Talk overview

1. Introduction
2. Method
3. Results
4. Future work
5. openQCD-FASTSUM
Introduction
Although mesons have been thoroughly studied at finite temperatures, baryons have not been given nearly the same attention.

- They have definite parity: $P \mathcal{O}_B(x) = \mathcal{O}_B(x)$
- Experimentally accessible results
- Important for model builders
  - Quark models, e.g. hadron resonance gas
  - Verification of thermodynamic models
More broken symmetries...

In nature baryon parity is a broken symmetry

\[ m_{\{uud\}^{1/2^+}} \equiv m_N = 0.939 \text{ GeV} \]
\[ m_{\{uud\}^{1/2^-}} \equiv m_{N^*} = 1.535 \text{ GeV} \]

Similar to other broken symmetries, what happens to this one as we increase temperature and enter the deconfined phase?
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Previous studies by FASTSUM:

1502.03603, 1703.09246, 1710.00566, ...
Open questions

• Does parity restoration happen at $T_c$?
• How does hadron content effect parity restoration?
• Is there a flavour hierarchy in the deconfinement transition?
• How does $m_\pi$ affect parity restoration?
Method
Lattice setup - Gen2l ensembles

Results produced with the FASTSUM "Gen2l" ensembles (lattice parameters by the HadSpec collaboration)

- $N_f = 2 + 1$ dynamical quarks, Wilson-Clover action
- Anisotropic action: $a_s = 0.1227(8)$ fm, $a_s/a_t = 3.5$
- $m_\pi = 236$ MeV, $m_s = physical$

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Have to be checked, numbers from Gen2 ensembles
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By the HadSpec collaboration
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Still generating
Use the following baryon interpolation functions:

\[ \chi_{N, \gamma} = \epsilon^{abc} u^a \gamma (u^b_\alpha (C_{\gamma 5})_{\alpha \beta} d^c_\beta) \]
\[ \chi_{\Delta^+, \gamma, \mu} = \epsilon^{abc} (2 u^a \gamma (u^b_\alpha (C_{\gamma \mu})_{\alpha \beta} d^c_\beta) + d^a_\gamma (u^b_\alpha (C_{\gamma \mu})_{\alpha \beta} u^c_\beta)) \]
\[ \chi_{\Delta^{++}, \gamma, \mu} = \epsilon^{abc} u^a \gamma (u^b_\alpha (C_{\gamma \mu})_{\alpha \beta} u^c_\beta) \]

for all baryons that can be constructed with from them having flavour content using \{u, d, s, c\}

- \( N, \Delta_{s/c}, \Sigma_{s/c}, \Sigma^*_{s/c}, \Xi_{s/c}, \Omega_{s/c} \)

Sinks and sources smeared with Gaussian smearing to extract ground states
Results
Due to charge conjugation symmetry (at $\mu = 0$)

$$G_\pm(\tau, p) = -G_{\mp}(1/T - \tau, p)$$

Thus the correlation function is a sum of forward moving parity$^+$ states and backwards moving parity$^-$ states.
Correlation functions

\[ \bar{G^+} \]

\[ \bar{G^-} \]

\[ \text{parity}^+ \]

\[ \text{parity}^- \]

\[ \frac{T}{T_c} = 0.63 \]

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Parity channels - nucleon

\[ \text{parity}^+ \quad \text{parity}^- \]

\[ \frac{\tau}{a_\tau} \quad \text{nucleon} \]

\[ T/T_c = 0.63 \]
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Parity channels - $\Omega$ particle

\[
\begin{align*}
\text{parity}^+ & \quad \text{parity}^- \\
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\end{align*}
\]
Parity channels - $\Omega_c$ particle

![Graph showing the relationship between parity channels and $\Omega_c$ particle](image)
Symmetry restoration parameter - the R parameter

\[ R(\tau) = \frac{G_+(\tau) - G_+(1/T - \tau)}{G_+(\tau) + G_+(1/T - \tau)} \]

- \( R(\tau) \neq 0 \Leftrightarrow \) no parity doubling
- \( R(\tau) = 0 \Leftrightarrow \) parity doubling

The summed ratio is a quasi-order parameter (as we will see)

\[ R = \frac{\sum_n R(\tau_n)/\sigma^2(\tau_n)}{\sum_n 1/\sigma^2(\tau_n)} \]
The R-factor - $S = 0$
The R-factor - $S = -1$
The R-factor - \( S = -2 \)
The R-factor - $S = -3$
The R-factor - $\Omega_c$ particle

![Graph showing the relationship between $R$ and $T/T_c$. The x-axis represents $T/T_c$ ranging from 0 to 2, and the y-axis represents $R$ ranging from 0 to 1. The graph highlights a specific region marked as $\Omega_c^-$, indicating a critical point or phase transition.](image-url)
The R-factor - comparison with previous ensemble

![Graph showing the comparison of R-factor with previous ensemble.]

- $S = 0$

Legend:
- Green circles: Gen2l - nucleon
- Orange squares: Gen2l - $\Delta$
- Blue triangles: Gen2 - nucleon
- Yellow diamonds: Gen2 - $\Delta$
Future work
Still a lot more to be done

Study just getting started

- More thorough look at the masses and correlators
- Spectral reconstruction analysis
- Susceptibility calculations

Planned future ensembles

- Generation 2P
- Generation 3
Still a lot more to be done

Study just getting started

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Planned future ensembles

• Generation 2P (physical quark masses)
• Generation 3
Still a lot more to be done

Study just getting started

- More thorough look at the masses and correlators
- Spectral reconstruction analysis
- Susceptibility calculations

Planned future ensembles

- Generation 2P (physical quark masses)
- Generation 3 (higher anisotropy)
openQCD-FASTSUM
Two major features

- Anisotropic lattice actions
- Stout link smearing

+ AVX512 optimisations courtesy of the SA2C
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- Anisotropic lattice actions
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Future development plans

- Library/back-end interface
- Unit testing and CI

https://fastsum.gitlab.io
Questions?