Transfer reactions before, and with, HELIOS

Or - “...seems like an awful lot of work just to do (d,p)...”

Congratulations ATLAS! Happy 25th!
Prologue:
Long before ATLAS...

Detailed survey of single-particle states in $p$-shell nuclei with $(d,p)$.

Wouldn’t it be nice to go further?!
Two faces of transfer reactions—Facilitated by ATLAS

• Heavy-ion transfer
  – e.g.: \((A+n,p) + B \rightarrow A + (B+n,p)\) where \(A, B\) are heavy ions.

• Light-ion transfer
  – e.g.: \((d,p)\) in inverse kinematics with RIBs

• Each demands:
  – High energies for heavy ions (E/A up to 10+ MeV)
  – Large variety of ions
  – High intensity and variability
The Enge Split-Pole spectrograph - The textbook picture

Dimensions of the Split-Pole Spectrograph are shown in the drawing where trajectories of particles with two different Bp's are indicated.
The experimentalist’s view...
Mass resolution

expected on the basis of previous studies. The large cross sections observed in our experiments for the neutron-pickup reactions could also have influence on other channels. It would be interesting to investigate correlations between neutron-transfer and fusion cross sections for systems where a strong entrance-channel dependence for $\sigma_{\text{fusion}}$ has been observed.\textsuperscript{15}

Characteristic angular distributions for elastic, inelastic scattering, and transfer.
Sub-barrier fusion enhancement

FIG. 2. Experimental and theoretical cross sections for complete fusion. Data symbols have the same meaning as in Fig. 1. Smooth curves represent generalized liquid-drop-model calculations (Ref. 15).

Strong entrance-channel dependence of fusion enhancement

Coupling of transfer channels, in addition to inelastic excitations, is an essential key to understanding HI fusion enhancement (H. Esbensen and S. Landowne)
dPtr/dD inconsistent with BE: "slope anomaly" with BE: "slope anomaly"

Expect PTR~e-2αD

Prc

Ser 255, 316 (1991)

narrow, universally works!
Why stop at 1 or 2n?!  
6 (!) neutron transfer

Just some of the many papers!
RIBS at ATLAS and nucleon transfer

• Problem: how do we study single-particle states via \((d,p)\) with unstable nuclei?
• Exchange light beam, heavy target, work in inverse kinematics
• RIBS at ATLAS to the rescue!
  – Two-accelerator method
  – In-Flight beams
  – Need the energy and intensity of ATLAS
You heard yesterday-
Experiments with light nuclei: \((d,p)\)

- **CD\(_2\) target**: 100-500 \(\mu\)g/cm\(^2\)

**Au Monitor target**

Annular proton detectors
- \(\Omega_{\text{lab}} \sim 3.5\) sr
- \(\theta_{\text{lab}} = 109^\circ - 159^\circ\)

Forward-angle E\(\Delta\)E detectors
- \(\theta_{\text{lab}} = 1^\circ - 7^\circ\)

Secondary-beam intensities are \(\sim 1-5 \times 10^4\) particles/sec

Event rate for 10 mb/sr \(\sim 10-50\) counts/hour
(d,³He) Experimental setup

Beam axis

CD₂ target
420 µg/cm²

Annular silicon detectors
Ω_{lab} ~ 2.2 sr
θ_{lab} = 9°-50°

³He

Au Monitor target

Monitor E\Delta E telescope

⁴,⁶He

Forward-angle E\Delta E detectors
θ_{lab} = 1°-7°
Detectors

Segmented proton detectors

500µm/1000µm silicon $E\Delta E$ telescope
In-flight RIBS – light nuclei – testing QMC calculations

9Li from 8Li(d,p)
Test of QMC – angular distributions with DWBA + QMC overlap functions

Pickup and stripping to 7He-Broad, resonant excited states identified by cross-reaction analysis, decay properties are in agreement with QMC predictions

PRC 78, 041302R (2008)
$^{13}\text{B}(\text{N}=8)$ via $^{12}\text{B}(d,p)^{13}\text{B}$: Experiment vs. shell model

From $^{11}\text{B}(t,p)^{13}\text{B}^*$:
- $\pi=+$: $J^\pi=(1/2^+,3/2^+,5/2^+)$
- $\pi=-$: $J^\pi=(1/2^-,5/2^-,7/2^-)$

study $l=0,2$ transitions in $^{12}\text{B}(d,p)^{13}\text{B}$

Underlined levels populated in $(d,p)$

$^{13}\text{B}(\text{Experiment})$

$(t,p)$: Middleton and Pullen, NP 50, 1964

$^{13}\text{B}(\text{Shell Model } \pi=+,\,-)$

(B. A. Brown, WBP interaction)
Approaching full circle... $^{12}\text{B}(d,p)^{13}\text{B}$ with Si detector array

Can answer some questions about astrophysical reaction rates

BUT – resolution insufficient to get at the interesting question of the re-ordering of $s$ and $d$ orbitals in neutron-rich light nuclei. **Need better resolution!!**

H. Y. Lee et al., PRC 81, 015802 (2010)
And then a miracle occurs...

\[ d(^{28}\text{Si}, p)^{29}\text{Si} \]

with HELIOS

HELIOS provides vastly improved excitation-energy resolution

J. C. Lighthall et al., NIMPRA 622, 97 (2010)
Now... with HELIOS

John returns to the $p$ shell – inversion of $s$ and $d$ orbitals in $^{13}$B confirmed!
Funny business in $^{16}$C?
Study wave functions of low-lying $2n$ states in $^{16}$C
The future – the Holy Grail of $^{132}\text{Sn}(d,p)^{133}\text{Sn}$

The magic nature of $^{132}\text{Sn}$ explored through the single-particle states of $^{133}\text{Sn}$

E($^{132}\text{Sn}$)=4.8 MeV/u
HELIOS with beams near $^{132}$Sn

First heavy-beam data

$^{136}$Xe, $p^{137}$Xe, 10 MeV/u
30° CM, 104° Lab.
96 keV FWHM
HELIOS Experiments to date:

- $^{28}\text{Si}(d,p)^{29}\text{Si}$
- $^{12}\text{B}(d,p)^{13}\text{B}$
- $^{17}\text{O}(d,p)^{18}\text{O}$
- $^{15}\text{C}(d,p)^{16}\text{C}$
- $^{130,136}\text{Xe}(d,p)^{131,137}\text{Xe}$
- $^{86}\text{Kr}(d,p)^{87}\text{Kr}$
- $^{14}\text{C}(^6\text{Li},d)^{18}\text{O}$
- $^{19}\text{O}(d,p)^{20}\text{O}$

We anticipate with CARIBU:
$^{134}\text{Te}(d,p)^{135}\text{Te}, \; ^{132}\text{Sn}(d,p)^{133}\text{Sn}$, many others
Quite a story

- Transfer reactions and ATLAS (really PHY) have gone hand in hand for 30+ years
- Capabilities provided by ATLAS enabled entirely new fields of research
- New accelerator (upgrades + CARIBU) and detector capabilities paint a very bright future: $(d,p)$, $(d,^3\text{He})$, $(\alpha,t)$ etc. with fission-fragment beams + HELIOS

THANKS!

and ONWARD!
Multineutron transfer in $^{58}\text{Ni} + ^{124}\text{Sn}$ collisions at sub-barrier energies

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(Received 10 December 1997)

FIG. 1. Mass spectrum for $Z = 28$ isotopes measured at $E_{\text{cm}} = 153.0$ MeV, $\theta_{\text{lab}} = 20^\circ$, and integrated over the charge states $q = 23 - 26$ in the system $^{58}\text{Ni} + ^{124}\text{Sn}$.

FIG. 8. Angle- and energy-integrated cross sections as a function of the number of transferred neutrons for the system $^{58}\text{Ni} + ^{124}\text{Sn}$ at four incident energies, together with data for the system $^{160}\text{Mo} + ^{58}\text{Ni}$ [4]. The solid lines are least-squares fits to the data. The reduction factors for each transferred neutron are given in Table IV.
What do we learn from nucleon transfer?

• Nuclear structure
  – Properties of single-particle states
  – Test/Tune shell-model interactions
  – Success of DWBA analyses
  – Spectroscopic factors

• The meat and potatoes of nuclear physics for many decades
What was new with ATLAS?

• What about nucleon transfer between heavy ions?
• Need:
  – Higher bombarding energies ($E_{CM} \sim V_c$)
  – High resolution (high-quality HI beams)
  – Systematics – a variety of HI beams throughout the periodic table
  – High-resolution experimental devices (Split-Pole spectrograph)

All become available with the development of ATLAS!
High-resolution ATLAS data

$^{92}\text{Mo}(^{36}\text{S},X)$ data from ATLAS + SPS:
Good resolution in $Z$, $M/q$, and $E_X$
Slope anomalies...

Expect: $P_t \sim e^{-2\alpha D}$
Observe: NOT!
Nucleon transfer and total reaction cross section

- Assumption was that transfer is a small fraction of total $\sigma_R$ for heavy projectiles; (based on limited, poor resolution data)
- Observation was that transfer is large fraction and increases with projectile mass
- Unexpected result.
- Influence on other channels (e.g. fusion) – suggests further investigation of that relationship...

The large cross sections observed in our experiments for the neutron-pickup reactions could also have influence on other channels. It would be interesting to investigate correlations between neutron-transfer and fusion cross sections for systems where a strong entrance-channel dependence for $\sigma_{\text{fusion}}$ has been observed.15
s\textit{d} states in light nuclei

Increasing $N/Z$

Energy of first cross-shell excitation (state with parity opposite of the ground state) in $N=7$ nuclei

And:
\begin{align*}
\text{\textsuperscript{11}Be}_{g.s.} \text{ is } J^\pi=1/2^+, \\
\text{\textsuperscript{12}Be}_{g.s.} \text{ has strong } (1s1/2)^2 \\
\text{components,} \\
\text{\textsuperscript{11}Li halo is predominantly } (1s1/2)^2
\end{align*}
The (short) story of $^{16}$C...

**Big hindrance!**

**Exotic behavior!**

No hindrance, and no exotic behavior.
Measured spectroscopic factors and predictions

Data normalization: $\Sigma S(0^+) = 2.0$
LSF: interaction only from $^{18}\text{O}$

Consistency test:
$\Sigma S(l=2)/\Sigma S(l=0)$ for $^{15}\text{C}$ and $^{16}\text{C}$ should be equal

Result:
$R(^{15}\text{C}) = .78(.15)$  $R(^{16}\text{C}) = .84(.10)$
Higher-order coupling effects in low energy heavy-ion fusion reactions

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(Received 8 January 1987)

Higher-order couplings to inelastic excitations of surface vibrations can strongly affect the enhancement of heavy-ion fusion cross sections at sub-barrier energies. Detailed second-order calculations are presented for reactions between different nickel isotopes. The agreement with measured fusion cross sections is considerably improved with respect to conventional coupled channels calculations based on linear couplings.

FIG. 2. Fusion cross sections resulting from including both vibrational and single-nucleon transfer channels. Shown are the no-coupling result (dotted line), the transfer only result (dashed line), and the result of the full calculation (solid line) compared to the data from Ref. 3.

FIG. 5. Comparison of second-order fusion data of Ref. 18 and $^{64}$Ni+$^{64}$Ni reactions. The pa
FIG. 2. Fusion cross sections resulting from including both vibrational and single-nucleon transfer channels. Shown are the no-coupling result (dotted line), the transfer only result (dashed line), and the result of the full calculation (solid line) compared to the data from Ref. 3.

FIG. 5. Comparison of second-order vibrational calculations with the fusion data of Ref. 18 for the $^{58}\text{Ni}+^{58}\text{Ni}$, $^{58}\text{Ni}+^{64}\text{Ni}$, and $^{64}\text{Ni}+^{64}\text{Ni}$ reactions. The parameters are given in Table I.
Characteristics of HI transfer

Lower energy –
does not penetrate nucleus

Distant trajectory-
no nucleons to transfer

Peripheral trajectory –
transfer probability peaks

Close collision-
absorption

Transfer probability is peaked at
the angle corresponding to the trajectory
for which the two nuclei are the closest

\[ ^{16}\text{O} + ^{208}\text{Pb} \quad E(^{16}\text{O}) = 130 \text{ MeV}, \quad V_C \approx 93 \text{ MeV} \]

(Satchler 1980, pp 36)