Structural effects in nuclide distributions from fission and fragmentation

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- Structural effects in low-energy fission.  
  - Even-odd structure.  
  - Fission channels.

- Structural effects in fragmentation products.  
  - Enhancement of specific classes of nuclei.

- Recent experimental results.  
- Theoretical interpretation.  
- Speculative ideas.

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“Symposium on Nuclear Clusters: from Light Exotic to Superheavy Nuclei“  
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Even-odd structure in low-energy fission

Results from e.m.-induced fission of 70 different secondary projectiles (Steinhäuser et al., NPA634 89, 1998)

\[ \delta Z \text{ is a measure of the deviation of 4 yields from a Gaussian curve (Tracy et al., PRC5 222, 1972)} \]

Strong even-odd effect at asymmetry:
Odd protons prefer heavy fragment

Even-odd effect for even-Z systems at symmetry:
Measure of pairing correlations
Survival of cold proton (neutron) subsystem

New idea (F. Rejmund et al., NPA678, 215, 2000)
Even-odd structure due to survival of completely paired configuration.

\[ P^Z_0 = \text{Probability for completely paired proton configuration:} \]

\[ P^Z_0 = \frac{\sum_{n_z=0}^{n_N} \rho_{n_z,n_N}}{\sum_{n_z,n_N} \rho_{n_z,n_N}} \]

\[ \delta_Z = \text{Local proton even-odd effect} \]
Fission channels in low-energy fission

Mass distributions (conventional experiments)

Z distributions (secondary beams)
(K.-H. Schmidt et al., NPA655, 221, 2000)

Survival of shell structure at saddle $\rightarrow$ scission
Structural effects in fragmentation, overview

Light fragments of $^{238}$U (1 A GeV) produced in collisions in a Ti target

M. V. Ricciardi, PhD in preparation

First analysis of fine structure in fragmentation with individual production yields of fully identified nuclides.
Cuts with fixed N-Z

Complex fine structure:
- Even-even enhanced
- Multiples of alpha particles strongly enhanced
- Very neutron-rich odd-Z (even-N) enhanced
Local even-odd effect (Tracy)

Quantitative measure of even-odd effect.
## Observations of fine structure in fragmentation

<table>
<thead>
<tr>
<th>Authors</th>
<th>Publication</th>
<th>Reaction</th>
<th>Beam energy</th>
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<tbody>
<tr>
<td>B. Blank et al.</td>
<td>NIM A 286 (1990) 160</td>
<td>40Ar + 12C</td>
<td>403 A MeV</td>
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<tr>
<td>W. R. Webber et al.</td>
<td>PRC 41 (1990) 547</td>
<td>56Fe + 12C</td>
<td>600 A MeV</td>
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<tr>
<td>C. N. Knott et al.</td>
<td>PRC 53 (1996) 347</td>
<td>e.g. 32Si + 1H</td>
<td>e.g. 571 A MeV</td>
</tr>
<tr>
<td>C. Zeitlin et al.</td>
<td>PRC 56 (1997) 388</td>
<td>56Fe + div.</td>
<td>1.05 A GeV</td>
</tr>
<tr>
<td>S. Cavallaro et al.</td>
<td>PRC 57 (1998) 731</td>
<td>35Cl + 24Mg</td>
<td>8 A MeV</td>
</tr>
<tr>
<td>L. B. Yang et al.</td>
<td>PRC 60 (1999) 041602(R)</td>
<td>58Fe + 58Fe 58Ni + 58Ni</td>
<td>45 to 105 A MeV</td>
</tr>
<tr>
<td>E. M Winchester et al.</td>
<td>PRC 63 (2000) 014601</td>
<td>40Ca + 58Ni 40Ar + 58Fe</td>
<td>25 A MeV</td>
</tr>
<tr>
<td>M. V. Ricciardi</td>
<td>PhD</td>
<td>238U + Ti</td>
<td>1 A GeV</td>
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</table>

Fine structure appears over wide range of:
- projectile,
- target,
- energy!

**Hypothesis:** Fine structure measures the phase space of bound levels at the end of the evaporation process.
Expectation from conventional models

Proton quasiparticle excitations in the Boltzmann-gas model (Strutinski, 1958)

Fluctuation of $S_n = \text{backshift in } \rho$

[Ericson, AP9 425 (1960)]

Number of bound levels below $S_n$ is “smooth”.
Experimental information on excited levels

Excitation energy – energy of liquid drop for $N = Z$ nuclei.

Small part of even-odd structure is preserved in excited levels!

Complex nuclear-structure phenomena which go beyond the conventional understanding.
Even-odd structure in binding energies

\[ \delta \] is a measure of the deviation of 4 masses from a parabola.

Exceptionally strong even-odd structure along \( N=Z \).

- Alpha clustering?
- Neutron-proton pairing?
Speculative list of phenomena

- All even-even nuclei enhanced:
  - Mean-field contributions to pairing effects?

- Even-even N=Z nuclei strongly enhanced:
  - Alpha clustering?
  - Neutron-proton pairing?
  - Congruence energy, Wigner term?

- Neutron-rich odd-Z even-N nuclei enhanced:
  - Continuum effects on neutron pairing?
Conclusion

Structural effects in low-energy fission:
- Survival of pairing and shells in cold nuclei.
- Qualitatively explained by conventional models.
- Quantitative prediction needs more advanced dynamical models.

Structural effects in fragmentation etc.:
- Appearance of complex structures after the deexcitation of highly excited systems:
  - Even-even nuclei
  - N = Z nuclei
  - Neutron-rich odd-Z, even-Z nuclei
- Not explained by conventional models.
- New experimental information on complex nuclear-structure phenomena.