Fragmentation Cross Section Database

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Database Project History

- Early 1990’s situation: sparse data on GCR-like ions except for extensive measurements by Webber et al.
- Webber’s group measured several ions and energies on He, C, and CH$_2$ targets, using subtraction to get results for H targets for GCR propagation models.
Schimmerling/Miller Group

- Formed in 1991 to make systematic fragmentation measurements at the LBL Bevalac using many beam ions, energies, and targets.
  - Standard target list: C, CH$_2$, Al, Cu, Sn, Pb
- Fall 1995, AGS radiation biology program started runs with 1 GeV/amu $^{56}$Fe.
HIMAC and NSRL

- AGS cave difficult to work in, beam tuned for radiation biology experiments (large spot, high intensity, lots of spill structure).

- HIMAC experiments started 1997 – just 1 week/yr, but many beams available, $E_{\text{beam}} \leq 800\ \text{MeV/amu}$.
  - Superb beam $\rightarrow$ high quality data, easy analysis.

- First NSRL physics runs in October 2003.
  - Much better than AGS (not yet as good as HIMAC).
AGS Revisited

- Last physics experiment at AGS in 2005 to measure C, Si, and Fe ions at 3 high-energy points each (3, 5, and 10 GeV/amu).
- LBL 0° experiment plus 3 off-axis systems: high-energy neutron counters, ZDDS (Christl and Kuznetsov, MSFC), and SSDs (Pinsky et al., UH).
  - 3 separate data acquisition systems, tricky to merge in off-line analysis, but UH group has succeeded.
Different approach from typical experiments: measure “light” fragments with $Z < Z_{\text{beam}}/2$.

Most experiments report $Z > Z_{\text{beam}}/2$ only.

To get low $Z$, need detectors far from target and data need model-dependent corrections for angular distribution losses. (Or could use highly segmented detectors).
Present Status


PRELIMINARY DATA

Some of this data has not been published. For those data, errors have been set to 5% for charge changing cross sections and 10% for fragment cross sections. Actual published errors will be smaller in most cases. Green cells are active links to data tables.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV/nucleon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}$Fe</td>
<td>400 600 600 800 1,000 3,000 5,000 10,000</td>
</tr>
<tr>
<td>$^{48}$Ti</td>
<td>400 650 1,000</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>290 400 650</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>290 650 1,000</td>
</tr>
<tr>
<td>$^{28}$Si</td>
<td>290 400 600 800 1,200 3,000 5,000 10,000</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>400</td>
</tr>
<tr>
<td>$^{20}$Ne</td>
<td>290 400 600</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>290 400 600</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>290 400</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>290 400 3,000 5,000 10,000</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>400</td>
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<tr>
<td>$^{10}$B</td>
<td>400</td>
</tr>
<tr>
<td>$^4$He</td>
<td>230</td>
</tr>
</tbody>
</table>
Published Cross Section Data

- **Older:** $^{56}$Fe at 1 GeV/amu, $^{20}$Ne at 600 MeV/amu.

- **Newer:** $^{28}$Si at 290, 400, 600, 800, 1200 MeV/amu, and $^{12}$C at 290, 400 MeV/amu.

- **Almost done:** $^{35}$Cl at 650 and 1000 MeV/amu, $^{40}$Ar at 290, 400, and 650 MeV/amu, and $^{48}$Ti at 1000 MeV/amu.

- **Next:** AGS 2005 data with 9 sets of cross sections.
Selling Points

- Range of targets spans the period chart from H to Pb.
  - Scaling from H target cross sections to targets heavier than H is dubious.
- Light fragment cross sections are available.
  - Few previous data for modelers to work with.
  - It’s more complicated than simple models predict.
- Careful & conservative evaluation of systematic errors in measurement (often underestimated).
- Large number of data points: ~ 200 charge-changing and 2000 fragment production cross sections.
Cl – Ar – Ti Paper (In Progress)

- Comparison of different ions and energies in a narrow range of projectile mass (35 to 48).
- Demonstrates all the main points: light fragments, model tests, differences between H and other target materials, neutron-excess dependence of the fragment cross sections.
Fragments from $^{40}$Ar ($Z = 18$)

- Large acceptance spectrum is typical, hard to distinguish peaks below charge 10, impossible below charge 8.

- Small acceptance spectrum shows peaks for all species and some combinations, e.g., $Z \sim 3.5$ corresponding to 3 He fragments in coincidence.
NUCFRG2 (and PHITS, not shown) do well for Cl beams but are systematically off 5-10% for Al and heavier targets for Ar and Ti beams.

Was NUCFRG2 tuned to Webber et al. H and C target data?
- NUCFRG2 $\sigma_{cc}$ matches H target data very well. (PHITS off 10-15% for H.)
- We don’t always agree w/Webber (e.g., $^{28}$Si data).
Fragment Cross Sections

- Normalizing to $\sigma_{cc}$ allows data for all targets to be plotted on the same scale.
- Curves are similar for all targets except H.
- Cross section for F production ($Z = 9$) is always minimum for non-H targets.
  - This would not be apparent if we only measured $Z > Z_{\text{beam}}/2$.
- Bigger odd-even effect for $^{35}\text{Cl}$ beam than for others.
Odd-Even Effect

- Previously reported by many.
- Depends on neutron excess.
  - Stronger effect seen for $T_z = 0$ than for $T_z = -2$.
- Iancu et al. defined $V(Z_f)$ to measure the effect.
  - They find weak target dependence; we agree.
- We go further: lump all odd-Z V’s together into an average, do same for even-Z V’s, take ratio.
  - Excessively reductionist, but…
Excessive Reductionism Pays Off

- Include other data sets — $^{28}$Si from our recent paper and $^{40}$Ca from Chen et al.
- Effect strongest for $T_z = 0$ projectiles, weaker but not negligible for $T_z = -2$.
- For H targets, there seems to be energy dependence for $T_z = 0$, not for $T_z = -2$.
  - Note $^{35}$Cl has $T_z = -1/2$.
- Hard to see trend for C+Al data; possibly differing trends for Ar, Fe beams.
Most models are oversimplified and this appears in two ways.

- Lack of odd-even effect.
- Cross sections decrease monotonically with increasing $\Delta Z$.

Contrast with PHITS: on average, not much closer to the data than others, but it predicts the odd-even effect and cross sections increase below $Z = 9$. 
Conclusions

- Many data available, with occasional updates, at http://fragserver.lbl.gov/main.html
  - Trying to get cross sections into NNDC at Brookhaven.

- Links to tables of cross sections and our articles, including neutron cross section papers by Lawrence Heilbronn et al.
  - Lawrence and Prof. Nakamura of Tohuko Univ. have also published a handbook of neutron cross section data.

- We plan to publish as much charged particle data as possible – maybe not much given that support → 0.

- More could be mined from existing data, but…