Breakup Reactions of $^{17}\text{Ne}$ to Study its Two-Proton Halo Structure

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- **Motivation:**
  Nuclear Structure of $^{17}\text{Ne}$ & Astrophysics Impact

- **Experimental Methods:**
  Knockout Reactions & Coulomb Dissociation

- **Results:**
  Proton Knockout and Inelastic Breakup on a C Target
  Ingredients to the 2p-Removal Cross Section
  $^{17}\text{Ne}$ 3-Body/Coulomb Spectra

- **Summary & Outlook**
"The $^{17}\text{Ne}$ Nucleus - Why is it interesting?"

$^{17}\text{Ne}$ is a proton-dripline nucleus, with strong indications of having a 2p – halo

Zhukov & Thompson, PRC 52 (1995) 3505

$^{17}\text{Ne} \approx ^{15}\text{O} + 2\text{p}$, a borromean 3-body system ($\text{p-p}$ and $^{16}\text{F}$ are unbound)

- $S_{2\text{p}} = 950$ keV
- $T_{1/2} = 109.2$ ms ($\beta^{+}$ to $^{17}\text{F}$)
- Groundstate $J^\pi=1/2^-$; no bound exc. states

Is there a 2p-halo? Is there $\geq 50\%$ s- or p-wave content in the valence protons?

- Grigorenko et al., PRC 71 (2005) 051604(R).
  - 3-body cluster model: $s^2$ content 48%.

  - Q-radius measurement + FMD: 42% $s^2$.

  - Reaction cross-sections: Long tail in $^{17}\text{Ne}$ matter density, dominant $s^2$ configuration.

  - 3-body model: $s^2$ content 15%.

Shell model view of the $^{17}\text{Ne}$ ground-state
15O(2p,γ)17Ne in Nuclear Astrophysics: X-ray Bursts, rp-process, Neutron Stars

Cataclysmic binary systems (X-ray bursts):
- rp-process  
  Görres et al., PRC 51 (1995) 392

CNO cycle:  
- ... 14N(p,γ)15O(β)15N(p,a)  
- 15O is a waiting point for CNO-cycle breakup:  
- Heavier elements:  
- Alternative (rp):  
  ... 15O(a,γ)19Ne(p,γ) ...  
  ... 15O(2p,γ)17Ne(β)17F(p,γ)

The reaction rate can be enhanced by a few orders of magnitude by taking into account the three-body continuum states. Grigorenko et al., PLB 641 (2006) 254
The S318 Experiment: Coulomb Dissociation of $^{17}\text{Ne}$

Lead Target: $^{17}\text{Ne}(\gamma,2p)^{15}\text{O} \rightarrow ^{15}\text{O} + p + p$

![Diagram showing the reaction process]

$^{17}\text{Ne}$ Excitation energy spectrum

Virtual photon theory

\[ \frac{d\sigma_{CD}}{dE_\gamma} = \frac{1}{E_\gamma} n \sigma_{PD}(\gamma,2p) \]

Detailed balance theorem

\[ \sigma(b,\gamma) = \frac{2(2j_a + 1)}{(2j_b + 1)(2j_c + 1)} \frac{k_\gamma^2}{k^2} \sigma(\gamma,b) \]

Cross section for reverse reaction: radiative capture on $^{15}\text{O}(2p,\gamma)$

But also: $^{17}\text{Ne}$ nuclear-structure...
The S318 Experiment: Nuclear Inelastic Excitation of $^{17}\text{Ne}$

Inelastic / Diffractive Scattering

- (Nuclear) inelastic excitation
  - $^{17}\text{Ne}$ relative-energy spectrum
  - Competition/Interference with EM (Coulomb) excitation

- Estimation (and subtraction) of nucl. background of the Pb target

- Source of ‘contamination’ for the 1p knockout channel
The S318 Experiment: One-proton Knockout from $^{17}\text{Ne}$

One-proton Knockout

- $^{16}\text{F}$ relative energy spectrum
- Knocked-out proton's internal momentum distribution via momentum of $^{16}\text{F}$

Glauber-type reaction model
- Angular momentum of knocked-out proton
- $s^2/d^2$ configuration mixture in $^{17}\text{Ne}$
The S318 Experiment at GSI – Production of Radioactive $^{17}\text{Ne}$ Beams

Synchrotron SIS: $^{20}\text{Ne} \ @ 630 \text{ AMeV}$

Thick Be-Target

Fragment Separator: Select $^{17}\text{Ne}$

Cave C, R$^3$B/LAND setup: $^{17}\text{Ne} \ @ 500 \text{ AMeV}$

$B \rho = \frac{p}{Q} \propto \frac{A}{Z} \beta \gamma$
The S318 Experiment: 500 AMeV $^{17}$Ne beams $\rightarrow R^3B/LAND$

Beam detectors:
- **Crystal Ball:** Tracking & ID of incoming $^{17}$Ne beam
  - $4\pi$ NaI shell, $\gamma$-rays and recoil protons
- **DSSSD box:** Tracking & ID of recoil protons
- **Aladin:** Dipole magnet to deflect fragments and protons
- **Fragment arm:** Fibre detectors and a small ToF Wall
- **Proton arm:** Drift Chambers and a large ToF Wall
- **LAND:** Large-Area Neutron Detector
Selection of Reaction Channels – One-Proton Knockout from $^{17}\text{Ne}$

$^{17}\text{Ne} \sim 500 \text{ AMeV}: \text{C Target}$

$^{17}\text{Ne}(C,X)^{16}\text{F} \rightarrow ^{15}\text{O} + p$

Tracking of fragments and protons

$\rightarrow$ Mass and Momentum of Fragment
$\rightarrow$ Momenta and Multiplicity of Protons

Identification of oxygen mass

Proton-multiplicity distribution

Mass and Momentum of Fragment

$1 = 1\text{p-knockout}$
$2 = \text{inelastic exc.}$
One-Proton Knockout from $^{17}$Ne – $^{16}$F Excitation Energy

$^{16}$F* Invariant Mass ($P_\mu P_\mu$) $\rightarrow$ $E_{rel}$ ($^{15}$O+p)

$$E_{rel} = \sqrt{m_1^2 + m_2^2 + 2m_1m_2\gamma_1\gamma_2(1-\beta_1\beta_2\cos\varphi_{1,2})} - (m_1 + m_2)$$

Exclusive selection of knockout from ‘halo’-states possible

Grigorenko, PRC 71 (2005) 051604(R).
'Halo'-Proton Knockout from $^{17}$Ne – $^{16}$F (= $^{15}$O+p) Transverse Momentum

x-projection: $w(s^2) \sim 38\%$

y-projection: $w(s^2) \sim 42\%$

- s-wave content of $\sim 41\%$ in the $^{17}$Ne 'halo' (weighted average)
- Indication of a moderate halo character of $^{17}$Ne
- Good agreement with most theoretical predictions

Glauber-type calculation (MOMDIS)
Bertulani et al., CPC 175 (2006) 372

- x and y projections equivalent
- Different results reflect systematic uncertainty of the measurement

preliminary!
2-proton-removal cross section – Partial cross sections, spectrosc. strength

\[ ^{17}\text{Ne}(\text{Target},X)^{16}\text{F} \rightarrow ^{15}\text{O} + X \]

<table>
<thead>
<tr>
<th>CH(_2)</th>
<th>213 ± 5 mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>117 ± 4 mb</td>
</tr>
<tr>
<td>(H:</td>
<td>48 ± 3 mb</td>
</tr>
<tr>
<td>Pb:</td>
<td>483 ± 30 mb</td>
</tr>
</tbody>
</table>

\[ \sigma_{-2p} \approx \sigma_{ko-2p} + \sigma_{ko-1p} + \sigma_{inel} \]

Estimate for 1p efficiency: 87%

Calculations (MOMDIS), C. Bertulani

Single-particle cross sections:

\[ \sigma_s = 52.7 \text{ mb} \]
\[ \sigma_d = 34.1 \text{ mb} \]

41% s-wave content from \(^{16}\text{F}\) mom.:

\[ \sigma_{\text{calc}} = 0.41\sigma_s + 0.59\sigma_d = 41.70 \text{ mb} \]

‘Spectroscopic Strength’:

\[ S = \sigma_{\text{exp}}/\sigma_{\text{calc}} = 1.7 \]

Percentage of halo knockout: 67%

Corresponds to 71 mb.

\[ \text{Diffraction part still to be subtracted...} \]
Ne Breakup on Carbon: Experimental Response for Protons...

Proton Trigger Efficiency: 100% within statistical error

Proton Drift Chamber Efficiency:
1p: (87.0 +/- 0.5)%
2p: (75.6 +/- 0.9)%

G3 Simulations with R3BRoot:
1- and 2-proton acceptance
3-Body Dissociation of $^{17}$Ne: Reconstruction of the 3-Body rel. Energy

Tracking of 2p events after breakup on Pb or C targets

Precise position from two silicon strip detectors

Precise position from fiber detectors

Output from tracker:
masses, velocities $\rightarrow$ momenta

Precise position from drift chambers

Charge, ToF and rough position from tof wall

$B_\rho = \frac{A}{Z}\beta\gamma$
3-Body Dissociation of $^{17}$Ne: Comparison of Different Targets

preliminary results

Pb target

C target

Empty target

J. Marganiec
3-Body Dissociation of $^{17}$Ne: Total Excitation on Pb

$$\sigma_{tot} = (p_{Pb} - p_{Emp}) \cdot \left( \frac{M_m}{d_{Pb} \cdot N_{Av}} \right)$$

Integrated cross section (from fragments)

498 ± 33 mb
(6.54% - statistic)

Integrated cross section (from spectrum)

356 ± 41 mb
(11.5% - statistic)

140 mb from knockout

Adiabatic cutoff of photon spectrum

$$E_{\gamma_{max}} = \frac{\hbar \cdot c}{b} \cdot \left( \frac{\gamma \cdot b}{b} \right)$$

for $b_{min} = 10.8$ fm

$$E_{\gamma_{max}} = 21$$ MeV

J. Marganiec
3-Body Dissociation of $^{17}\text{Ne}$: Coulomb Excitation on Pb

$$
\sigma_{\text{Coul ex}} = \rho_{\text{Pb}} \cdot \left( \frac{M_{m(Pb)}}{d_{\text{Pb}} \cdot N_{AV}} \right) - \rho_C \cdot \left( \frac{\alpha_{\text{Pb}} \cdot M_{m(C)}}{d_C \cdot N_{AV}} \right) - \rho_{\text{Emp}} \cdot \left( \frac{M_{m(Pb)}}{d_{\text{Pb}} \cdot N_{AV}} - \frac{\alpha_{\text{Pb}} \cdot M_{m(C)}}{d_C \cdot N_{AV}} \right)
$$

Integrated CD cross section (from fragments)

$281 \pm 32 \text{ mb}$

(11.4\% - statistic)

Integrated CD cross section (from spectrum)

$291 \pm 40 \text{ mb}$

(13.7\% - statistic)
Coulomb Dissociation of $^{17}\text{Ne}$: $^{15}\text{O} + p + p$ 3-Body Correlation Analysis

For the description of three-body systems => Jacobi coordinates $\{ \vec{\mathcal{P}}_1, \vec{\mathcal{P}}_2 \}$

The Jacobi momenta are constructed as:

\[
\begin{align*}
\vec{\mathcal{P}}_1 &= \left( \frac{\vec{p}_i}{m_i} - \frac{\vec{p}_j}{m_j} \right) \frac{m_i m_j}{m_i + m_j} \\
\vec{\mathcal{P}}_2 &= \left( \frac{\vec{p}_i}{m_i} + \frac{\vec{p}_j}{m_j} \right) \frac{m_l (m_i + m_j)}{m_i + m_j + m_l} \\
\vec{\mathcal{P}}_{cm} &= \vec{p}_i + \vec{p}_j + \vec{p}_l
\end{align*}
\]

In the case when two of three particles are identical, there are two choices of Jacobi coordinate system, the so called „T” and „Y” systems, where (ijl)=(123) and (ijl)=(231), respectively.

For each three-body system the energy and angular correlations in „T” and „Y” Jacobi coordinate system are obtained.
Coulomb Dissociation of $^{17}\text{Ne}$: $^{15}\text{O}+\text{p}+\text{p}$ 3-Body Correlations

Exp. Sensitivity: Comparison of data to 100% s and 100% d-wave calculations

$E^*$ range (5 – 7 MeV) 100% of s – state 100% of d – state experimental data

J. Marganiec, L. Grigorenko et al.
Summary

- S318 experiment: Study of $^{17}\text{Ne}$ in inverse kinematics

  - Carbon-induced proton knockout $\rightarrow ^{15}\text{O}+\text{p}$
  - Carbon-induced inelastic excitation $\rightarrow ^{15}\text{O}+2\text{p}$
  - Pb-induced Coulomb excitation $\rightarrow ^{15}\text{O}+2\text{p}$

- Preliminary Results:

  - Structure of $^{17}\text{Ne}$ studied via $^{16}\text{F}$ transverse momentum after knockout
    **A moderate $s^2$ content in the two $^{17}\text{Ne}$ valence protons of $\sim 40\%$ is found**
  - Analysis of partial cross sections in progress

  - $^{17}\text{Ne}$ differential Coul.-Diss. Cross section determined
  - Recalculation into photodiss. and radiative-capture x.s. ongoing

  - Analysis of 3-body correlation observables promising for sufficient exp. sensitivity to determine $s^2/d^2$ content in $^{17}\text{Ne}$ g.s. halo.
Outlook

- Near Future:
  - Finalise efficiency, acceptance and resolution for proton detection
  - Spectroscopic factors of $^{17}\text{Ne}$ halo protons from partial cross sections
  - $^{15}\text{O}^*$ gamma rays $\rightarrow$ simulations for XB response

- Further Plans:
  - s/d ratio from shape of $^{16}\text{F}$ relative energy
  - Detailed understanding of higher excitation region in $^{16}\text{F}$

- Analysis of the (p,2p) quasi-free knockout channels
  - Work on theory: QFS reaction codes (C. Bertulani)

Recent QFS experiments at LAND/R$^3$B:

- Talks by Alina Movsesyan
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