Observation of the antimatter Helium-4 (anti-\(\alpha\)) nucleus

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- Introduction & Motivation
- Evidence of the observation of \(4\overline{He}\)
- Quality check for \(4\overline{He}\)
- \(4\overline{He}\) invariant yields
- Summary

arXiv:1103.3312v2
DOI: 10.1038/nature10079
History of antimatter
Relativistic heavy ion collider (RHIC)

• RHIC as an antimatter production facility, can create controllable, repeatable “little bangs”.

• Determine whether $^4\text{He}$ exists, provide a point of reference for future observations in cosmic radiation.
Production mechanisms

Coalescence


Statistical model

\[ N_i = V g_i \int \frac{d^3p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right) \]

• Relativistic Heavy Ion collisions:
  High antibaryon density
  High temperature
• Favorable environment for both production mechanisms.

STAR White paper NPA 757, (2005) 102-183
STAR detectors

- Time Projection Chamber (TPC) - momentum & dE/dx
- Online High Level tracking Trigger (HLT) - Select events with charge-2 tracks

• 2007 AuAu 200GeV (TPC).
• 2010 AuAu 200GeV and 62GeV selected by HLT (TPC +TOF).
• One billion AuAu collisions.
STAR high level trigger

- Sector level 3 (SL3).
  - 24 in total, each for a TPC sector.
  - data acquisition.
  - hit reconstruction.
  - online sector tracking

- Global level 3 (GL3).
  - event reconstruction.
  - selecting events with charge-2 tracks.

- ~70% efficiency for events with charge-2 tracks, compared to offline reconstruction.
- Select ~0.4% of events.

Poster #127, A. Tang
Particle identification


- 2 counts from year 2007 are identified by TPC alone.
- dE/dx merge together at higher momentum region, TOF information is needed.

\[ n\sigma_{dE/dx} = \frac{1}{R_{dE/dx}} ln\left( \frac{<dE/dx>^\text{measured}}{<dE/dx>^\text{expected}} \right) \]

\[ R_{dE/dx} \sim 7.5\% \]
Particle identification

- TPC:
  - Track path length: \( \frac{L}{\Delta t} \)
  - Magnetic rigidity: \( \frac{p}{|Z|} \)

- TOF, VPD:
  - Time of flight: \( \Delta t \)
  - Velocity: \( \beta = \frac{L}{\Delta t} \)

\[
m^2/Z^2 = p^2/Z^2 (\frac{1}{\beta^2} - 1)
\]
• An clean separation for $^3\text{He}$ and $^4\text{He}$ can be seen by projecting to mass axis.
• Candidates counted within the windows of, -2. $<n\sigma_{dE/dx}< 3.$, and, 3.35GeV/c$^2 < \text{mass} < 4.04\text{GeV/c}^2$.

16+2 $^4\text{He}$ counts in total.
$t^{\text{expected}} = l \sqrt{1 + m^2/p^2}, \quad t_A = t_A^{\text{expected}} + t_B - t_B^{\text{expected}}, \quad m_A = p_A \sqrt{(t_A^2/L_A^2 - 1)}$

- $^3\text{He}$ expands its mass distribution to $^4\text{He}$ area because of TOF timing resolution, and contributes to the backgrounds of $^4\text{He}$.
- We reproduce $^3\text{He}$ mass distribution using a “$t$” calculated with “$t^{\text{expected}}$” and time deviation ($\Delta t$) from other tracks.
- 1.4(0.05) backgrounds in 15(1) from 200GeV(62GeV) Au+Au collisions recorded in 2010.
- The miss-identification probability is $\sim 10^{-11}$ (a significance more than 6$\sigma$).
Quality check for $^4\text{He}$

Anti-α track qualities and event display figures

Anti-α information:
- Run10 200GeV Au+Au collisions

1. First anti-α candidate track qualities.

| runID    | evtID  | vtxZ   | RefMult | nHits | nHitsdEdx | p/|Z| | eta     | phi    | dca     | L     | chi2 | nσdHe | toflocalZ | toflocalY | tof | β | M     |
|----------|--------|--------|---------|-------|-----------|----|----|--------|--------|--------|--------|----------|-----------|-----|----|-------|
| 11073003 | 164108 | -4.21  | 478     | 41    | 20        | 2.319 | 0.791 | 2.835  | 0.789  | 250.75 | 1.62   | 2.11     | -0.92      | -1.49   | 12.14 | 0.78  | 3.726 |

- Red dots highlights the $^4\text{He}$ candidate.
- Hits and tracks within 5cm around the candidate are shown.
- Different colors stand for tracks with different magnitude of momentum.
$^{4}\text{He}$ invariant yields

Particle ratios:
- Measured:
  \[
  \frac{^{4}\text{He}}{^{3}\text{He}} \sim (3.0 \pm 1.3 \text{(stat)}) \times 10^{-3}
  \]
  \[
  \frac{^{4}\text{He}}{^{3}\text{He}} \sim (3.2 \pm 2.3 \text{(stat)}) \times 10^{-3}
  \]
- Statistical model:
  \[
  \frac{^{4}\text{He}}{^{3}\text{He}} \sim 3.1 \times 10^{-3}
  \]
  \[
  \frac{^{4}\text{He}}{^{3}\text{He}} \sim 2.4 \times 10^{-3}
  \]

E. Schnedermann. PRC 48, (1999), 2462

\begin{align*}
E_A \frac{d^3 N_A}{d^3 p_A} & \propto B_A \left( E_p \frac{d^3 N_p}{d^3 p_p} \right)^A \\
E_A \frac{d^3 N_A}{d^3 p_A} & = \frac{gV}{(2\pi)^3} E e^{-m_p A/T}
\end{align*}

An exponential trend is predicted by both coalescence and statistical model.
Production rate reduce by $1.6 \times 10^3$ (1.1 $\times 10^3$) for each additional anti-nucleon (nucleon) added to the anti-nucleus (nucleus).
The yield of the stable antimatter nucleus next in line (B = -6) is predicted to be down by a factor of $2.6 \times 10^6$ compared to $^{4}\text{He}$ and is beyond the reach of current accelerator technology.
Antimatter search in the Universe

$^4\text{He}$ in the Cosmos, hint of the existence of massive antimatter in the Universe.
Summary

• $^4\text{He}$ were observed in AuAu collisions with data from year 2007 and year 2010. Considering the background, the probability of miss-identification is $10^{-11}$ (a significance more than 6$\sigma$).

• The invariant yields of $^4\text{He}$ and $^4\text{He}$ were calculated with central events. An exponential trend was observed, consistent with the expectations from coalescence and thermodynamic models.

• Barring the dramatic discovery of heavier stable anti-nucleus in the Universe, or a new breakthrough in accelerator technology, it is likely that $^4\text{He}$ will remain the heaviest stable antimatter nucleus observed in the foreseeable future.

• RHIC is an ideal antimatter production facility, and, with TOF and HLT, STAR is in a good position to study exotic nuclei production.

Thank you!
Back up
18 counts in total.
- 15 from Run 10 Au+Au 200 GeV collisions
  5 minbias + 5 central with 1 tagged by both triggers
  6 from other triggers.
- 1 from Run10 Au+Au 62 GeV collisions
- 2 from Run7 Au+Au 200 GeV collisions

In Run 10 200 GeV Au+Au collisions.

<table>
<thead>
<tr>
<th></th>
<th>Counts</th>
<th>Background</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>26</td>
<td>3.5</td>
<td>7.6</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>15</td>
<td>1.4</td>
<td>6.5</td>
</tr>
</tbody>
</table>
$^{4}\text{He}$ yields

- $^{4}\text{He}/^{3}\text{He}$ ratio is measured with Run10 200GeV central collisions.
- Using $^{3}\text{He}$ invariant yields $dN/(2\pi p_T dp_T d\eta)$ from previous measurements to calculate $^{4}\text{He}$ yields.
- $p_T/A : 0.75 \sim 1 \text{ GeV/c}$
- $^{4}\text{He}: 5$  
- $^{4}\text{He}: 2$
- $^{3}\text{He}: 953$  
- $^{3}\text{He}: 352$

\[
\alpha/\text{primary He3} : 3.0 + 1.3 \text{ (stat)} + 0.5 - 0.3 \text{ (sys) e-3}
\]
\[
\text{anti } \alpha/\text{primary anti He3} : 3.2 + 2.3 \text{ (stat)} + 0.7 - 0.2 \text{ (sys) e-3}
\]

<table>
<thead>
<tr>
<th>helium3</th>
<th>$2.85e-06 \pm 0.30e-6\text{(stat)} + 0.29-1.14e-06\text{(sys)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-helium3</td>
<td>$1.02e-06 \pm 0.11e-06\text{(stat)} + 0.10-0.41e-06$</td>
</tr>
<tr>
<td>helium4</td>
<td>$8.6e-09 \pm 3.8e-09\text{(stat)} + 0.9-2.8e-09\text{(sys)}$</td>
</tr>
<tr>
<td>anti-helium4</td>
<td>$3.3e-09 \pm 2.4e-09\text{(stat)} + 0.5-0.9e-09\text{(sys)}$</td>
</tr>
</tbody>
</table>
• The miss-identification probability can be calculated with Poisson distribution as below:

\[ p = \frac{m^k}{k!} e^{-m} \]

\[ p(15/1.4) = \frac{1.4^{15}}{15!} e^{-1.4} \sim 3.0 \times 10^{-11} \]

• With the miss-identification probability, the significance “\( n \)” can be calculated with formula:

\[ P(x >= S + B) = \int_n^{+\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \, dx \quad n \sim 6.5 \]
\[ m^2 = p^2 \left( \frac{t^2}{l^2} - 1 \right) \]

\[ m \delta m = p^2 t \delta t / l^2 \]