Observation of the antimatter partner of
Rutherford’s $\alpha$-particle – $^4\text{He}$

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Abstract. The antimatter helium-4 nucleus ($^4\text{He}$, or anti-$\alpha$) has not been observed previously although the $\alpha$-particle was identified a century ago by Rutherford. High-energy nuclear collisions recreate energy densities similar to that of the universe microseconds after the Big Bang, and in both cases, matter and antimatter are created with comparable abundances. However, the relatively short-lived expansion in nuclear collisions makes it possible for antimatter to decouple quickly from matter. This makes a high-energy accelerator facility the ideal environment for producing and studying antimatter. In this paper, we report 18 antihelium-4 nuclei discovered by the STAR experiment at the Relativistic Heavy Ion Collider (RHIC). The measured invariant differential cross section is consistent with expectation from thermodynamics and coalescent nucleosynthesis models, which has implications for future production of even heavier antimatter nuclei, as well as for experimental searches for new phenomena in the cosmos. Future directions of rare and exotic matter searches from STAR will also be discussed.

1. Introduction

In the Big Bang[1], matter and antimatter are supposed to be created with comparable abundance. However, our world today consists almost entirely of matter rather than antimatter. It is therefore conjectured that the Big Bang could have made antimatter somewhere else in the distant universe, and our observable universe happens to be in the matter zone. One of the major goals in space-based experiments[2, 3, 4] is to look for tiny antimatter fragments that travel from the primordial antimatter zone. In matter nucleosynthesis, helium is the next most abundant element to hydrogen. Similarly, if there is any primordial antimatter, antihelium is the most likely form to be detected in cosmic rays. Lighter antiparticles in cosmos such as antiprotons and positrons are primarily produced by collisions of the cosmic rays with the interstellar medium. Thus, they are not direct indicators for the existence of an antimatter domain. Antihelium-4 has not been observed until the recent discovery[5], although the $\alpha$-particle was identified a century ago by Rutherford and is present in cosmic radiation at the ten per cent level[6].

High-energy nuclear collisions create an energy density similar to that of the Universe microseconds after the Big Bang. However, nuclear collisions produce negligible gravitational attraction and allow the system to expand rapidly. The relatively short-lived expansion in nuclear collisions allows antimatter to decouple quickly from matter, and avoid annihilation. Unlike space-based experiments where one can only conduct passive searches for antimatter
fragments, high-energy nuclear collisions actively produce antinuclei. The production of light antinuclei can be modeled successfully by macroscopic thermodynamics[7], which assumes energy equipartition, or by a microscopic coalescence process[8], which assumes uncorrelated probabilities for antinucleons close in position and momentum to become bound. The high temperature and high antibaryon density of relativistic heavy ion collisions provide a favourable environment for both production mechanisms. In contrast to the Big Bang which is a single event, high energy nuclear collisions are controlled, repeatable “little bangs” in which one can test the antinuclei production mechanism by colliding different species and/or colliding at different energies. The study of antinuclei production in high-energy nuclear collisions can prove the existence of a particle of particular interest, and provides point of reference for future observations in cosmic radiation.

2. Experimental Setup

The central detector used in our measurements of antimatter, the Time Projection Chamber (TPC)[9] of the STAR experiment (Solenoidal Tracker At RHIC), is situated in a solenoidal magnetic field and is used for three-dimensional imaging of the ionization trail left along the path of charged particles. In addition to the momentum provided by the track curvature in the magnetic field, the detection of $^4\text{He}$ particles relies on two measurements: the mean energy loss per unit track length, $\langle dE/dx \rangle$ in the TPC gas, which helps distinguish particles with different masses or charges, and the time of flight of particles arriving at the Time-Of-Flight barrel (TOF)[10] surrounding the TPC. In general, time of flight provides particle identification in a higher momentum range than $\langle dE/dx \rangle$. The $\langle dE/dx \rangle$ resolution is 7.5% and the timing resolution for TOF is 95 picoseconds on typical time-of-flights of 8 – 12 nanoseconds. Other details of TPC and TOF performance can be found in refs. [9] and [10], respectively.

In this search $\sim 10^9$ Au+Au collisions were used, consisting of $870 \times 10^6$ ($170 \times 10^6$) collisions at 200 (62) GeV in the center of mass energy per nucleon. Preferential selection of events containing tracks with charge $Ze = \pm 2e$ (where $e$ is the electron charge) was implemented using a High-Level Trigger (HLT) for data acquired in 2010. The schematic layout of the HLT is presented in Fig. 1. The HLT used computational resources at STAR to perform a real-time fast

![Figure 1](image)

**Figure 1.** The HLT consists of two parts: the Sector Level 3 (SL3), and the Global Level 3 (GL3). The SL3 does the tracking with clusters within one TPC sector (sector-tracking) with Data Acquisition (DAQ)’s CPU. When the sector-tracking is finished in SL3, the tracking information from all sectors is sent to GL3 machines in which it is assembled together with information from other subsystems (Barrel Electromagnetic Calorimeter (BEMC), TOF, and in the future, Muon Telescope Detector and Heavy Flavor Tracker) to make a real-time decision on event selection.
track reconstruction to tag events that had at least one track with \( \langle dE/dx \rangle \) above a threshold set to three standard deviations below the theoretically expected value\[11\] for \(^3\)He at the same momentum. At both energies the HLT successfully identified \( \sim 70\% \) of the events where a \(^4\)He track was present while selecting only \( 0.4\% \) of the events for express analyses.

3. Result and Discussion

Figure 2 shows \( \langle dE/dx \rangle \) versus the magnitude of magnetic rigidity, \( p/|Z| \), where \( p \) is the momentum. A distinct band of positive particles centered around the expected value\[11\] for \(^4\)He particles indicates that the detector is well calibrated. On the left side of Fig. 2, where \( p/|Z| \) is less than \( 1.4 \text{ GeV}/c \), four negative particles are particularly well separated from the \(^3\)He band and are located within the expected band for \(^4\)He. Above \( 1.75 \text{ GeV}/c \), the \( \langle dE/dx \rangle \) values of \(^3\)He and \(^4\)He merge and the TOF system is needed to separate these two species.

![Figure 2](image)

Figure 2. \( \langle dE/dx \rangle \) versus \( p/|Z| \) for negatively charged particles (left) and positively charged particles (right). The black curves show the expected values for each species. The lower limit for bands consisting of large solid circles correspond to the HLT’s online calculation of 3\( \sigma \) below the \( \langle dE/dx \rangle \) band center\[11\] for \(^3\)He.

Figure 3 shows the \( \langle dE/dx \rangle \) (in units of multiples of \( \sigma_{dE/dx} \), \( n\sigma_{dE/dx} \)) versus calculated mass \( m = (p/c)\sqrt{(t^2c^2/L^2 - 1)} \), where \( \sigma_{dE/dx} \) is the rms width of the \( \langle dE/dx \rangle \) distribution for \(^4\)He or \(^3\)He, \( t \) and \( L \) are the time of flight and path length, respectively, and \( c \) is the speed of light. The top (bottom) panel shows negatively (positively) charged particles. In both panels, majority species are \(^3\)He and \(^4\)He. (Anti)triton nuclei are well separated from (anti)helium nuclei, and the less population of (anti)triton nuclei is due to the \( \langle dE/dx \rangle \) cut introduced in the HLT. In the bottom panel, the \(^4\)He particles cluster around \( n\sigma_{dE/dx} = 0 \) and mass = \( 3.73 \text{ GeV}/c^2 \), the appropriate mass for \(^4\)He. A similar but smaller cluster of particles can be found in the top panel for \(^4\)He, clearly in evidence. Eighteen counts for \(^3\)He are observed\[5\]. Of those, sixteen are from collisions recorded in 2010. Two counts\[12\] identified by \( \langle dE/dx \rangle \) alone from data recorded in 2007 are not included in this figure, because the STAR TOF was not installed at that time.

To evaluate the background in \(^4\)He due to \(^3\)He contamination, we simulate the \(^3\)He mass distribution with momenta and path lengths, as well as the expected time of flight from \(^3\)He particles with timing resolution derived from the same data sample. The contamination from misidentifying \(^3\)He as \(^4\)He is estimated by integrating over the region of the \(^4\)He selection. We estimate that the background contributes 1.4 (0.05) counts of the 15 (1) total counts from Au+Au collisions at \( 200 \text{ (62) GeV} \) recorded in 2010.
The differential invariant yields for $^4\text{He}(^4\overline{\text{He}})$ is plotted together with other light (anti)nuclei in Fig. 4. The production rate is seen decreasing exponentially with increasing absolute value of baryon number ($B$), a trend that is expected from thermodynamic[7] and coalescent nucleosynthesis[8] models. The consistency with thermodynamic and coalescent production implies that the sensitivity of current space-based charged particle detectors is below what would be needed to observe antihelium produced by nuclear interactions[6] in the cosmos, and consequently, any observation of antihelium or even heavier antinuclei in space would indicate the existence of a large amount of antimatter elsewhere in the Universe.

Figure 5 shows the discovery year for a selection of antiparticles. With the observation of antihelium-4 nuclei, the STAR collaboration has broken its own record set in 2010 for the heaviest antimatter nucleus[13]. If the exponential decreasing trend of yields continues to hold for even heavier antinuclei, the production rate 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. For that reason, barring new exotic production mechanisms or a new breakthrough in accelerator technology, it is likely that $^7\text{He}$ will remain the heaviest stable antimatter nucleus observed for the foreseeable future.

4. Conclusion and Outlook

In summary, we have presented the observation of 18 counts of antihelium-4 nuclei from $10^9 \text{ Au+Au collisions}$ recorded by the STAR experiment at RHIC. The yield is consistent
Figure 4. Differential invariant yields as a function of baryon number $B$, evaluated at $p_T/|B| = 0.875$ GeV/$c$, in central 200 GeV Au+Au collisions. Yields for (anti)triton ($^3\text{H}$ and $^3\bar{\text{H}}$) nuclei lie close to the positions for $^3\text{He}$ and $^3\bar{\text{He}}$, but are not included here because of poorer identification of (anti)triton nuclei. The lines represent fits with $e^{-r|B|}$ for positive and negative particles separately, where $r$ is the production reduction factor. Analysis details of yields other than $^4\text{He} (^4\bar{\text{He}})$ have been presented elsewhere[14, 15].

Figure 5. Discovery year for a selection of antiparticles.

with expectations from thermodynamics and coalescent nucleosynthesis models, which has implications beyond nuclear physics. As an interesting synergy with the Rutherford Centennial Conference on Nuclear Physics, this finding happens to coincide with the 100th year of Rutherford’s $\alpha$-scattering experiments which marked the dawn of modern subatomic physics.

In the future, STAR will continue to watch for rare and exotic particles. One such effort is to enrich data sample for antinuclei production by triggering on energy deposition in Barrel Electromagnetic Calorimeter (BEMC), as antinuclei tend to deposit larger amount of energy in BEMC than nuclei. This, when combined with the on-going DAQ 10k upgrade, will allow STAR to take the full advantage of high luminosity of the RHIC II era for antimatter search. The DAQ 10k upgrade changes TPC’s read-out scheme from all sectors together to sector-by-sector, thus
allows STAR to record partial events at a high rate without missing the desired track. STAR also intends to install Graphic Processing Units (GPU) to Global Level 3 machines. GPUs will significantly accelerate secondary vertex finding, thus making the topological reconstruction of $H^0$-like strangelet[16] in real time possible. Note that besides the decay topology of $H^0$ dibaryon, in principle other exotic decay topologies can also be reconstructed, as shown in Fig. 6. Triggering on and studying these exotic decay topologies offers the potential for new discoveries.

**Figure 6.** Exotic decay topologies that can benefit from the secondary vertex finder with GPU acceleration. Dashed lines represent neutral particles, of which each decays into a pair of tracks (curved lines) with opposite signs of charge. Solid straight lines represent charged tracks, of which each can be either positive or negative. The dashed square highlights the decay topology of $H^0$.

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