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

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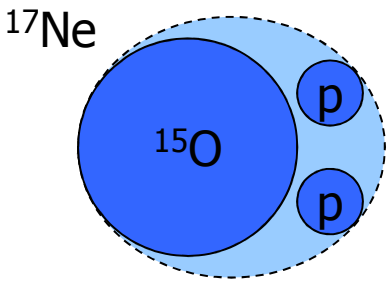
- Motivation:
  - Nuclear Structure of ^{17}Ne & Astrophysics Impact
- Experimental Methods:
  - Knockout Reactions & Coulomb Dissociation
- Results:
  - Proton Knockout and Inelastic Breakup on a C Target
  - Ingredients to the 2p-Removal Cross Section
  - ^{17}Ne 3-Body/Coulomb Spectra
- Summary & Outlook

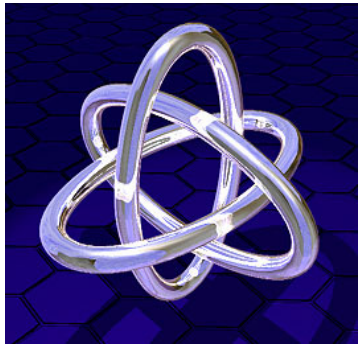
The ^{17}Ne Nucleus - Why is it interesting?

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

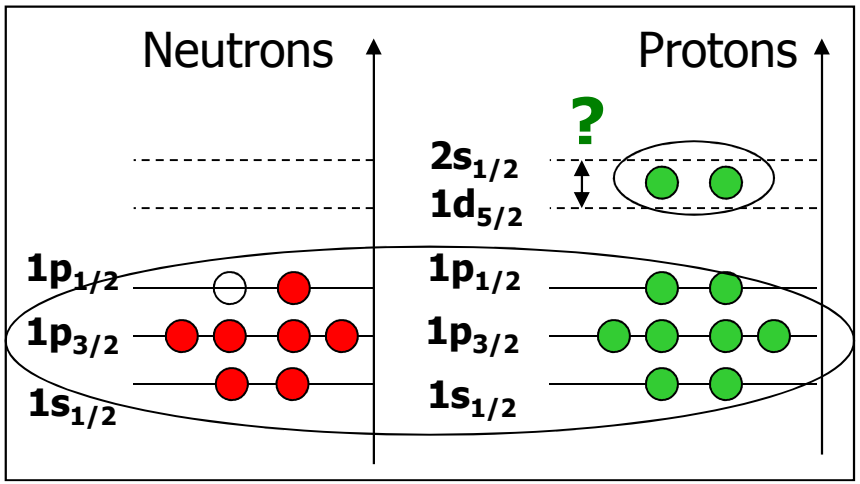
Zhukov & Thompson, PRC 52 (1995) 3505



- ^{17}Ne ≈ ^{15}O + 2p, a borromean 3-body system (p-p and ^{16}F are unbound)
- S_{2p} = 950 keV
- $T_{1/2}$ = 109.2 ms (β^+ to ^{17}F)
- Groundstate $J^\pi=1/2^-$; no bound exc. states



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

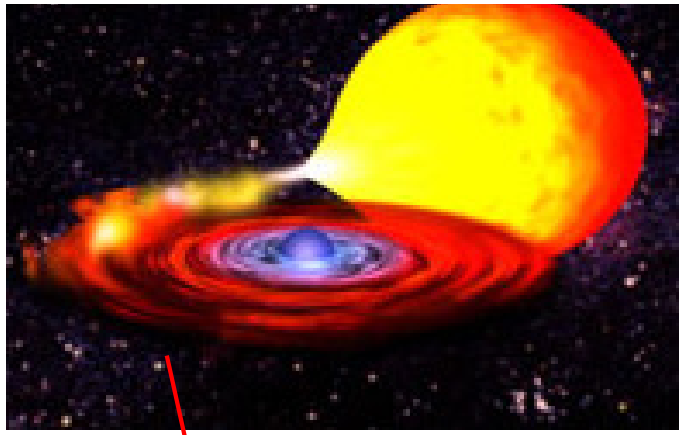


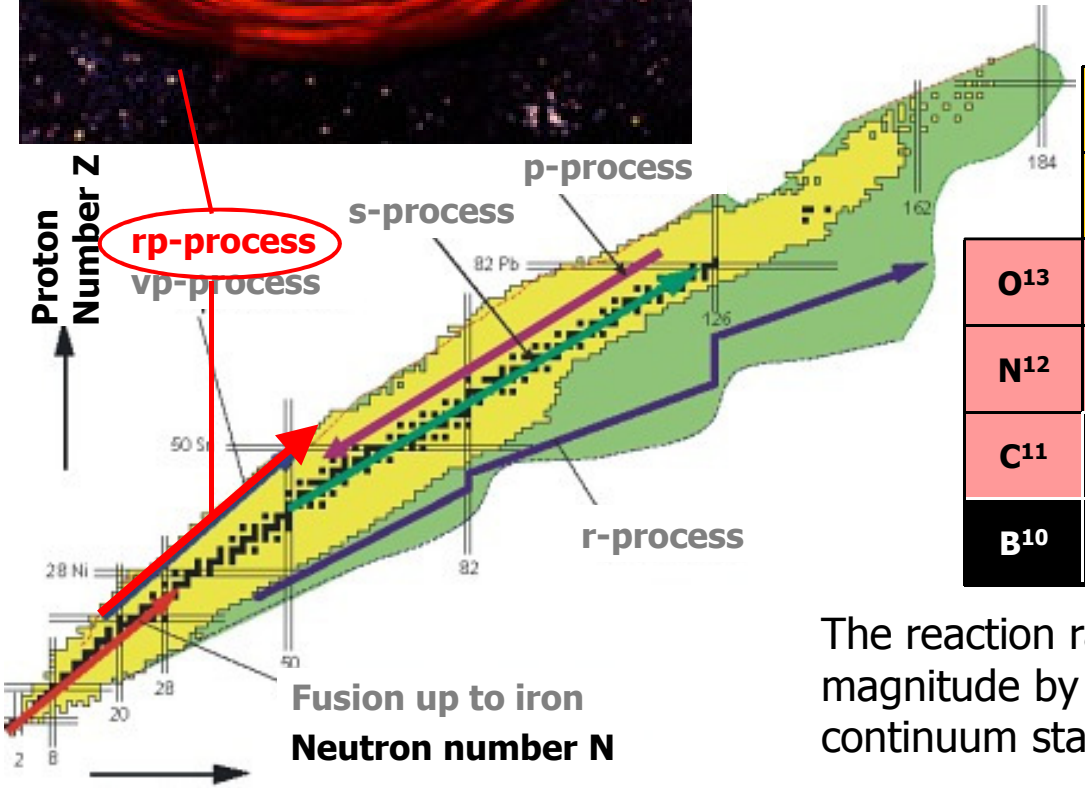
Shell model view of the ^{17}Ne ground-state

- *Grigorenko et al., PRC 71 (2005) 051604(R).*
  - 3-body cluster model: s^2 content 48%.
- *Geithner&Neff et al., PRL 101 (2008) 252502.*
  - Q-radius measurement + FMD: 42% s^2.
- *Tanaka et al., PRC 82 (2010) 044309.*
  - Reaction cross-sections: Long tail in ^{17}Ne matter density, dominant s^2 configuration.
- *Oishi et al., PRC 82 (2010) 024315.*
  - 3-body model: s^2 content 15%.

$^{15}O(2p,\gamma)^{17}Ne$ 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*



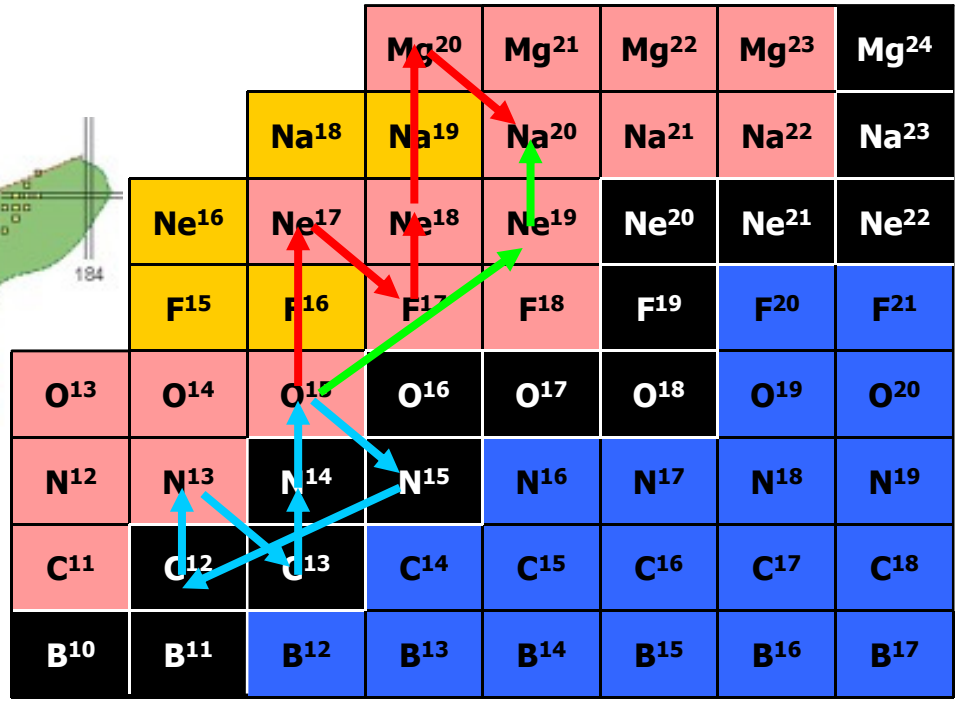


CNO cycle: … $^{14}N(p,\gamma)^{15}O(\beta^-)^{15}N(p,a)$

^{15}O is a waiting point for CNO-cycle breakup:

Heavier elements: … $^{15}O(a,\gamma)^{19}Ne(p,\gamma)$ …

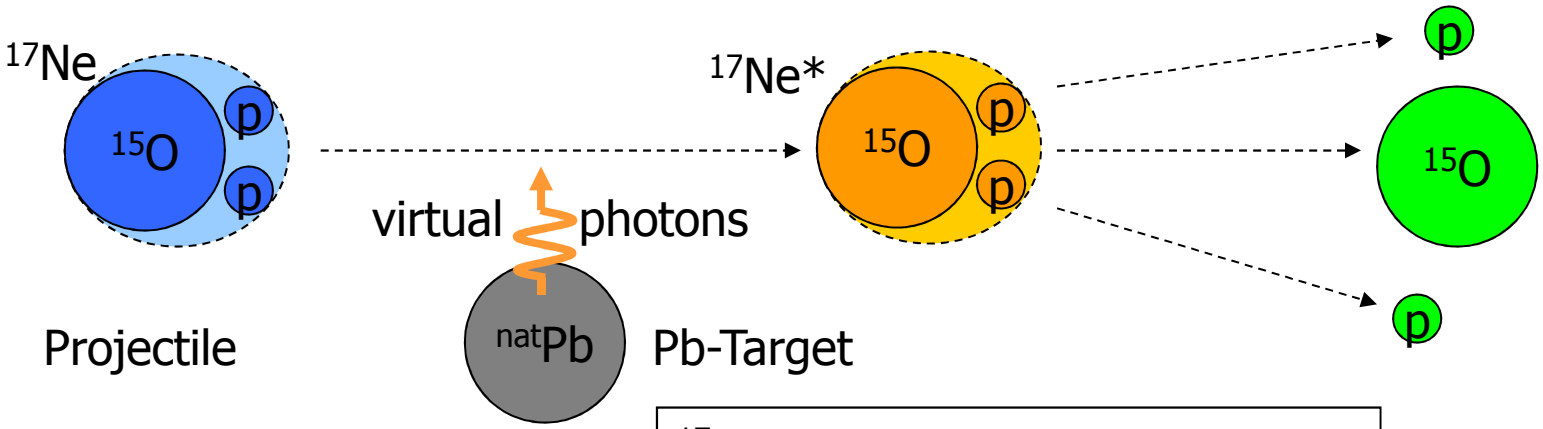
Alternative (rp): … $^{15}O(2p,\gamma)^{17}Ne(\beta^-)^{17}F(p,\gamma)$



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}Ne

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



^{17}Ne Excitation energy spectrum

virtual photon theory

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

detailed balance theorem

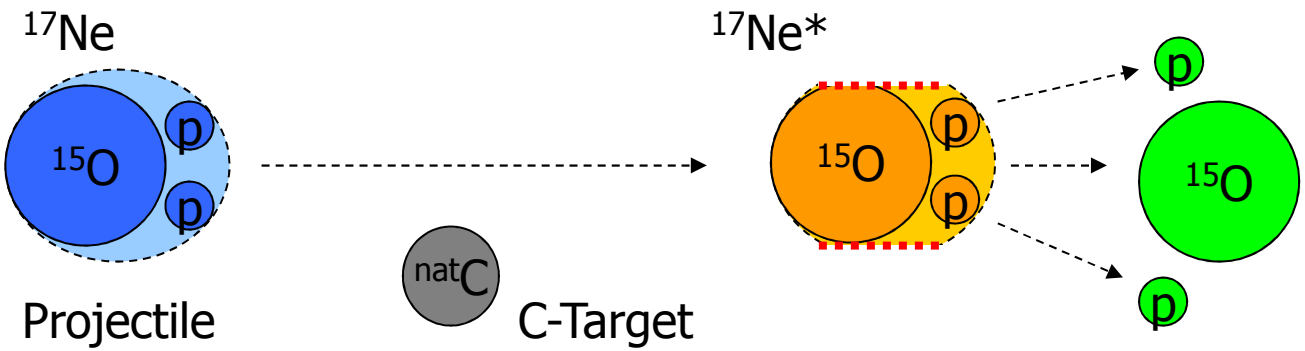
$$\sigma_{(b,\gamma)} = \frac{2(2j_a+1)}{(2j_b+1)(2j_c+1)} \frac{k_\gamma^2}{k^2} \sigma_{(\gamma,b)}$$

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

But also: ^{17}Ne nuclear-structure…

The S318 Experiment: Nuclear Inelastic Excitation of ^{17}Ne

Inelastic / Diffractive Scattering



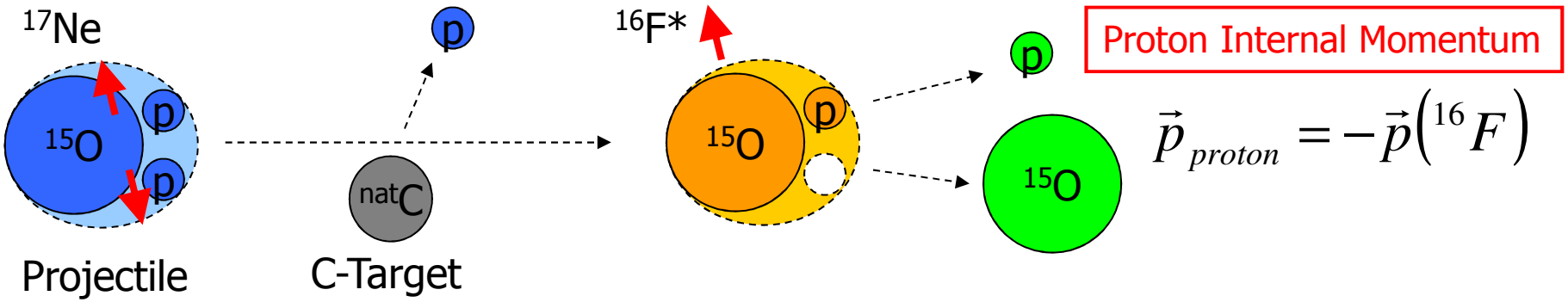
- (Nuclear) inelastic excitation → ^{15}O+p+p final channel
  - ^{17}Ne relative-energy spectrum
  - Competition/Interference with EM (Coulomb) excitation

- 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}Ne

One-proton Knockout



One-proton knockout → ^{15}O+p final channel

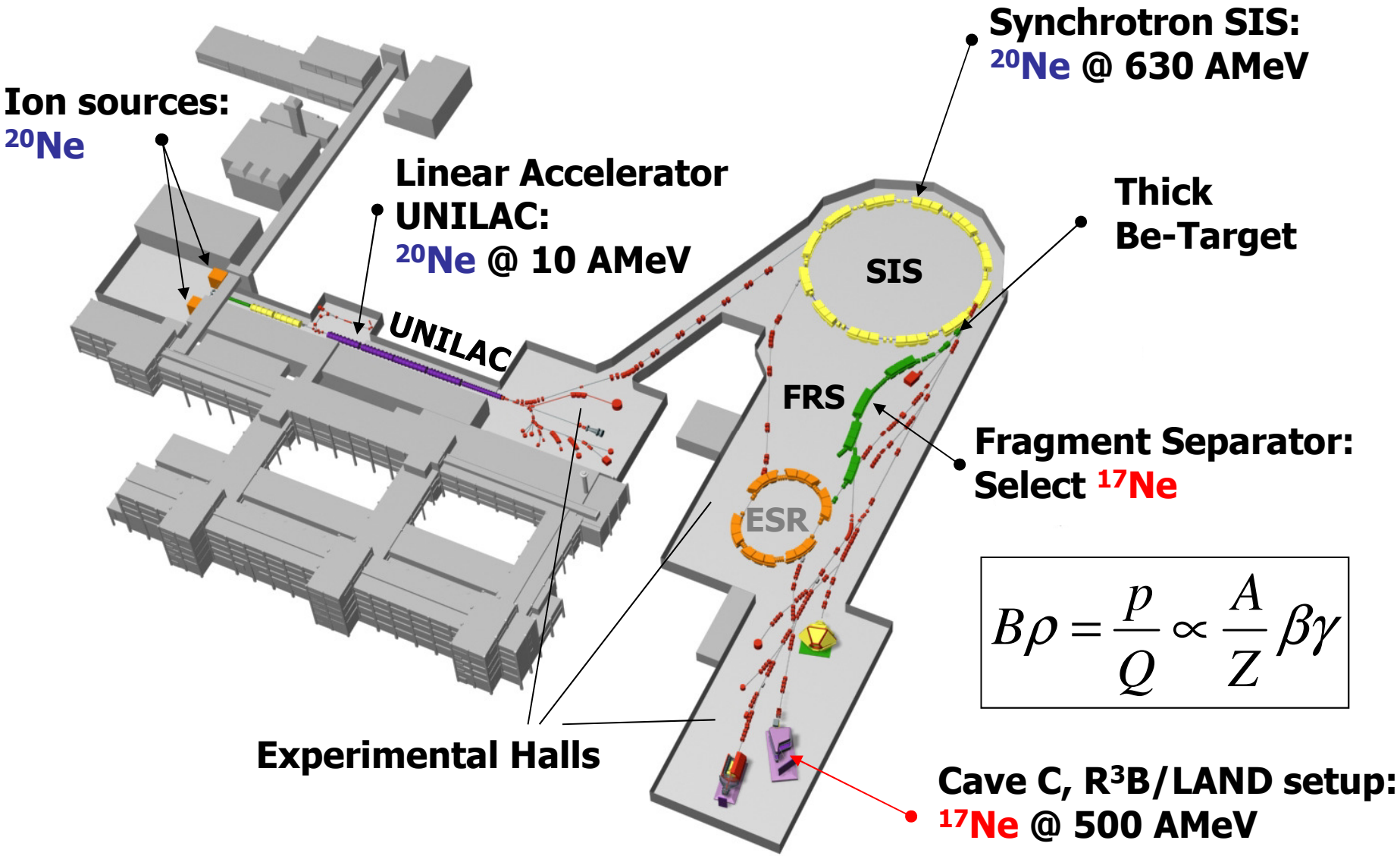
- ^{16}F relative energy spectrum
- Knocked-out proton's internal momentum distribution via momentum of ^{16}F

Glauber-type reaction model

→ Angular momentum of knocked-out proton

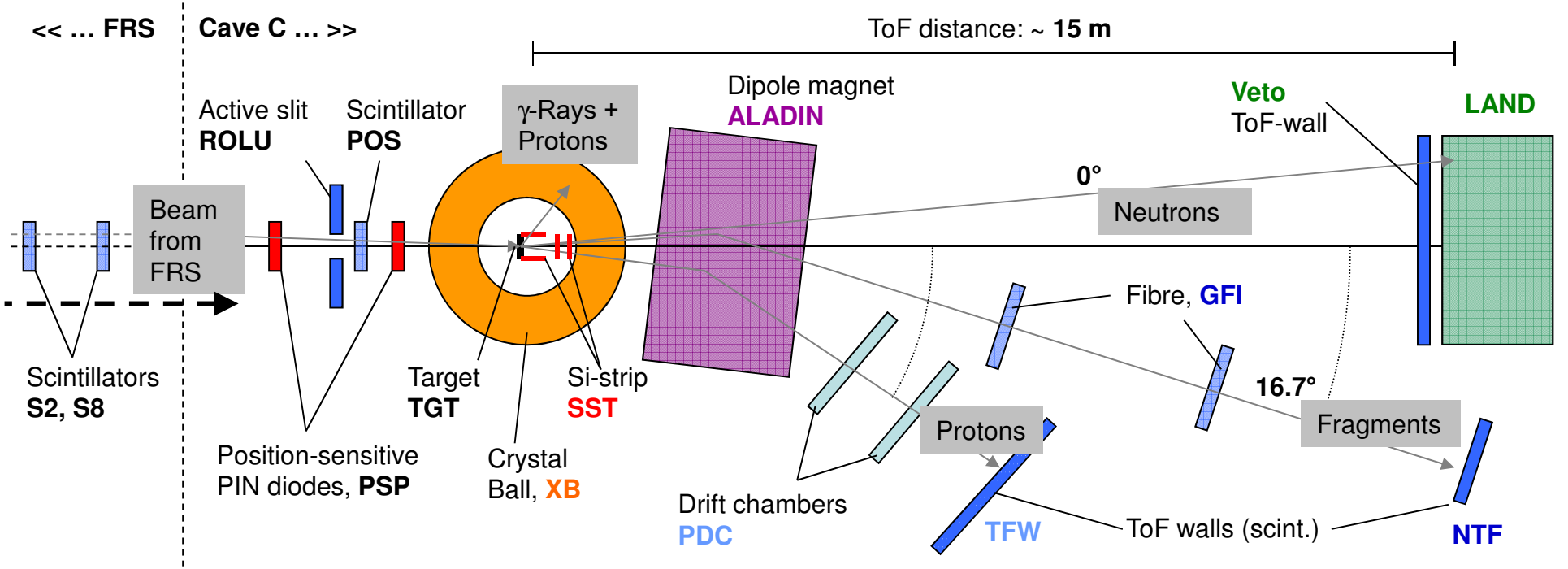
→ s^2/d^2 configuration mixture in ^{17}Ne

The S318 Experiment at GSI – Production of Radioactive ^{17}Ne Beams



$$B\rho = \frac{p}{Q} \propto \frac{A}{Z}\beta\gamma$$

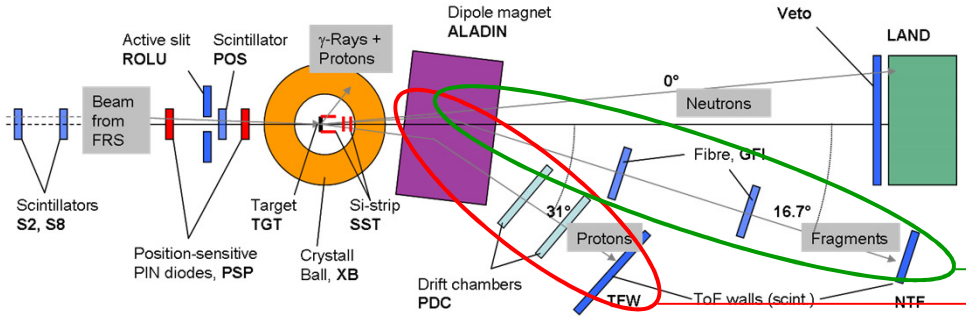
The S318 Experiment: 500 AMeV ^{17}Ne beams → R^{3}B/LAND



Beam detectors:	Tracking & ID of incoming ^{17}Ne beam
(**Crystal Ball**:	4π NaI shell, γ-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)

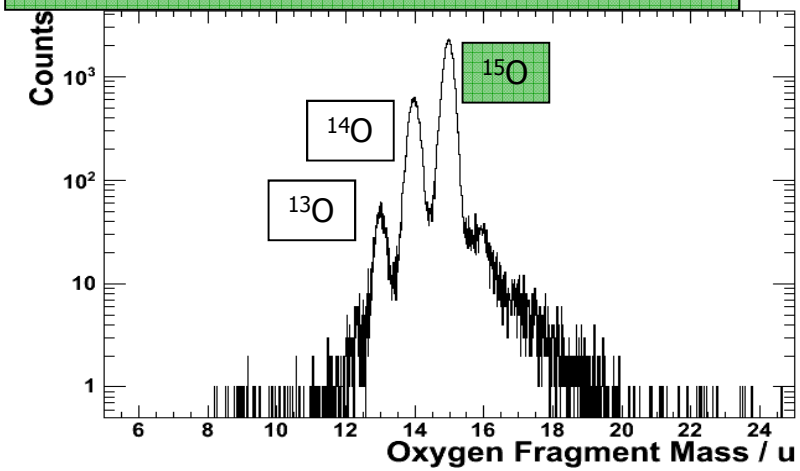
Selection of Reaction Channels – One-Proton Knockout from ^{17}Ne

^{17}Ne ~ 500 AMeV: **C** Target

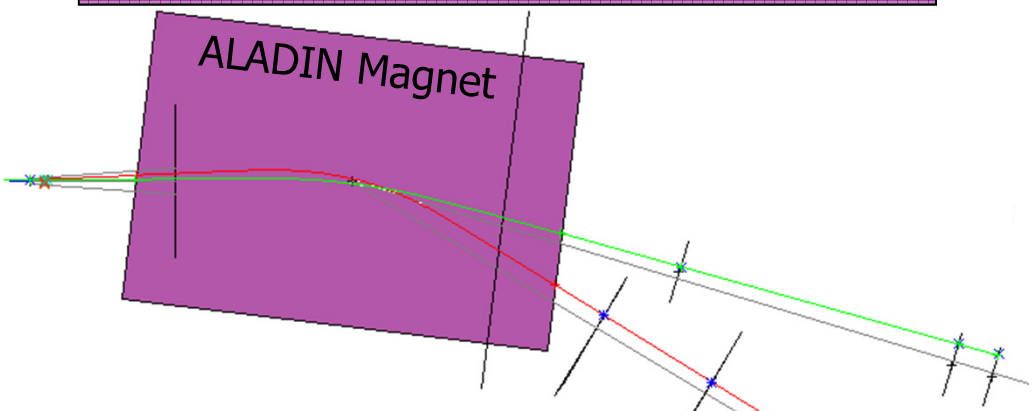


^{17}Ne(C,X)^{16}F → ^{15}O + p

Identification of oxygen mass



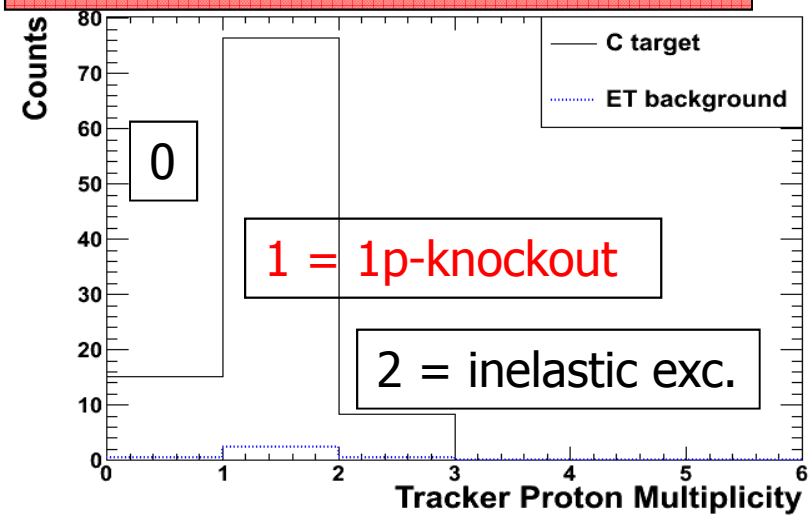
Tracking of fragments and protons



→ Mass and Momentum of Fragment

→ Momenta and Multiplicity of Protons

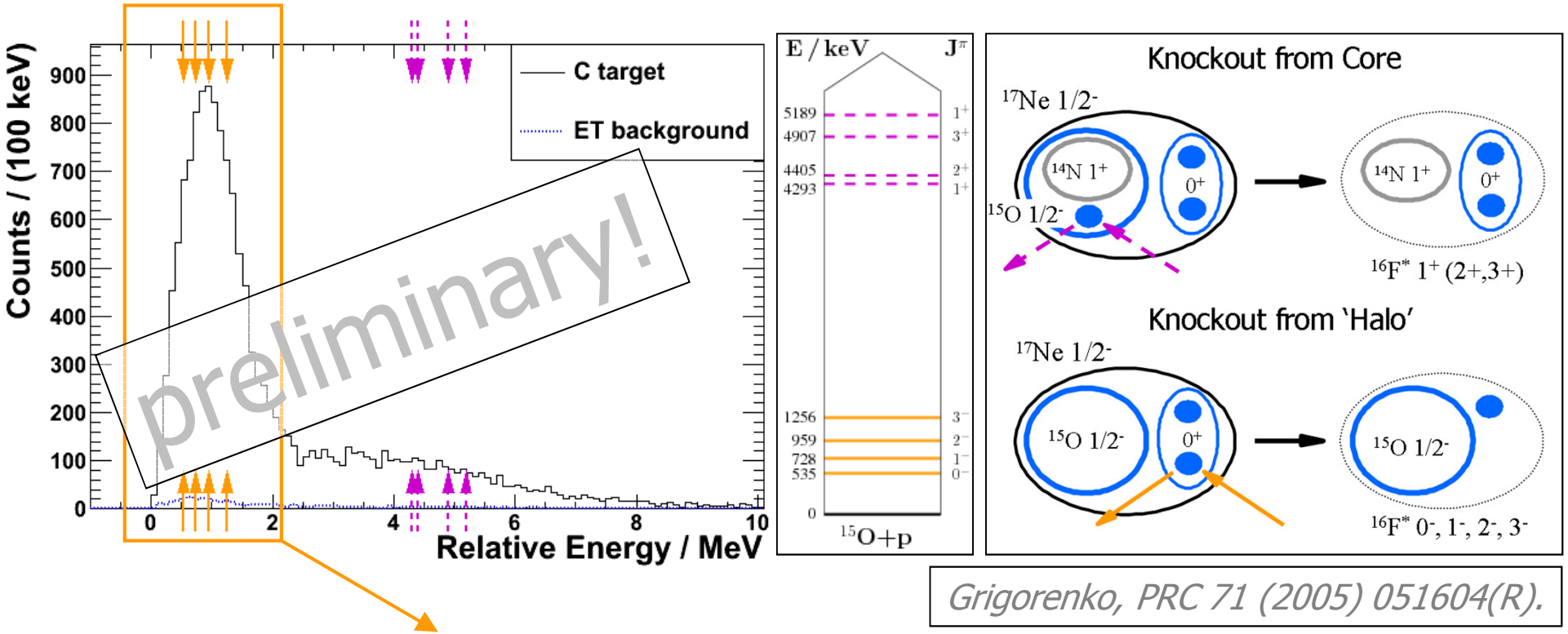
Proton-multiplicity distribution



One-Proton Knockout from ^{17}Ne – ^{16}F Excitation Energy

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

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

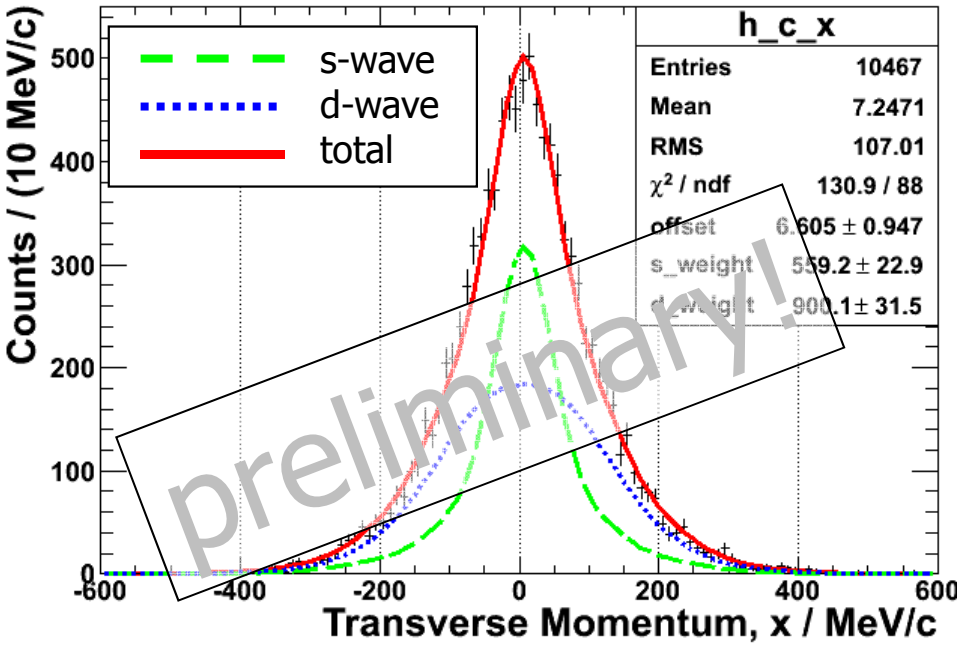


Grigorenko, PRC 71 (2005) 051604(R).

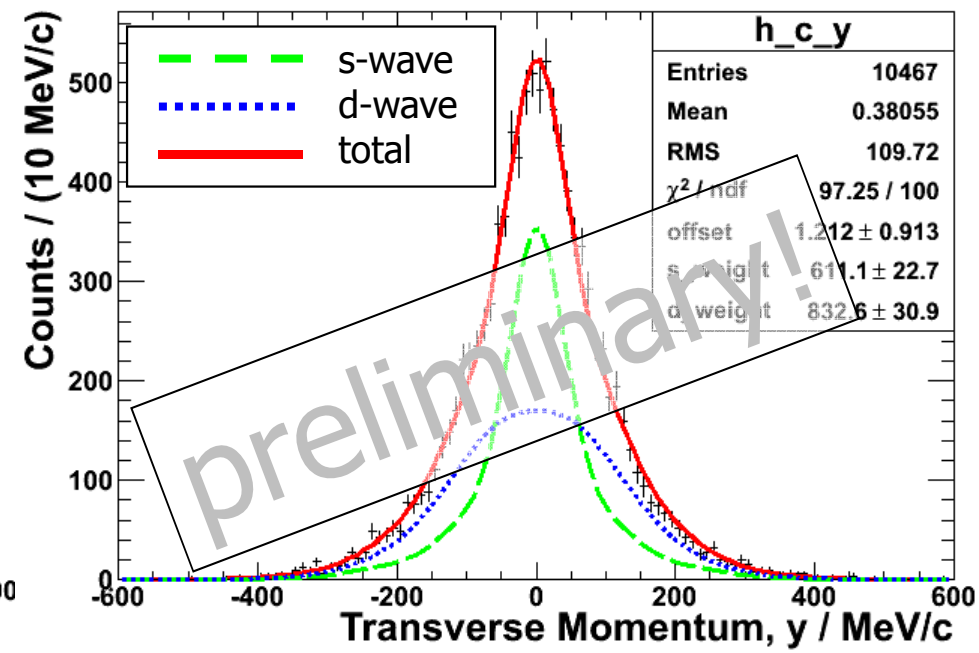
Exclusive selection of knockout from 'halo'-states possible

‘Halo’-Proton Knockout from ^{17}Ne – ^{16}F (=^{15}O+p) Transverse Momentum

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



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



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

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

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

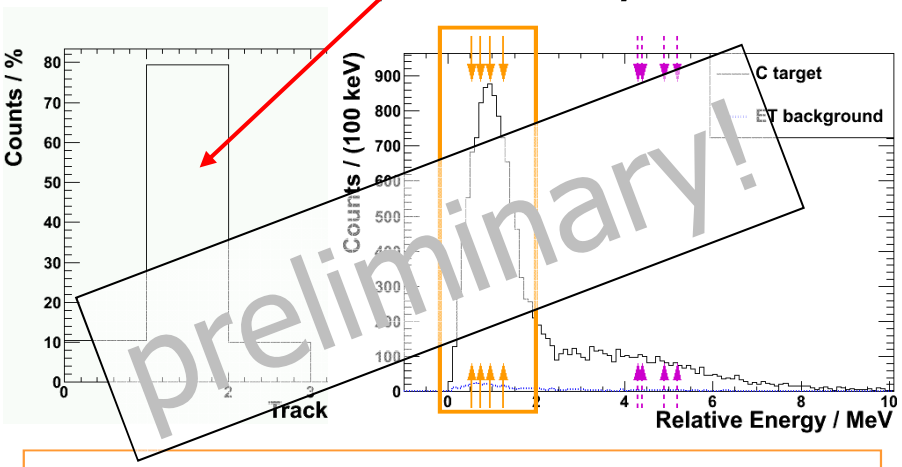
2-proton-removal cross section – Partial cross sections, spectrosc. strength

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

CH_2:	213 ± 5 mb
C:	117 ± 4 mb
(H:	48 ± 3 mb)
Pb:	483 ± 30 mb

$$\sigma_{-2p} \approx \sigma_{ko\_2p} + \sigma_{ko\_1p} + \sigma_{inel.}$$

Estimate for 1p-efficiency: 87%



Percentage of halo knockout: 67%
Corresponds to 71 mb.

Calculations (MOMDIS), C. Bertulani

Single-particle cross sections:

σ_s = 52.7 mb
σ_d = 34.1 mb

41% s-wave content from ^{16}F mom.:

$\sigma_{calc} = 0.41*\sigma_s + 0.59*\sigma_d = 41.70$ mb

'Spectroscopic Strength':

$S = \sigma_{exp}/\sigma_{calc} = 1.7$

Diffractive part still to be subtracted…

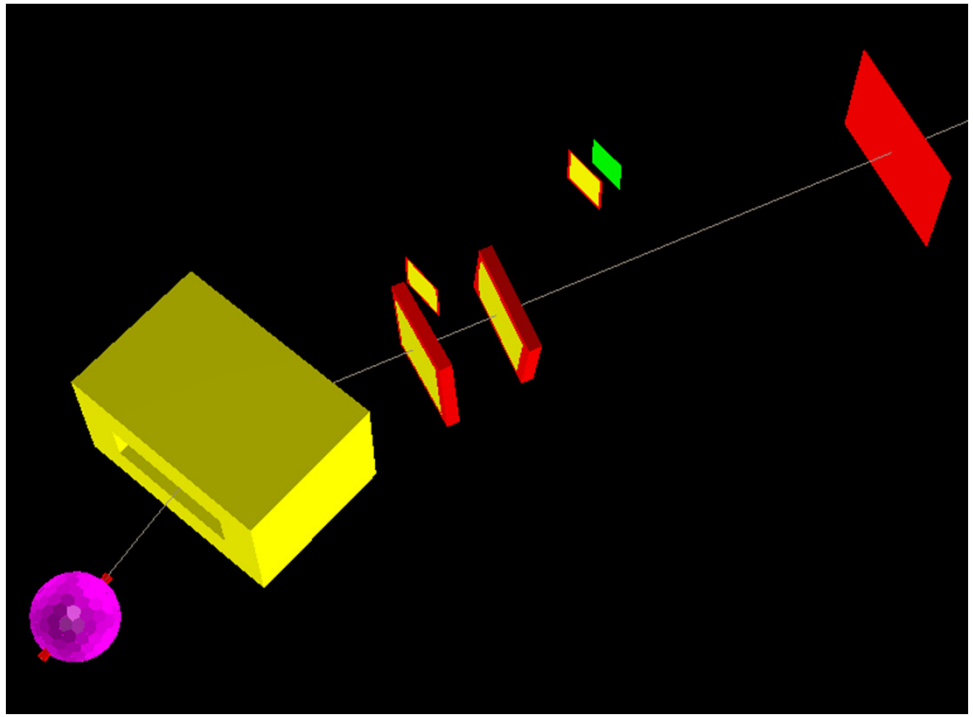
^{17}Ne Breakup on Carbon: Experimental Response for Protons…

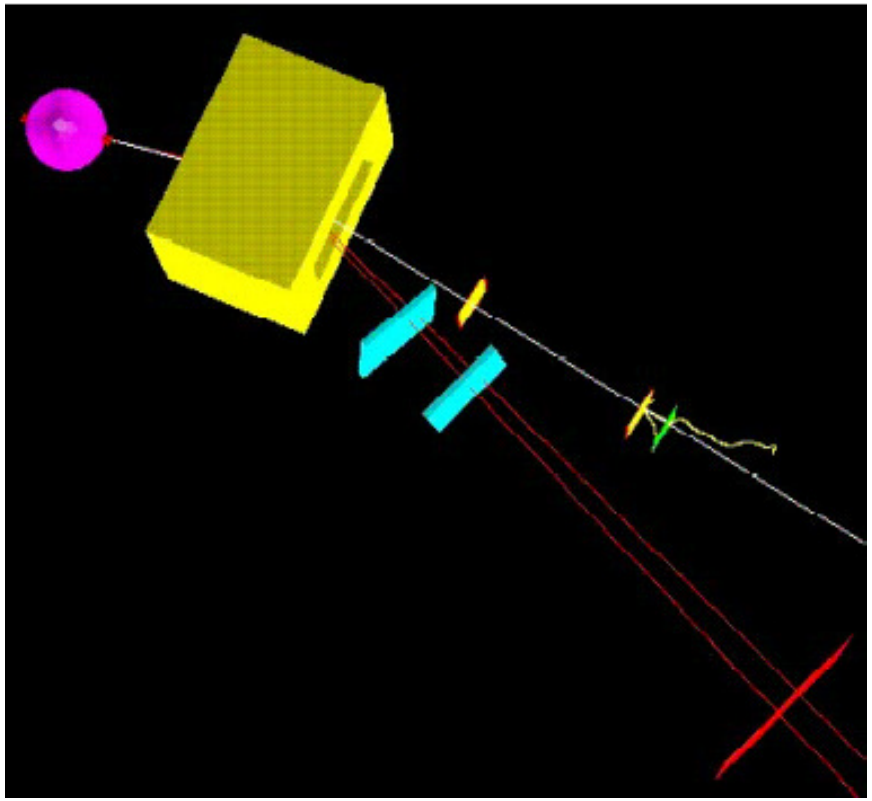
Proton Trigger Efficiency:
100 % within statistical error

Proton Drift Chamber Efficiency:

1p:	(87.0 +/- 0.5)%
2p:	(75.6 +/- 0.9)%

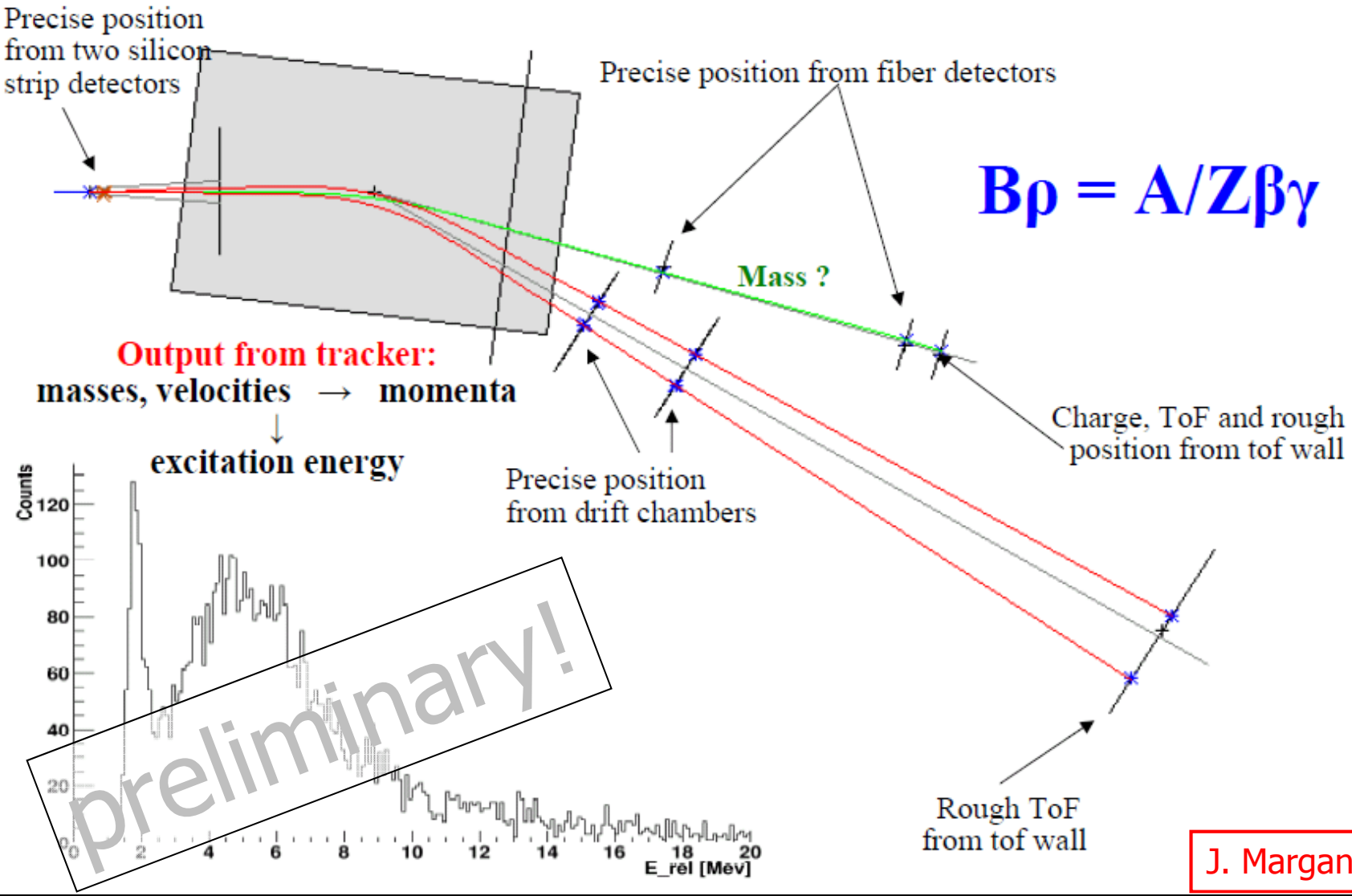
G3 Simulations with R3BRoot:
1- and 2-proton acceptance





3-Body Dissociation of ^{17}Ne: Reconstruction of the 3-Body rel. Energy

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



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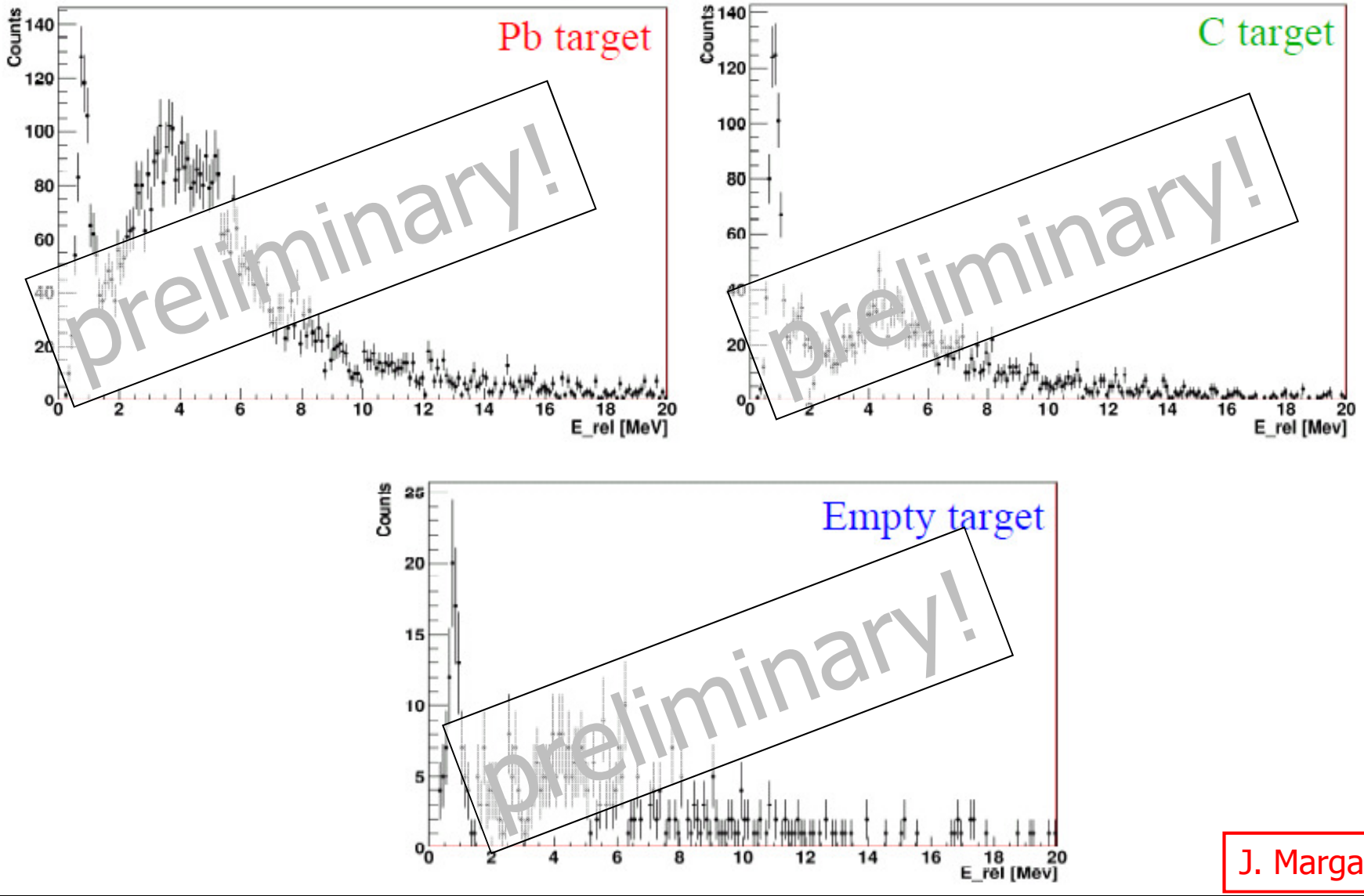
3-Body Dissociation of ^{17}Ne: Comparison of Different Targets

preliminary results



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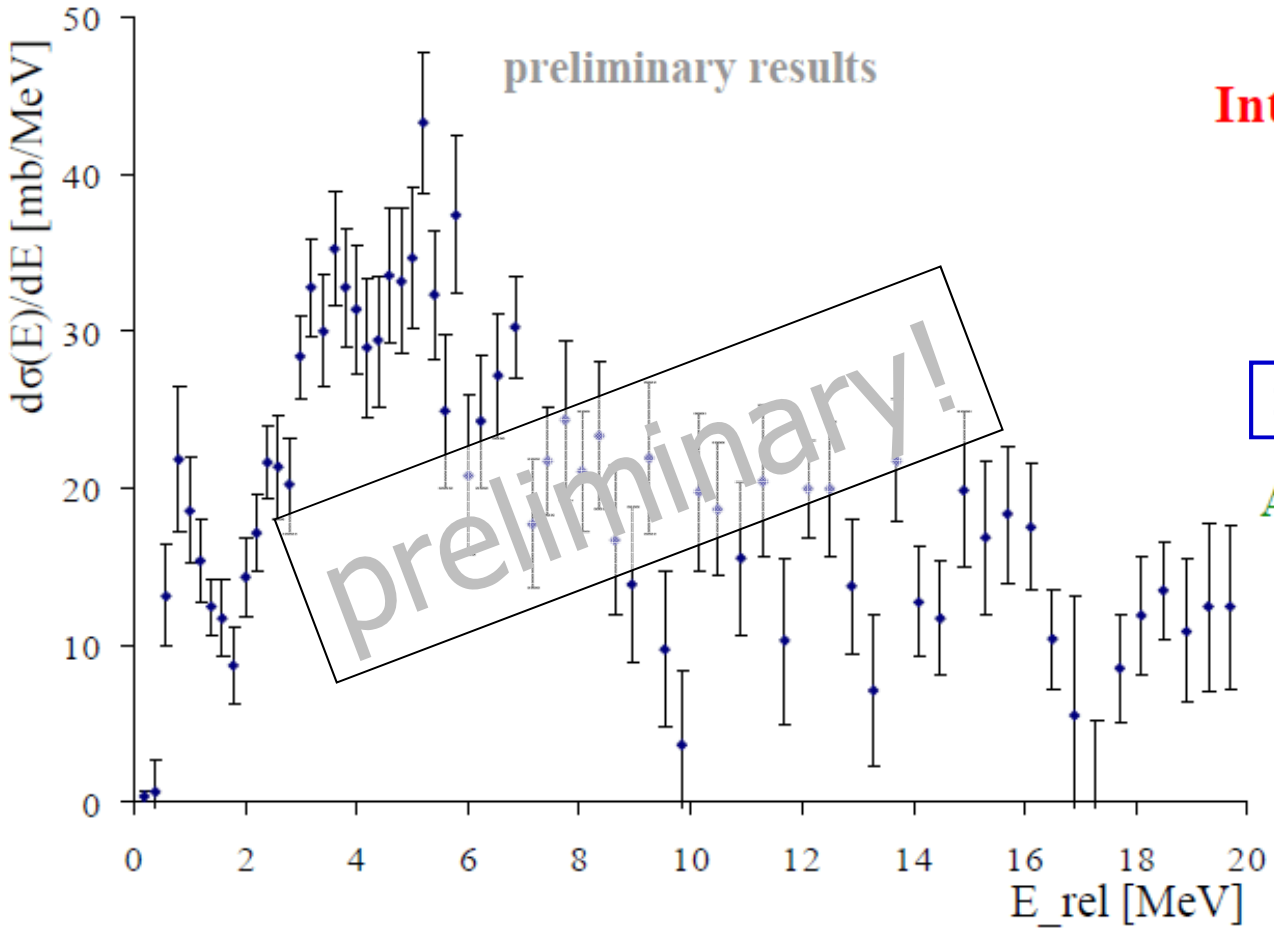
3-Body Dissociation of ^{17}Ne: Total Excitation on Pb

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



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

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

for b_{min} = 10.8 fm

$E_{\gamma max}$ = 21 MeV

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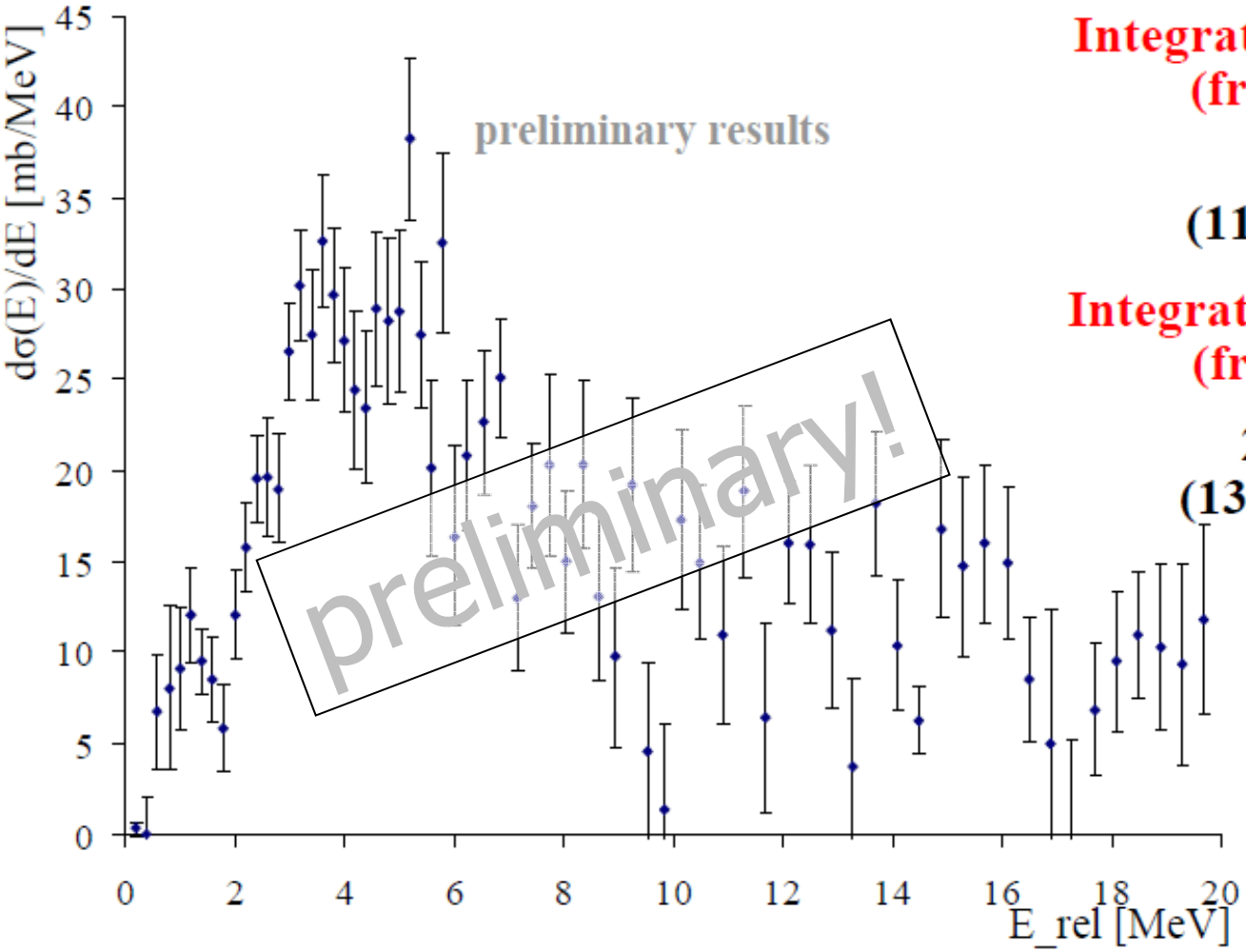
3-Body Dissociation of ^{17}Ne: Coulomb Excitation on Pb

$$\sigma_{Coulex} = p_{Pb} \cdot \left(\frac{M_{m(Pb)}}{(d_{Pb} \cdot N_{Av})} \right) - p_C \cdot \left(\frac{\alpha_{Pb} \cdot M_{m(C)}}{(d_C \cdot N_{Av})} \right) - p_{Emp} \cdot \left(\frac{M_{m(Pb)}}{(d_{Pb} \cdot N_{Av})} - \frac{\alpha_{Pb} \cdot M_{m(C)}}{(d_C \cdot N_{Av})} \right)$$



Integrated CD cross section (from fragments)

281 ± 32 mb
(11.4% - statistic)

Integrated CD cross section (from spectrum)

291 ± 40 mb
(13.7% - statistic)

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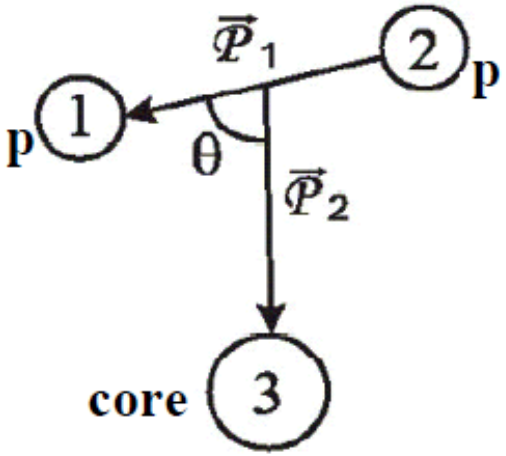
Coulomb Dissociation of ^{17}Ne: ^{15}O+p+p 3-Body Correlation Analysis

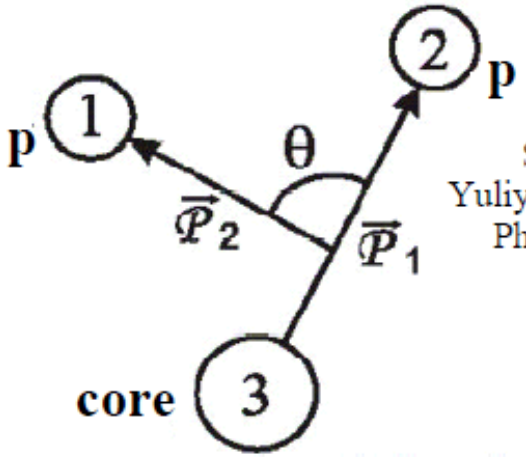
For the description of three-body systems => Jacobi coordinates $\{\vec{\mathcal{P}}_1, \vec{\mathcal{P}}_2\}$

The Jacobi momenta are constracted as:

$$\begin{cases} \vec{\mathcal{P}}_1 = \left(\frac{\vec{p}_i}{m_i} - \frac{\vec{p}_j}{m_j}\right)\frac{m_i m_j}{m_i + m_j} \\ \vec{\mathcal{P}}_2 = \left(\frac{\vec{p}_l}{m_l} - \frac{\vec{p}_i + \vec{p}_j}{m_i + m_j}\right)\frac{m_l(m_i + m_j)}{m_i + m_j + m_l} \\ \vec{\mathcal{P}}_{cm} = \vec{p}_i + \vec{p}_j + \vec{p}_l \end{cases}$$

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.





Source:
Yuliya Aksyutina
PhD Thesis

For each three-body system the energy and angular correlations in „T" and „Y" Jacobi coordinate system are obtained.

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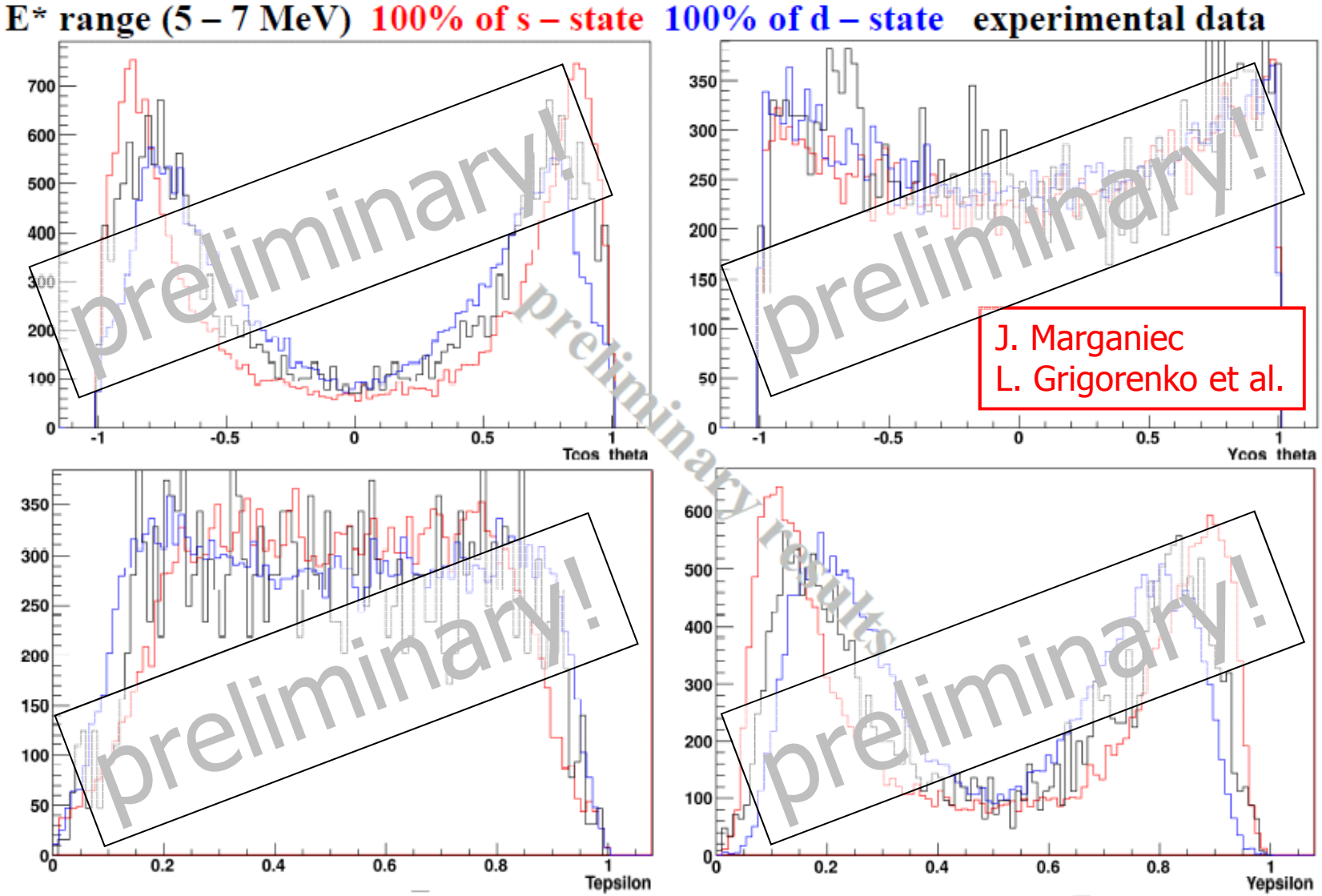
Coulomb Dissociation of ^{17}Ne: ^{15}O+p+p 3-Body Correlations

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



Summary & Outlook

Summary

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

  - Carbon-induced proton knockout → ^{15}O+p
  - Carbon-induced inelastic excitation → ^{15}O+2p
  - Pb-induced Coulomb excitation → ^{15}O+2p

- Preliminary Results:

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

  - ^{17}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}Ne g.s. halo.

Summary & Outlook

Outlook

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

- Further Plans:
  - s/d ratio from shape of ^{16}F relative energy
  - Detailed understanding of higher excitation region in ^{16}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
- Posters by Leyla Atar, Matthias Holl, and Valerii Panin

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Thanks for your attention!