDE)

Benjamin P. Kay
The University of York

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Overview

Inverse kinematics, HELIOS
- Direct reactions with RI beams
- HELIOS at the ATLAS facility

Recent highlights
- Inelastic scattering, Isomer beams

Upgrades, ISS and SOLARIS
- Better hardware: HELIOS’s new siblings
Transfer reactions

- An essential probe of nuclear structure
- Energies, angular momentum, overlaps
- (High-resolution detectors developed accordingly)
- Direct reactions, well understood models
- Highly selective
- (Over 50-60 years experience)
- Count rates Beams, nA-μA

- ~pre-90s, technique limited to stable systems
  - Few doubly-magic systems studied
  - Limited to changes of ~12 neutrons/protons excess
  - Poor overlap with nuclei involved in astrophysical processes
Direct reactions with RI beams

10 MeV/u (5-20 MeV/u), >10⁴ pps

- **single-particles states**, $E_{(\text{ex, spe})}$, $l$-values, spectroscopic factors, e.g., $(d, p)$, ...

- **pair correlations**, e.g., $(p, t)$, $(t, p)$, $(^3\text{He}, p)$, ...

- **Collective properties** via, e.g., $(p, p')$, $(d, d')$, $(\alpha, \alpha')$, ...

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**Diagram:**
- Pairing
- Occupancies
- Collectivity
- Vacancies
- Pairing
Excellent Si arrays have been developed, with high angular granularity, large acceptance, and (often) coincident gamma-ray detection, e.g., MUST2 (GANIL), T-REX (ISOLDE), SHARC (TRIUMF), ORRUBA (ORNL, elsewhere), TIARA (GANIL, Texas A&M), etc.

**Kinematics: normal vs inverse**

**Inverse-kinematics challenges:**

- Particle identification, ΔE-E techniques more challenging at low energies
- Strong energy dependence with respect to laboratory angle
- Kinematic compression at forward c.m. angles (in fact nearly all angles)
- Typically leading to poor resolution (100s of keV)
- ... and beams a few to $10^6$ orders of magnitude weaker (than stable beams)
Transport through a solenoidal field

\[ E_{\text{cm}} = E_{\text{lab}} + \frac{m}{2} V_{\text{cm}}^2 - \frac{m V_{\text{cm}} z}{T_{\text{cyc}}} \]

And the cyclotron period gives provides particle ID.
HELIOS (it works)

- Up to 2.85 T superconducting solenoid
- ~250 cm overall length
- 90-cm diameter
- Adjustable in z
- 35-cm prototype position-sensitive Si array
- e.g. Protons from \((d,p)\)
- e.g. Recoil

Beam

ATLAS, home to HELIOS

Comment on AIRIS

**Stable beams** at high intensity and energies up to ~20 MeV/u

**In-flight beams** approx. 10 < A < 30 at energies up to ~20 MeV/u

**CARIBU beams** at low intensity and energies up to ~15 MeV/u

**Low energy beams** for trap measurements

**State-of-the-art instruments**

*upcoming instruments / capabilities*
ATLAS, e.g. beams (2015)

- **54 unique beams**
  - **37% resulting in a RIB on target**

- **CARIBU** (24%)
- **In-flight** (13%)
- **Stable** (59%)
- **AMS** (4%)

From the report on ATLAS at the Low Energy Community Meeting 2016, Notre Dame, G. Savard
A highly versatile instrument

- **Major research programs** from UConn, LANL, LSU, etc. Others include Berkeley, Lowell, CMU, Manchester, ...
- **Apollo, gas target, ion chamber**, backwards / forwards / all routine
- Use of **tritium** target

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**13B(d,p)**

**10B(p,p')**

**18N(d,p)**

**19O(d,p)**

**136Xe(d,p)**

**15C(d,p)**

**12B(d,p)**

**14,15C(d,α)**

**14,15C(d,3He)**

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**86Kr(d,p)**
Recent highlights

**Goal:** Improve long standing uncertainties in the $\alpha$-decay branch of the second ($T=1$) $2^+$ state in $^{10}$B

Why? Contributes to $B(E2)$ value, which have been used as precision tests of ab-initio calculations of the $A=10$ isospin triplet

A new technique n HELIOS ...

Mass 10 triplet

Status of Uncertainties:

- Width (7%)
- Alpha-particle branching ratio (25%)
- $\gamma$-decay branching ratio: (25%)

Gyürky et al., EPJA 21(2), 355 (2004).

‘Downstream’ mode

- $^{10}$B beam (stable) at 10 MeV/u
- Thin CH$_2$ target
- 'All' recoils detected, including those following decay of the recoil
- Method allows multiple analysis techniques

Branch ratio

Challenging measurement. Alpha branching ratio now better constrained after some 50 years …

… a follow-up measurement with Gammasphere constrain E2 gamma branch
Isomer beams, studying $^{19}\text{F}$

Transfer reactions are highly selective in $I$ transfer

How do the valence nucleons (single-particles) contribute to each state of this rotational band?

Cannot study via transfer on the 0+ ground state of $^{18}\text{F}$ …

D. Santiago-Gonzalez et al. (2017)
Isomer beams

$^{18}\text{F}$ has a $5^+$ isomeric state at around 1.1 MeV.

Probing high-j states via low-l transfer.

Can populate every member of the rotational band in $^{19}\text{F}$ via $l=0$ and 2 transfer.

D. Santiago-Gonzalez et al. (2017)
Production

$^2\text{H}(^{17}\text{O},^{18}\text{F})\text{n}$

15 MeV/u

$\sim 5 \times 10^5$ pps

$^{18}\text{mF}/^{18}\text{gF}=0.58$

At HELIOS

$^{18}\text{m,F(d,p)}^{19}\text{F}$

14 MeV/u

$^{18}\text{mF}/^{18}\text{gF}=0.11$

(11/2$^+$ at higher ex)

D. Santiago-Gonzalez et al. (2017)
Excellent agreement with shell-model calculations (perhaps not surprisingly).

Powerful technique, many future possibilities ($^{26}\text{Al}$, $^{34}\text{Cl}$, etc)
HELIOS going forwards

New 6-sided Si array, new digital DAQ (based on Gammashpere/Gretina/GRETA digitizers)

The Argonne In-flight Radioactive Ion Separator (AIRIS), improved in-flight beams

CARIBU beams, e.g., $^{134}\text{Te}(d,p)$, $^{144,146}\text{Ba}(d,d)$, ...

Tritium target, and so on.

[Tritium-target tests, Kuvin, Wuosmaa (2017)]
Primary beam from ATLAS, a few to 20 MeV/u, <few pμA

Provide in-flight beams to all experimental areas downstream of ATLAS, with up to \(x100\) increase in yield, and access to higher mass beams.

See e.g. http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis
Estimated Beam Rates at AIRIS Exit

- Particles / sec
  - \( >10^7 \)
  - \( >10^6 \)
  - \( >10^5 \)
  - \( >10^4 \)
  - \( >10^3 \)
  - \( >10^2 \)

- Up to \( \times 10 \) uncertainty in rate estimates
- Up to \( \times 100 \) increase of in-Eight production yields following facility upgrades

- Weak cross-section measurements — astro / fusion
- Pairing in Nuclei
- Single-Particle Structure
- Possibly fusion-evap. with e.g. \( ^{38}\text{Ca}, ^{42}\text{Ti}, ^{56}\text{Ni} \) beams

See e.g. [http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis](http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis)
ISS @ HIE-ISOLDE

10 MeV/u beams opens up the possibility of a major direct-reaction program at ISOLDE ... ISS being developed

Chart of nuclides taken from talk by Liam Gaffney
Early physics opportunities

\( N = 127 \) isotones below Pb

- **Terra incognita.** Below Pb, around \( N = 126 \), very little known (limited knowledge on masses, decays).
- Evolution of single-particle states has not been explored in nuclei around \( ^{208}\text{Pb} \) as these require radioactive ion beams.
- Data on \( 2^+ \) and \( 3^- \) in even nuclei allows us to make some assumptions.
- Few / no theoretical studies on single-particle excitations.
Early physics opportunities

The $^{206}\text{Hg}(d,p)$ reaction at 10 MeV/u using the ISOL Solenoidal Spectrometer (ISS)

Why (close to) 10 MeV/u?
- Cross sections
- Angular momentum matching
- Angular distributions

Why ISS?
Resolution
- Charged-particle spectroscopy with <100-keV Q-value resolution using thin targets

Efficiency
- Limited only by geometrical acceptance, not intrinsic efficiency of the detectors.

Direct probe of excited states
- Does not require coincident $\gamma$-rays de-exciting the states (\(\therefore\) no concerns with isomers*, ground state, states not connected by $\gamma$-ray decay, etc).

*Isomers prevalent in the region around Pb
Cross sections estimated using DWBA code Ptolemy using standard parameterizations.
In collaboration with ANL

For potential 2018 experiments, $^{28}\text{Mg}(d,p)$ and $^{206}\text{Hg}(d,p)$, the HELIOS digital DAQ and Si array will be shipped to CERN in 2018.

Shorter ‘test’ Si-array to be shipped in spring/summer for stable beam tests.
SOLARIS at NSCL/FRIB

Will operate in dual modes, like the ISS.

http://www.anl.gov/phy/group/solaris
SOLARIS

Website and white paper available shortly (email me if interested). Anyone is welcome to join us.

http://www.anl.gov/phy/group/solaris
Summary

Solenoidal spectrometers are a valuable tool for studying direct reactions in inverse kinematics with Q-value good resolution
- ‘Simplicity’
- Efficiency
- Versatility
- Resolution

Demonstrated with a ~10-year program with HELIOS at ATLAS

… BUT, the beams are king
- AIRIS upgrade at ATLAS, CARIBU beams …

… ISS at HIE-ISOLDE and SOLARIS at FRIB (ReA)