TRANSPORT OF $\vec{3He}^{2+}$, FROM SOURCE TO COLLISION

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RHIC Run 14: collisions with Helium-3 for the first time, on Gold

### PARTICLE DATA / POLARIZATION

<table>
<thead>
<tr>
<th></th>
<th>units</th>
<th>proton</th>
<th>$^2$H$^+$</th>
<th>$^3$He$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>mass</strong></td>
<td>$MeV/c^2$</td>
<td>938.272046</td>
<td>1875.6128</td>
<td>2808.39148</td>
</tr>
<tr>
<td></td>
<td>$10^{-27}kg$</td>
<td>1.672621777</td>
<td>3.34358348</td>
<td>5.00641234</td>
</tr>
<tr>
<td><strong>mass/amu</strong></td>
<td>$MeV/c^2$</td>
<td>1.00727646</td>
<td>2.013553212</td>
<td>3.01493222</td>
</tr>
<tr>
<td><strong>charge Q</strong></td>
<td>$</td>
<td>e</td>
<td>$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$Q/A$</td>
<td>1</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td><strong>number of nucleons, N</strong></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td><strong>number of protons, Z</strong></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>spin quantum number</strong></td>
<td>1/2</td>
<td>1</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td><strong>magnetic moment, $\mu$</strong></td>
<td>$\mu_N$</td>
<td>2.7928474</td>
<td>0.85743823</td>
<td>-2.1276253</td>
</tr>
<tr>
<td>gyromagnetic ratio $g = \frac{\mu}{\mu_N} \times \frac{2m_p\mu_N}{Ze\hbar}$</td>
<td>$\mu/\mu_N$</td>
<td>2</td>
<td>1.99900759</td>
<td>2.99315281</td>
</tr>
<tr>
<td>anomalous mag. moment $G = \frac{g-2}{2}$</td>
<td>1.7928474</td>
<td>-0.1429872</td>
<td>-4.18415382</td>
<td></td>
</tr>
<tr>
<td>Imp. resonance interval $</td>
<td>mc^2/G</td>
<td>$</td>
<td>$MeV$</td>
<td>523.3</td>
</tr>
</tbody>
</table>

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nuclear magneton unit, $\mu_N = \frac{e\hbar}{2m_p}$ eV/T 3.1524512 $\times 10^{-8}$

atomic mass unit, amu $MeV/c^2$ 931.494061

elementary charge, e C 1.602176565 $\times 10^{-19}$

speed of light in vac. m/s 2.99792458 $\times 10^8$

$\hbar$ J.s 1.054571726 $\times 10^{-34}$

eV.s 6.58211928 $\times 10^{-16}$
### SOME PARAMETERS OF RHIC AND INJECTORS

#### Proton, for comparison

**BOOSTER INJECTION:**
- kinetic E (GeV): 0.2
  - Hyp.: Energy out of linac (Ref. CJG)
- $B\rho$ (T.m): 2.1496
- $\gamma$: 1.2132
- $\beta\gamma$: 0.6868
- $G\gamma$: 2.175

**BOOSTER EXTRACTION / AGS INJECTION:**
- kinetic E (GeV): 1.4167
  - Max. $B\rho$ in Booster is 17 T.m
- $B\rho$ (T.m): 7.2051
- $\gamma$: 2.5100
- $\beta\gamma$: 2.3021
- $G\gamma$: 4.5

**AGS EXTRACTION / RHIC INJECTION:**
- kinetic E (GeV): 22.8738
- $B\rho$ (T.m): 79.3668
- $\gamma$: 25.3786
- $\beta\gamma$: 45.5
- $G\gamma$: 45.5

**Comments**

#### $^3\text{He}^{2+}$ data, best knowledge:

**BOOSTER INJECTION:**
- kinetic E (MeV/N): 2.0146
  - Hyp.: $\beta = 0.0655$ from EBIS IH DTL
- $B\rho$ (T.m): 0.3075
- $\gamma$: 1.0022
- $\beta\gamma$: 0.0656
- $G\gamma$: -4.1932

**BOOSTER EXTRACTION / AGS INJECTION:**
- kinetic E (GeV): 2.2256
  - Consistent w/ p: $B\rho_{\text{inj,} ^3\text{He}^{2+}} \approx B\rho_{\text{inj,p}}$
- $B\rho$ (T.m): 6.9678
- $\gamma$: 1.7925
- $\beta\gamma$: 1.4876
- $G\gamma$: -7.5
  - Alternate possibility: -10.5
    - Requires $Q_y < 4.5$ so to escape $12 - Q_y$
    - Interest: injection into AGS beyond 0+; requires $Q_y > 4.5$ so to avoid $6 + Q_y$

**AGS EXTRACTION / RHIC INJECTION:**
- kinetic E (GeV): 27.7311
  - $B\rho_{\text{xtr,} ^3\text{He}^{2+}} \ll B\rho_{\text{xtr,p}}$, whereas
  - $B\rho = 79.36 \to G\gamma = -71$,
  - this leaves room for extraction beyond 60-.
- $B\rho$ (T.m): 50.7185
- $\gamma$: 10.8743
- $\beta\gamma$: 10.8282
- $G\gamma$: -45.5

**Other possibilities?**
- $B\rho \rightarrow 55$ T.m: -49.5
  - Better spin match to vertical $\vec{m}_0$ in RHIC; plateau is further away from 36+, 36+ crossed faster.
- $B\rho \rightarrow 79$ T.m: $<-51$
  - -60+$Q_y$ is a strong depolarizing resonance
3He SOURCE

- EBIS has provided He2+, Ne5+, Ar10+, Fe20+, Ti18+, Cu11+, Au32+, U39+ ... for NSRL or RHIC.

  Helion adds to the list ... polarization requires dedicated developments.

- High polarization of optically-pumped 3He cell requires the latter to be placed inside the solenoid. The second solenoid, part of EBIS upgrade.

- Requirements:
  - $2 \times 10^{11} \, ^{3}\text{He}^{2+}$ in a 2$\mu$s pulse (4 mA)
  - spin-flip every pulse
  - compatibility with regular EBIS operation

- Plans:
  - EBIS upgrade, on-going
  - Installation 2022 - 2023
  - Expected polarization 80%
BOOSTER

OPTION 1/2: Extract at $G^\gamma = -7.5$ / acceleration to $B^p \approx 7$ (today’s proton)

- **Imperfection resonances**, $G^\gamma - n = 0$

  - proton range: $G^\gamma : 2.175 \rightarrow 4.5$
  - $^{3}\text{He}^{2+} : G^\gamma : -4.19 \rightarrow -7.5$
  - 2 resonances,
  - at $G^\gamma = 3, 4$
  - 3 resonances, at $G^\gamma = 5, 6, 7$

- Correction method: orbit harmonic correction or excitation (spin flip)

- **Intrinsic resonances**, $G^\gamma - n = \pm Q_y$

```
\left\{ \begin{array}{l}
  \text{set injection } Q_y \approx 4.11 \text{ to avoid } 0 + Q_y (\text{injection } G^\gamma = 4.19) \\
  \text{maintain } 12 - Q_y \text{ beyond extraction } G^\gamma = -7.5, \text{ using } Q_y < 4.5
\end{array} \right.
```
OPTION (2/2)

- Extract at a higher \( G_\gamma \)
- \( G_\gamma = -10.5 \) is the next best match to AGS \( \vec{n}_0 \) beyond \( G_\gamma = -7.5 \):

\[ G_\gamma = -10.5 \]

\( \vec{n}_0 \) in the AGS:

- blue: vertical component of the stable spin direction \( \vec{n}_0 \)
- red: spin tune
Extraction $G\gamma = -10.5$ imposes crossing $G\gamma = -12 + Q_y \approx -8^+$

That also requires crossing $G\gamma = -6 - Q_y \approx -10^-$
as extracting before -6-Qy would require moving $Q_y > 4.5$ and we do not like that!

- Interest of extraction $|G\gamma| > 7.5$:
  - $G\gamma = -7.5$ is $B\rho = 6.97$ T.m, even lower than proton’s at $B\rho = 7.21$ at $G\gamma = 4.5$;
  - this low-rigidity region is one of substantial optics perturbations in the AGS:
    strong betatron distortion, and coupling.

- Higher extraction rigidity from booster requires visiting capabilities:
  Booster MM power supplies; booster extraction kicker (9.5 T m); injection system limits in AGS ...

[C. Gardner, Injector setup for Helions in eRHIC, Spin Meetings, Nov. 18, 2015]
AN AC DIPOLE

Has been installed in Booster.

\[ G_\gamma = -12 + Q_y \]

\[-6 - Q_y\]

AC dipole & tune kicker at booster E3 straight:

\[ f_{osc} \approx 250 \text{ kHz} \]

Plans:

- Next Fall: Establish beam dynamics and acceptance upon wide vertical beam shaking
- January 2021: polarized proton beams will allow establishing spin flipping

Resonance crossed will be \( G_\gamma = 0 + Q_y \) (\( Q_y \approx 4.2 \))

\[ ^3\text{He in AGS} \]

• $^3$He in AGS (cont’d)

- $G = -4.18$: AGS partial snakes are 2.3 times stronger than for protons

- This is ok for overcoming 1.5 times stronger resonances.

- Issue however: snakes induce $\vec{n}_0$ tilt resulting in harmful $81$ resonance series

\[ G_{\gamma} = \text{int.} \pm Q_x, \text{stronger with } ^3\text{He}. \]

- With $^3$He, snakes are

\[ \frac{|G_{^3\text{He}}|}{G_p} = 2.3 \text{ times stronger than for protons} : \]

<table>
<thead>
<tr>
<th>B max (T)</th>
<th>Warm snake</th>
<th>Cold snake</th>
</tr>
</thead>
<tbody>
<tr>
<td>B nominal (T)</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>snake angle (deg.)</td>
<td>{ proton: $^3\text{He}^{2+}$: } $\approx 11$</td>
<td>$\approx 21$</td>
</tr>
<tr>
<td>“$%$ snake”</td>
<td>{ proton: $^3\text{He}^{2+}$: } $6$</td>
<td>$12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$15$</td>
</tr>
</tbody>
</table>

- At identical normalized emittance, strengths of intrinsic resonances satisfy

\[ \frac{|\epsilon_{^3\text{He}}|}{|\epsilon_p|} = \sqrt{\frac{|G_{^3\text{He}}|}{G_p}} \approx 1.5 \]
• Foreseen: two 35%+15% partial snakes generate a large spin tune gap.
• Both betatron tunes can be put into gap to avoid all depolarizing resonances.

\[ Q_x \text{ and } Q_y \text{ in spin gap } \Rightarrow G\gamma = \text{int. } \pm Q_{x,y} \text{ never happens :} \]

\[ G g = \frac{1 - Q_s}{Q_x, Q_y}, \quad n_{0,y} \]

Proof-of-principle tracking simulation: a 2000-\(^3\)He bunch, \( G\gamma = -7.5 \rightarrow -45.5 \):

• Higher injection rigidity from booster requires visiting capabilities: injection system limits in AGS; RF systems/frequencies ...

[\text{C. Gardner, Injector setup for Helions in eRHIC, Spin Meetings, Nov. 18, 2015}]
Vertical component of $\vec{n}_0$ at AGS extraction septum (red) and at RHIC Blue injection kicker (blue curve). Snakes 6% and 15%.

Proton case for comparison.

The ATr line.
• Todays 100% transmission to 100 eV and 15% loss to 255 GeV indicate a resonance compensation threshold (by the pair of full snakes) in 0.18-0.45.

• Resonances with $^{3}\text{He}^{2+}$ are stronger by
  \[
  \left( \frac{|G_{^{3}\text{He}}|}{G_{p}} \right)^{1/2} = 1.53,
  \]
snakes are \( \frac{G_{^{3}\text{He}}}{G_{p}} = 2.3 \) as strong.

• On the other hand:
  - resonance spectrum is denser
  - imperfection and intrinsic resonances overlap, this affects polarization (excites snake resonances)

• Simulations show that 2 snakes do not maintain polarization upon crossing of
  \( G_{\gamma} = -411 + Qy \ (\gamma = 91) \) or
  \( G_{\gamma} = -393 - Qy \ (\gamma = 101) \) ...
- Whereas 6-snake do ... and beyond $G_{\gamma} = 717 + Q_{y} (\gamma \approx 170)$

$1 \times \text{sigma invariant} = 0.75 \mu m$

- 6 snakes ensure $N_{\text{snakes}} > 5 \times \text{Max}[\epsilon_{\text{int}}] \approx 5$,
- $2\pi/6$ distance ensures energy-independent $Q_{s}$,
- snake axes at $\phi_{k} = \pm 45^o$ yield
  $Q_{s} = \frac{1}{\pi} \sum_{k=1}^{6} (-)^{k} \phi_{k} = 3/2$
- build 4 additional snakes from existing, like-helicity, rotator modules
In Summary:

- No showstopper
- Substantial amount of work left to converge on design and parameters:
  - conclude on possible options
  - settle questions related with higher rigidity out of Booster / into AGS
  - complete whatever work is needed to assure $> 70\%$ at store ...
- ... for real soon, 2023+ ?

Thank you for your attention