Transfer reactions in Inverse Kinematics

* an experimental overview

Nucleon Transfer with Radioactive Beams

- focus on 10-30 MeV/A reactions
- kinematics are then generic
- a general array can be envisaged
- resolution issues are general
- three classes of solution/choice
- catalyst to discussion
- outline of TIARA array

- overview: Nucl Phys A701 (2002) 1c-6c
- resolution: JSW et al NIM A396 (1997) 147-164
Particles exit close to 90 degrees

Forward scattered target particle in c.m. frame

Backscattering of target particle

\[ V_{\text{centre of mass}} = \frac{m_{\text{beam}}}{m_{\text{beam}} + m_{\text{tgt}}} V_{\text{beam}} = V_{\text{light}} \]
**Velocity Addition**

(non-relativistic)

Reaction: 
\[ T( P, e ) R \]

\[ v_e = \sqrt{\frac{M_R}{M_e}} \]

\[ v_{CM} = \frac{1}{\sqrt{q}} \frac{M_T}{M_P} \]

\[ q = 1 + \frac{Q gs - E_x}{E_{CM}} \]

\[ v_{unit} = \sqrt{\frac{2q E_{CM}}{M_R + M_e}} \]
\( q \approx 1 + \frac{Q_{\text{tot}}}{(E/A)_{\text{beam}}} \)

\( f = 1/2 \) for \((p,d)\), \( 2/3 \) for \((d,t)\)

\( v_{\text{cm}} \) is the velocity of the centre of mass, in the laboratory frame.
## Reaction Q-values in MeV

### Table 1: Q-values for Various Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Q-value (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p, d)</td>
<td>-2.1</td>
</tr>
<tr>
<td>(d, p)</td>
<td>-2.1</td>
</tr>
<tr>
<td>(t, S)</td>
<td>-2.1</td>
</tr>
<tr>
<td>(t, T)</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

### Diagram 1: Reaction Q-value in MeV

- (p, d): refer to cell of TARGET
- (d, p): (−1) x (Cell of PRODUCT)
- (t, S): Cell of TARGET + 4.0 MeV

### Table 2: Reaction Q-values for Additional Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Q-value (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p, d)</td>
<td>12.0</td>
</tr>
<tr>
<td>(d, p)</td>
<td>12.0</td>
</tr>
<tr>
<td>(t, S)</td>
<td>12.0</td>
</tr>
<tr>
<td>(t, T)</td>
<td>12.0</td>
</tr>
</tbody>
</table>

### Diagram 2: Reaction Q-value in MeV

- (p, d): refer to cell of TARGET
- (d, p): (−1) x (Cell of PRODUCT)
- (t, S): Cell of TARGET + 4.0 MeV
Kinematics of nucleon transfer in inverse kinematics

beam → beam-like

light ejectile

pickup (p,d)

velocity of c.m. in lab

stripping (d,p)

maximum

double valued

main yield

single valued

theta lab

theta c.m.
The general form of the kinematic diagrams is determined by the light particle masses, and has little dependence on the beam mass or velocity.
$^{72}$Kr at 15 MeV/A on p and d targets
kinematics for neutron, proton and deuteron transfer

$^{72}$Kr at 25 MeV/A on d target
kinematics for neutron, proton and deuteron transfer

(p,d) and (d,t) and (d,p) on $^{74}$Kr in inverse kinematics

(p,d) and (d,t) and (d,p) on $^{56}$Ni in inverse kinematics
(p,d) and (d,t) and (d,p) on $^{56}$Ni in inverse kinematics

$E_{\text{beam}} = 1680$ MeV (30 MeV/A)

- (d,p) g.s.
- (d,p) 4 MeV
- (d,d) elastics
- (d,t) g.s.
- (d,t) 4 MeV
- (p,d) g.s.
- (d,$^3$He) g.s.
\((^{12}\text{C},^{8}\text{Be})\) and \((^{6}\text{Li},d)\) on \(^8\text{He}\) in inverse kinematics

\[E_{\text{beam}} = 120 \text{ MeV (15 MeV/A)}\]

![Graph showing energy vs. lab angle for different reactions](image-url)
DWBA ZR: $^{94}\text{Sr}(d,p)^{95}\text{Sr}^*(1.0\text{MeV};s_{1/2})$ at 4.894 MeV/u

Adiabatic deuteron potential (B–G) and Perey proton potential

\[
\frac{d\sigma}{d\Omega} \text{ (mb/sr)}
\]

\[
\text{angle (degrees)}
\]

- **versus theta c.m. normal kinematics**
- **versus theta lab inverse kinematics**
- **$d\sigma/d\theta$ (mb/deg) lab inverse kinematics**
Calculations of $E_x$ resolution from particle detection

### Table 2

Major contributions in keV to the resolution of the excitation energy spectra of single neutron stripping and pickup reactions in inverse kinematics, where the heavy ion is detected in a spectrometer. The detection angle corresponds to $10^\circ_{ca}$. The last column is an approximate estimate as a sum in quadrature of the net effect of five non-Gaussian contributions. Other symbols are explained in the text.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_i/A$ (MeV)</th>
<th>$\theta_{lab}$</th>
<th>$\Delta \theta$</th>
<th>$\Delta p$</th>
<th>$E_{stragg}$</th>
<th>$\Theta_{1/2}$</th>
<th>$dE/dx$</th>
<th>$\Sigma_{quad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(^{12}\text{Be}, ^{11}\text{Be})d$</td>
<td>30</td>
<td>1.07°</td>
<td>172</td>
<td>147</td>
<td>101</td>
<td>74</td>
<td>23</td>
<td>259</td>
</tr>
<tr>
<td>$p(^{12}\text{Be}, ^{11}\text{Be})d$</td>
<td>15</td>
<td>1.06°</td>
<td>84</td>
<td>71</td>
<td>99</td>
<td>74</td>
<td>37</td>
<td>169</td>
</tr>
<tr>
<td>$p(^{77}\text{Kr}, ^{76}\text{Kr})d$</td>
<td>30</td>
<td>0.16°</td>
<td>1404</td>
<td>811</td>
<td>808</td>
<td>723</td>
<td>56</td>
<td>1952</td>
</tr>
<tr>
<td>$p(^{77}\text{Kr}, ^{76}\text{Kr})d$</td>
<td>10</td>
<td>0.10°</td>
<td>334</td>
<td>143</td>
<td>502</td>
<td>570</td>
<td>268</td>
<td>883</td>
</tr>
<tr>
<td>$d(^{88}\text{Kr}, ^{77}\text{Kr})p$</td>
<td>10</td>
<td>0.21°</td>
<td>1140</td>
<td>614</td>
<td>2177</td>
<td>1859</td>
<td>1321</td>
<td>3408</td>
</tr>
</tbody>
</table>

### Table 3

Major contributions in keV to the resolution of the excitation energy spectra of single neutron pickup and stripping reactions in inverse kinematics, where the light particle is detected in a silicon detector. Symbols as described in text and Table 2.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_i/A$ (MeV)</th>
<th>$\theta_{lab}$</th>
<th>$\Delta \theta$</th>
<th>$\Delta E_f$</th>
<th>$\Delta E_i$</th>
<th>$\Theta_{1/2}$</th>
<th>$dE/dx$</th>
<th>$\Sigma_{quad}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(^{12}\text{Be, d})^{11}\text{Be}$</td>
<td>30</td>
<td>19.0°</td>
<td>136</td>
<td>74</td>
<td>114</td>
<td>96</td>
<td>649</td>
<td>685</td>
</tr>
<tr>
<td>$p(^{12}\text{Be, d})^{11}\text{Be}$</td>
<td>15</td>
<td>17.8°</td>
<td>66</td>
<td>72</td>
<td>55</td>
<td>89</td>
<td>984</td>
<td>995</td>
</tr>
<tr>
<td>$p(^{77}\text{Kr, d})^{76}\text{Kr}$</td>
<td>30</td>
<td>15.0°</td>
<td>124</td>
<td>55</td>
<td>64</td>
<td>63</td>
<td>186</td>
<td>249</td>
</tr>
<tr>
<td>$p(^{77}\text{Kr, d})^{76}\text{Kr}$</td>
<td>10</td>
<td>6.0°</td>
<td>26</td>
<td>24</td>
<td>23</td>
<td>19</td>
<td>775</td>
<td>777</td>
</tr>
<tr>
<td>$d(^{88}\text{Kr, p})^{77}\text{Kr}$</td>
<td>10</td>
<td>155.3°</td>
<td>52</td>
<td>93</td>
<td>37</td>
<td>60</td>
<td>1309</td>
<td>1316</td>
</tr>
</tbody>
</table>
Some advantages to detect beam-like particle (gets difficult at higher energies)

Better to detect light particle (target thickness limits resolution)
$^{94}\text{Sr} \; (d,p) \; ^{95}\text{Sr}$

$4.0 \text{ MeV/A}$
($\sim 24 \text{ MV} \; 15+)$
$376 \text{ MeV}$

$V_e$ (proton)

$106 \text{ deg}$

$V_{\text{CM}}$

$V_R$

experiment to study $\theta_{\text{cm}}$ between 10, 32 deg

<table>
<thead>
<tr>
<th>$\theta_{\text{lab}}$</th>
<th>$\theta_{\text{cm}}$</th>
<th>$E_{\text{proton}}$</th>
<th>$\Delta \Theta$</th>
<th>$E_{\text{res}}$</th>
<th>ENRGY</th>
<th>STRAG</th>
<th>MULT/SCATT</th>
<th>DIFF'N</th>
<th>DE/DX</th>
<th>TOTAL</th>
<th>QUAD</th>
<th>DE(Ex)/DE(Ep)</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>32</td>
<td>3.33</td>
<td>23</td>
<td>50</td>
<td>19</td>
<td>56</td>
<td>393</td>
<td>401</td>
<td>-1.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>154</td>
<td>10</td>
<td>1.58</td>
<td>7</td>
<td>87</td>
<td>21</td>
<td>23</td>
<td>389</td>
<td>400</td>
<td>-2.53</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Study of the $^{56}\text{Ni}(d,p)^{57}\text{Ni}$ Reaction and the Astrophysical $^{56}\text{Ni}(p,\gamma)^{57}\text{Cu}$ Reaction Rate

$^{11}\text{Be (p, d)}^{10}\text{Be}$

beam energy
resolution 2.0-3.0 MeV

angular spread $\pm 1^\circ$

dispersion-matched spectrometer "SPEG"
(Spectromètre à Perte d'Energie du Ganil)

microchannel plate
polythene target
ten Silicon PSD's

momentum analysis
measure reaction angle
Inverse kinematics $^{11}\text{Be} (p,d)^{10}\text{Be}$

10 coincident detectors

$^{10}\text{Be}$ entrance to SPEG

50 x 50mm$^2$
Si sheet PSDs

(\(\text{CH}_2\))$_n$

50 x 10mm$^2$
target frame

range of incident beam angles

J. Winfield, W. Catford (Surrey)
Focal plane spectrum from SPEG magnetic spectrometer

singles

coincidence

gamma-ray broadening

carbon background removed
Separation Energy form factor

Vibrational form factor

- poor form factor
- no core coupling
- no $^{11}\text{Be}/d$ breakup

0.49 \times 0.51

- vibrational model
- core-excited model
- realistic form factor

0.84 \times 0.16

\{ 0.74 \times 0.19 \}

\text{Shell model}
Radial form factor for the transferred nucleon (in $^{11}$Be)

The relative magnitudes of the s- and d-wave form factors can be changed by changing the potential geometry OR by using a core excitation model and solving the coupled equations. The two have subtly different effects.
Inverse kinematics $^{11}\text{Be}(d,^{3}\text{He})^{10}\text{Li}$

NE102 plastic scintillator sheets 200 x 200 x 10 mm

S. Fortier, S. Pita et al. (Orsay)

$^{9}\text{Li}$

$\pm 7$ deg

6 coincident detector telescopes (MUST)

8 - 26 deg

$^{3}\text{He}$

$60 \times 60 \text{mm}^2$

Si DSSDs 0.3 mm

+ 3 mm Si(Li) + CsI

$n$

$10 \times 5 \text{mm}^2$

beam spot

range of incident beam angles

$(\text{CH}_2)_n$
Excitation energy spectra from the Orsay experiment

S. Fortier, S. Pita et al., (2000)
Results from $d(^7\text{Be},^6\text{He})^6\text{Li}$ at 37.3 MeV/A

unpublished data of S. Pita & S. Fortier et al (Orsay)
Resonance scattering at ORNL: $^{18}\text{F} \,(p,\alpha)\,^{15}\text{O}$

$E_{\text{beam}} = 0.65 \text{ MeV/A}$

$\theta_{\text{lab}} \,(\text{Si}) = 15 - 45 ^\circ$

$Q = + 2.88 \text{ MeV}$

$q = 5.563 \gg 1$

Diagram actually similar to generic (d,p) diagram
(Note: low E/A compared to Q)

Angle and energy of light particle crucial for resolution
1) Rely on detecting the beam-like ejectile in a spectrometer
   - Kinematically favourable unless beam mass (and focussing) too great
   - Spread in beam energy (several MeV) translates to $E_X$ measurement
   - Hence, need energy tagging, or a dispersion matching spectrometer
   - Spectrometer is subject to broadening from gamma-decay in flight

2) Rely on detecting the target-like ejectile in a Si detector
   - Kinematically less favourable for angular coverage
   - Spread in beam energy generally gives little effect on $E_X$ measurement
   - Resolution limited by difference [$\frac{dE}{dx}(\text{beam}) - \frac{dE}{dx}(\text{ejectile})$]
   - Target thickness limited to 0.5-1.0 mg/cm$^2$ to maintain resolution

3) Detect decay gamma-rays in addition to particles
   - Need exceptionally high efficiency, of order > 25%
   - Resolution limited by Doppler shift and/or broadening
   - Target thickness increased up to factor 10 (detection cutoff, mult scatt’g)

Proof of Principle using weak $^{36}$S beam and inverse $^{36}$S(d,p)$^{37}$S

C. Grund et al. (Heidelberg/Darmstadt)

Note: peaks from room b/gnd

counts/2keV

singles
singles + Doppler
singles + Doppler + RF
singles + Doppler + RF + PPAC

Energy [ keV ]
Backward Annular Si
\[ 144^\circ < \theta_{\text{lab}} < 168.5^\circ \]

Barrel Si
\[ 36^\circ < \theta_{\text{lab}} < 144^\circ \]

Forward Annular Si
\[ 5.6^\circ < \theta_{\text{lab}} < 36^\circ \]

Target Changing Mechanism

Beam

VAMOS

University of Surrey
Forward and Backward annular detectors

Barrel detector
Coulomb excitation (Coulex) of $^{46}$Ar ($2^+; 1.577$ MeV) on Ni & Pb targets.

$B(E2) = 196 \text{ e}^2\text{fm}^4$; safe energies of 90 MeV (Ni) and 155 MeV (Pb).

Graph showing the angular distribution of Coulomb excitation cross-sections for Ni and Pb targets. The graph indicates that 82% of the total cross section occurs at angles greater than 50 degrees, and 70% at angles greater than 50 degrees. The angular range of the experiment covers angles from 0 to 180 degrees.
Experimentally proven
- inverse kinematics manageable
- gamma-ray detection often desirable

Reactions on p and d targets
- identify angular momentum and $E_x$
- then, measure spectroscopic factors

Alpha 2-nucleon transfer
- $(d,^6\text{Li})$ or $(^12\text{C},^8\text{Be})$ or $(^6\text{Li},d)$ possible
- $(t,p)$ or $(^9\text{Be},^7\text{Be})$ or $(^{10}\text{B},^8\text{B})$ possible

Experimental challenges
- pushing beyond 35-40 deg in $(p,d)$ etc.
- stopping all particles & detecting gammas
- low energy thresholds for particles
- detection of beam-like particle (identify Z)
- scattered beam particles are radioactive