Direct Reactions in Normal Kinematics in the (F)RIB era

Ben Kay, Argonne National Laboratory
Science with the FSU Super Enge Split-Pole Spectrograph
Florida State University, March 2019
Overview (an evolution of a short talk I gave at the LECM in August 2016)

Direct reactions as a probe of nuclear structure - an essential tool

- Some background

- Some parameters
  - Beams, energies, resolution, targets, etc.

- Some examples from the last decade, with the Yale Enge SPS [2006-2011], Munich Q3D, IPN Orsay
  - Enge SPS, RCNP Grand Raiden [2007-present]
    - Double-beta work
    - Occupancies, evolution of SPEs
    - Pair transfer

- Some things that could be done at FSU?
  - (see above)
The Yale Enge

Figure 3.6: Schematic of an Enge split-pole spectrograph, showing the different paths taken by ions of different angular momenta. One can clearly see the two pole pieces and the coil which surrounds them both. Figure modified taken from [51].

Particles which have small momentum differences. This is its resolving power and depends on the magnification and momentum dispersion of the spectrograph. The split-pole spectrograph at WNSL was designed to have a particularly large acceptance: its limits are $\pm 80$ mrad in the horizontal plane and $\pm 40$ mrad in the vertical plane, providing a maximum solid angle of 12.8 msr. A better resolution can be achieved with a smaller aperture, but the trade off is lower statistics. For these experiments it was possible to gain sufficient statistics with a moderately narrow aperture. For Experiment I, it was chosen to be 3.2 msr. In Experiment II, two different apertures were used: data taken from the June 2006 run implemented a 2.80 msr aperture, whilst the February run made use of a 1.50 msr aperture.

Several papers detail the mathematics of the ion-optic properties of split-pole spectrograph (for example [51]). Below is a brief discussion of some of these properties.

Table 3.2 shows the specifications of the Yale split-pole spectrograph which can be...
Transfer reactions (with charged outgoing ions)

- e.g., neutron adding and removing ... (d,p), (p,d), (d,t) (α,₃He), (₃He,α)
- e.g., proton adding and removing ... (d,₃He), (₃He,d), (α,t), (t,α)
- e.g., pair transfer ... (p,t), (t,p), scattering ... (p,p), (p,p'), (d,d') ...

- Typically carried out a few MeV/u above the Coulomb barrier
  - but done at many energies

- Relatively well understood in terms of relating cross sections to spectroscopic factors, which contain the nuclear structure information

- A tremendous endeavor by the community in the 60s and 70s to gather the wealth of data which, to first order, defined our understanding of nuclear structure ... but, it was not preserved (only SFs provided)

- (Many datasets analyzed with antiquated codes, limited descriptions of the inputs, rarely were consistent studies done)
Nuclear structure from light-ion reactions

~5-10 MeV/u (few-10s MeV/u), >$10^4$ pps

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

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

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

![Diagram of nuclear structure](image-url)
Stable beams/targets ... (or long lived)

- Complementing the theoretical insights ...
- ...great acc./instrum. developments in "the early days"
- Resolution (~5-100 keV)

- Beams, \text{nA-\mu A}


**Figure 2:** Fission coincident proton spectrum for excitation energies in $^{232}$Pa. Fully drawn is a fit assuming three rotational bands.

- Whilst limited to stable beams, it is rarely obvious when we need to visit/revisit them ...,
ultimately, it is always a compromise

With a 9 MV tandem, and maybe a linac boost, expect the following to be useful for structure studies:

(d,p), (p,d), (d,t) (α,³He), (³He,α), (d,³He), (³He,d), (α,t), (t,α), ...
(p,t), (t,p), (d,a), (³He,t), (t,³He), (⁶Li,d), ... etc

Our work used mostly 10-28 MeV p/d, 27-42 MeV ³He,⁴He ...
ultimately, it is always a compromise

Sb spectra: AJ Mitchell priv. com (Yale, SPS)
So what?! *Hasn't it all been done?*

- Structure of stable nuclei well understood, all measurements done several times, no need to dredge up the past? "... let’s focus on RIBs"

Yeah, but ...

- … e.g., double beta decay properties, evolution of s.p. states due to tensor force proven in stable nuclei (insights from RIBs), weak binding, ..., quenching of cross sections
- … reaction theory – the plethora of data available makes for an exciting playground for people revisiting reaction theory in new energy regimes, N/Z ratio, etc.

The machines [*accelerators and spectrometers*] used to gather these high precision data are all but gone – high precision data will be sparse in the future. *(BUT several reappearances, FSU, ANU?, ..., future Munich set up?)*
Some examples *(from the last ~10 years)*
Neutrinoless double-beta decay

REACHING FOR THE HORIZON

Matrix element (dimensionless)

- IBM-2
- QRPA-Jy
- QRPA-Tu
- ISM-StMa
- ISM-CMU

The Site of the Wright Brothers' First Airplane Flight
What is the occupancy and vacancy of the active orbitals? How does it CHANGE from initial to final state?—the microscopic anatomy can be probed with NUCLEON TRANSFER reactions.
Nuclear structure

\[ \sigma_{\text{exp}} = C^2 S \sigma_{\text{model}} \quad \text{...removing, e.g. (p,d)} \]

\[ \sigma_{\text{exp}} = (2j + 1)C^2 S \sigma_{\text{model}} \quad \text{...adding, e.g. (d,p)} \]

‘model’ typically DWBA, or ADWA, leads to \( \pm 0.1\text{-}0.2 \) nucleons

\[ 61^{\text{Ni}} \]

Example – occupancies (IPN Orsay, 2015)

Essential data for discriminating against / constraining nuclear-structure calculations used in the theoretical determination of 0ν2β-decay NMEs (significant discrepancies are apparent in most cases we have explored)

This was done in 2015 requiring competitive PAC processes, two runs, etc. Arguably a choice of two facilities in Europe back then, now ~1. Would be ideal (better) for a university facility (and excellent for grad students, US work force)

From the proton-pair adding Te($^3\text{He},n$) reactions, significant strength is seen in $\ell=0$ transitions to excited states. A classic case of pair vibration! NOT included in QRPA, not necessarily treated correctly in shell-model calculations.

→ Much could be done with (t,p) on many other $0\nu2\beta$-decay candidates, plus structure around shape-changing regions ...

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E$ (MeV)</th>
<th>$\sigma$ (mb/sr)</th>
<th>Ratio</th>
<th>Normalized strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{128}\text{Te}(p,t)$</td>
<td>0</td>
<td>4.21</td>
<td>90</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>1.873</td>
<td>0.06</td>
<td>20</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>2.579</td>
<td>0.15</td>
<td>21</td>
<td>0.04</td>
</tr>
<tr>
<td>$^{130}\text{Te}(p,t)$</td>
<td>0</td>
<td>3.49</td>
<td>89</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.979</td>
<td>0.05</td>
<td>50</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2.313(4)^c</td>
<td>0.05</td>
<td>&gt;20</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{128}\text{Te}(^3\text{He},n)$</td>
<td>0</td>
<td>0.24</td>
<td>–</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>2.13</td>
<td>0.095</td>
<td>–</td>
<td>0.32</td>
</tr>
<tr>
<td>$^{130}\text{Te}(^3\text{He},n)$</td>
<td>0</td>
<td>0.26</td>
<td>–</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1.85</td>
<td>0.098</td>
<td>–</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>2.49</td>
<td>0.062</td>
<td>–</td>
<td>0.21</td>
</tr>
</tbody>
</table>

In many cases, single-particle strength is fragmented over several states. $^{41}\text{Ca}$ is an excellent example of this: just one neutron outside the doubly-magic $^{40}\text{Ca}$ (20 protons, 20 neutrons) ...

$$E'_{j} = \sum_{i} \frac{E_{j}^{*}(i)S_{j}(i)}{\sum_{i} S_{j}(i)}$$

The lowest $1/2^-$ and $3/2^-$ states lie at 3613.5 and 1942.7 keV, respectively.

The centroid of single-particle strength, the energy of the $2p_{1/2}$ and $2p_{3/2}$ orbitals, lie at 4491 and 2327 keV. This is significantly different, a fact often overlooked.
Evolution of s.p. states

**Energy Differences** deduced from the current work between (b) the stable
orbital and the s.p. states of monopole shifts arising from central and tensor forces

$N = 50 + n$

Determination of single-particle energies from fragments
(Note, Kr missing due to being a gas ... more later)

Sb isotopes

<table>
<thead>
<tr>
<th>Target</th>
<th>7/2^+</th>
<th>11/2^-</th>
<th>Ratio</th>
<th>C^2S_7/2</th>
<th>C^2S_11/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>112Sn</td>
<td>14.6</td>
<td>21.4</td>
<td>1.47</td>
<td>0.99</td>
<td>0.84</td>
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<tr>
<td>114Sn</td>
<td>19.6</td>
<td>27.3</td>
<td>1.39</td>
<td>1.10</td>
<td>0.93</td>
</tr>
<tr>
<td>116Sn</td>
<td>19.7</td>
<td>30.9</td>
<td>1.57</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>118Sn</td>
<td>20.4</td>
<td>33.5</td>
<td>1.64</td>
<td>0.88</td>
<td>0.99</td>
</tr>
<tr>
<td>120Sn</td>
<td>27.9</td>
<td>39.4</td>
<td>1.41</td>
<td>1.13</td>
<td>1.12</td>
</tr>
<tr>
<td>122Sn</td>
<td>24.6</td>
<td>35.5</td>
<td>1.45</td>
<td>0.98</td>
<td>1.00</td>
</tr>
<tr>
<td>124Sn</td>
<td>24.7</td>
<td>39.2</td>
<td>1.59</td>
<td>1.00</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Explanation? Tensor force

Important data for Otsuka’s demonstration of the ubiquitous role of the tensor force in NS ... coupling with many other SPS measurements (N=51, 81, Z=19, etc.)

Some things
Some things – double-beta decay


D. K. Sharp et al., upcoming works on A = 116, 124, and 150 neutron occupancies

We used a cryogenically cooled Xe target developed by the Berkeley group (S. J. Freedman's group) ... use for Kr (inc. the N=51 case), for example, and for Ar isotopes

Some things – indium anomaly?

**Proton** hole-states below Sn – anomalous trends in 9/2+ and 1/2− states [(t,a) would be ideal! – positive Q value, not possible anywhere]

**Neutron** occupancies not known sufficiently well ... think (d,p) and (p,d) ... though Munich data now available
Some things – quenching

The “quenching puzzle” seen in exotic systems with knockout reactions – if a binding phenomena, then weak binding can be probed in stable systems via excited states near the particle threshold …, and even the most "exotic" systems can be probed with "stable" techniques

Great opportunity to study the $^{14}$C+n system at FSU, though many considerations -- a reanalysis of several data sets yields ~1!! (which is likely incorrect -- check essential)

BPK, work in progress
New analysis of the "Elbek" data on rare-earth nuclei suggests sums rules are obeyed beautifully, but not clear on the normalization -- using \((d,p)\) and \((p,d)\) on many targets would help clear up recent Munich results.
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<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\alpha$</th>
<th>Reactions</th>
<th>Summed S / 2C&lt;sub&gt;ij&lt;/sub&gt; (Modern parameters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{174}\text{Yb}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td>(d,p) and (d,t) Elbek cross sections (12 MeV deuterons)</td>
<td>1.50(17)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>1.32(15)</td>
</tr>
<tr>
<td>$^{170}\text{Er}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td>(d,p) and (d,t) MLL cross sections 2018 (12 MeV deuterons)</td>
<td>1.40(19)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>1.36(13)</td>
</tr>
<tr>
<td>All*</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>1.21(22)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>1.09(17)</td>
</tr>
<tr>
<td>$^{174}\text{Yb}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td>(d,p) and (p,d) MLL cross sections 2018 (12 MeV deuterons)</td>
<td>0.90(11)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>0.74(10)</td>
</tr>
<tr>
<td>$^{170}\text{Er}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>0.73(9)</td>
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<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{174}\text{Yb}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td>(d,p) and (p,d) MLL cross sections 2018 (12 MeV deuterons, 18 MeV protons)</td>
<td>0.52(7)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>0.52(9)</td>
</tr>
<tr>
<td>$^{170}\text{Er}$</td>
<td>1/2&lt;sup&gt;−&lt;/sup&gt;</td>
<td></td>
<td>0.59(7)</td>
</tr>
<tr>
<td></td>
<td>7/2&lt;sup&gt;−&lt;/sup&gt;</td>
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</table>
Brief summary

- **Ample opportunities at FSU with the Enge/tandem/linac:**
  - Links to fundamental symmetries in $0\nu2b$
  - Nuclear structure, $NN$ force
  - Weak binding phenomena, quenching

- **... all not necessarily apparent yesteryear, plenty more to tackle**

- While some limitations in terms of energy, many reactions still possible

- **Potential for unique couplings:**
  - ... **frozen** target (gases, often poorly studied)
  - ... long-lived radioisotopes, targets (FSU chemistry group)
  - ... **tritium beams** of HUGE interest as largely phased out in the 90s $(t,\alpha), (t,p)$
  - ... not mentioned polarized ion source (adds j assignments)?

- ... and I have not even mentioned astrophysics once!

**FSU + SE-SPS is likely to be very popular!**

**Thanks to J. P. Schiffer who inspired much of the recent work**