High Energy Protons from C-12 Fragmentation

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Experiment FRAGM

$^{12}\text{C} + \text{Be} \rightarrow f + X$

$^{12}\text{C}$ fragments at $3.5^0$: $p, d, t, ^3\text{He}, ^4\text{He}, ^6\text{He}, ^8\text{He}, \ldots \text{C}$

$^{12}\text{C}$ kinetic energies: $T_0 = 0.2 - 3.2$ GeV/nucleon

Here we focus mostly on: protons with momentum higher than momentum per nucleon of the projectile

Motivation:

✓ origin of high momentum (cumulative) particles in interactions with nuclei is still an open question
✓ there is a lot of data in $\text{pA,nA,\Pi A,\ldots}$ interactions (A.M.Baldin, V.S.Stavinsky, G.A.Leksin and others) and only a few in ion-ion collisions
ITEP accelerator complex TWAC

TWAC = TeraWatt Accumulator Complex

**TWAC current parameters**

- **Proton acceleration**: 50 – 10000 MeV
- **Ion acceleration**: up to 4 GeV/nucleon
- **Ion accumulation**: up to 700 MeV/nucleon
- **Accelerating ions**: up to $^{56}\text{Fe}$
- **Typical intensity**: $10^{11}$ nucleons / s

**Diagram details**:
- **Proton linac I–2**: 25 MeV, 200 mA
- **Ion linac I–4**: 7 MeV/n, 100 mA
- **Ion beam injection line**
- **Ion laser source**
- **Booster synchrotron**: 20 Hz, 1 GeV/n
- **Main ring**
- **Experimental Hall**
- **Medicine ion beam**
- **Medicine proton beam**
- **Multiple injection**
- **Fast extraction, 0.7 GeV/n**
- **Beamline 313 (FRAGM)**
- **Proton and ion beams from internal target**
- **Beams from internal target and slow extraction of protons and ions up to 10 GeV**

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Beam line № 313

- Beam line length: 42 m
- Two bending magnets: K310C3 (bending angle: $\alpha=0.259$ rad.), B313C2 ($\alpha=0.276$ rad.)
- Five quadrupoles: K310I1, B313I3 (vertical focusing) and K310I2, B313B1, B313I4 (horizontal focusing)

- Scintillation counters: CF1, CF2, C2, C3
- C2 generates trigger
- H1 – hodoscope of 20 elements
- Č – Cherenkov counter
Example of fragment selection at 0.3 GeV/nucleon

- QDC (from CF1) vs TOF between CF1 and C2
- Regions of the different fragments are well separated and can be clearly selected
- TOF is a function of Z/A, so it gives a mark for clear fragment identification
Proton selection at high energy

C – Be collisions at 2.0 GeV/nucleon

Number of events

5 GeV/c
Z=1

d
p
t

TOF channel

300 320 340 360 380 400 420 440 460 480 500

316x11
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Relative yields of H and He isotopes

C – Be collisions at 0.3 GeV/nucleon

Proton spectrum has non-Gaussian right tail

Z is a fragment charge
Proton momentum spectrum at 300 MeV/n

In inverse kinematics it is easy to measure evaporation protons even with zero momentum in r.f. and to compare with cumulative protons (C+d→p+..., p=2.35GeV/c)
Variables for physics analysis

(Projectile) + (Target) $\rightarrow$ $P_{\text{forward}} + \text{all}$

$T_0 = T_{\text{proj.}}$ (GeV/nucleon), $p_0 = p_{\text{proj.}}$ (GeV/c/nucleon),

$p$ – outgoing proton momentum

$X = p/p_0$, where $p_0$ is projectile momentum per nucleon and it is also maximal proton momentum for collisions of free nucleons

$X_{lf} = \frac{E+p}{E_0+p_0}$ – relativistic invariant light front variable, for our energy range the difference between $X$ and $X_{lf}$ is 3% – 15%

$X_s$ – introduced by V.S. Stavinsky (JINR) – $(X_s * M_N \text{ – min. projectile mass})$

that can produce proton with given momentum, it is obtained from energy-momentum conservation $(X_s * p_0 + M_N - p)^2 = (X_s * M_N)^2$ for free nucleon target

$X = X_{lf} = X_s$ at high energy but at our energy region $\rightarrow$
For 0.3 GeV/n, $X=2.3 \rightarrow X_s = 12$
Comparison of $X_s$ and $X$-spectra at 300 MeV/n

Our data cover 8 orders in $X_s$ and almost 7 in $X$.

Invariant cross section (a.u.)

Limit for $C+p \rightarrow p + \ldots$

$\sim (X_s)^{-6.8}$

$\sim \exp(-10X)$

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Nature of **cumulative protons** is under discussion up to now.

Within appropriate models they can come from:

- highly excited nuclear pre-fragments (FLUKA, RQMD)
- intranuclear multiple scattering (V. Kopeliovich)
- fluctuations of nuclear matter density (Blokhintsev)
- short-range correlations (SRC) of nucleons (Frankfurt, Strikman)
- **multiquark clusters** (Burov, Lukyanov, Titov (1984); Efremov, Kaidalov, Lykasov, Slavin (1994))

We tried to estimate the probabilities of the existence in nucleus of the multiquark clusters using approaches by Efremov and Kaidalov in the framework of quark–gluon string model (QGSM)
Cumulative protons from multiquark clusters

Production of cumulative protons is considered as fragmentation into protons of clusters consisting of 3k valence quarks (k=1: (3q) – nucleon, k=2: (6q) – two-nucleon cluster, k=3: (9q) – three-nucleon cluster); \( w_k \) is the probability to find \( k \)-nucleon cluster in \(^{12}\text{C}\); \( x = \frac{p}{p_0} \)

\[
\frac{E d^3\sigma}{d^3p(x,p_t^2)} = C'(w_1g(x,p_t^2)+w_2b_2(x,p_t^2)+w_3b_3(x,p_t^2))
\]

\[
g(x,p_t^2) = G \exp(-0.5 \frac{(1-x-\Delta)^2}{\sigma_x^2}) \exp(-0.5 \frac{p_t^2}{\sigma_p^2})
\]

\[
b_2(x,p_t^2) = B_2 \frac{x}{2}^3 (1-x/2)^3 \exp(-\alpha_1 p_t^2), \quad b_2(x,p_t^2) = 0 \text{ at } x > 2
\]

\[
b_3(x,p_t^2) = B_3 \frac{x}{3}^3 (1-x/3)^6 \exp(-\alpha_2 p_t^2), \quad b_3(x,p_t^2) = 0 \text{ at } x > 3
\]

where \( g, b_2, b_3 \) are known fragmentation functions (QGSM).

\( G, B_2 \) and \( B_3 \) are known normalization constants.

Transverse parameters \( \alpha_1 \) and \( \alpha_2 \) from Phys. Rev. C 28 (1983) 1224

\[
G = \frac{1}{(2 \cdot \sigma_x \cdot \sqrt{2\pi}) \cdot 1/(2 \cdot \sigma_p^2)}, \quad \sigma_p = \sigma_x \cdot m_p \cdot p_0/E_0,
\]

\[
\int \int B_i \cdot b_i(x,p_t^2) dx dp_t^2 = i/2, \quad i = 2, 3
\]

Fitted variables are: \( C', W_2 = w_2/w_1, W_3 = w_3/w_1, \Delta, \sigma_x \)
X spectra at different energies

- $T_0 = 300$ MeV
  - $\sigma_{max} = 0.1467 \pm 0.009341$
  - $k = 0.344 \pm 0.4847$
  - $w2 = 0.0062 \pm 0.01254$
  - $w3 = 0.001727 \pm 0.001546$
  - $x(0) = 0.9085 \pm 0.01314$

- $T_0 = 600$ MeV
  - $\sigma_{max} = 0.1386 \pm 0.004797$
  - $k = 1.406 \pm 0.101$
  - $w2 = 0.06352 \pm 0.0113$
  - $w3 = 0.004472 \pm 0.001944$
  - $x(0) = 0.9877 \pm 0.009375$

- $T_0 = 2$ GeV
  - $\sigma_{max} = 0.1776 \pm 0.009593$
  - $k = 28.19 \pm 2.782$
  - $w2 = 0.11 \pm 0.020391$
  - $w3 = 0.005861 \pm 0.0008154$
  - $x(0) = 0.9202 \pm 0.01745$

- $T_0 = 3.2$ GeV
  - $\sigma_{max} = 0.1819 \pm 0.002343$
  - $k = 2.257 \pm 0.3503$
  - $w2 = 0.3207 \pm 0.105$
  - $w3 = 2.359e-013 \pm 0.3694$
  - $x(0) = 0.9655 \pm 0.04442$
# Probabilities of quark clusters existence

<table>
<thead>
<tr>
<th>$T_0$, GeV/n</th>
<th>$w_1$ (3q)</th>
<th>$w_2$ (6q)</th>
<th>$w_3$ (9q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.95</td>
<td>0.05(1)</td>
<td>0.002(1)</td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>0.06(1)</td>
<td>0.004(1)</td>
</tr>
<tr>
<td>0.6</td>
<td>0.915</td>
<td>0.08(1)</td>
<td>0.005(2)</td>
</tr>
<tr>
<td>2.0</td>
<td>0.894</td>
<td>0.10(2)</td>
<td>0.006(1)</td>
</tr>
<tr>
<td>3.2</td>
<td>0.76</td>
<td>0.24(8)</td>
<td>-</td>
</tr>
</tbody>
</table>

V.Burov et al (1977), pions, fluctuation


H.J. Pirner, J. P. Vary (2011)(QCM)

- Quantitative estimates on few nucleon clusters in nuclei could be obtained from fragmentation data
- Wider range on X and wider projectile energy range are desirable
Proton yields from reaction $^9\text{Be} \; (^{12}\text{C},\; \text{p}) \; X$ were measured at $T_0 = 0.2 \; – \; 3.2 \; \text{GeV/nucleon}$ in projectile fragmentation region.

✓ Proton momentum spectra are obtained in both evaporation and cumulative regions. Data cover seven orders of cross section magnitude.

✓ For the first time data were obtained in a region unreachable for nucleon-nucleus interactions.

✓ Cumulative number $X$ spectra were analyzed in a multi quark cluster + quark gluon string model.

✓ Probabilities of existence of 6q and 9q clusters in $^{12}\text{C}$ were estimated to be $w_6 \sim 10\%$ and $w_9 < 1\%$. Results for $w_6$ are in reasonable agreement with theoretical predictions and J–LAB measurements.
Thank You