



Probing the temperature of the quark soup at trillions of degrees

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Following over 20 years of research, a direct measurement of the QGP temperature has been achieved at Relativistic Heavy-Ion Collider (RHIC), free from the blue-shift effect and contamination from strong interactions. This viewpoint discusses a recent measurement of the QGP temperature at different stages at the Solenoidal Tracker at RHIC (STAR), which used e^+e^- pairs as penetrating probes.

Temperature, one of the most fundamental physical parameters, serves as a critical probe for studying the core properties of matter in macroscopic and microscopic thermal systems, such as nuclear systems [1–4]. In the first microseconds following the Big Bang, the Universe was filled with an extremely hot primordial soup of quarks and gluons—a state of matter known as Quark–Gluon Plasma (QGP) [5]. Today, this exotic phase of matter can be recreated in laboratories via high-energy heavy-ion collisions, offering a unique avenue to investigate the dynamics and phase structure of Quantum Chromodynamics (QCD) [6–10]. To achieve these physics objectives, direct measurement of QGP temperatures is indispensable. It not only enables the exploration of the thermodynamic properties of this hot and dense matter but also provides direct access to the QCD phase structure, which is usually described by the relationship between temperature and baryon chemical potential of nuclear matter [11, 12].

In the realm of high-energy nuclear physics, the direct quantification of the QGP temperature is contingent upon the utilization of leptons and their antiparticles as golden probes. Dileptons, such as dielectron (e^+e^-) pairs, are regarded as an effective tool for directly probing the temperature of the emitting source [13]. These pairs are generated

throughout the entire evolutionary process of the collision system. Despite their lack of strong interactions, dileptons within different kinematic ranges provide profound insights into the hot, dense matter formed during collisions, capturing information from distinct evolutionary stages. Notably, when focusing on the invariant mass spectra of dileptons, the measurements remain unaffected by the blue-shift effect induced by rapidly expanding collision systems. These characteristics make dileptons one of the key penetrating electromagnetic probes at major international high-energy nuclear physics facilities, including Bevalac, SIS18, SPS, RHIC, and LHC. Furthermore, this probe represents one of the primary experimental observables of the under-construction mega-projects, such as NICA and FAIR.

Recently published in *Nature Communications* [14], a new study by the STAR Collaboration reports the direct measurement of QGP temperatures across different evolution stages. Led by Frank Geurts, Zhangbu Xu, Chi Yang, and Zaochen Ye, the research was primarily driven by a joint team from Kent State University, Rice University, Shandong University, and South China Normal University. After two decades of effort, this measurement marks a significant milestone in achieving one of the core physics goals of electromagnetic probe research at the Relativistic Heavy-Ion Collider (RHIC). The findings confirm the formation of a hot QGP phase during heavy-ion collisions based on the most critical parameter in thermodynamics. More notably, the team identified a stage where the temperature remained relatively stable and was close to the QCD phase boundary across varying collision energies and species.

This breakthrough is made possible by the successful development and operation of the Time-Of-Flight (TOF) detector [15, 16], which enables the measurement of electrons and positrons at STAR. Based on a joint effort between the Chinese and American teams [7], the TOF modules produced by the STAR China group were successfully installed at STAR in 2010, introducing electron identification capability and extending the particle identification capability of charged hadrons to a higher momentum region. During the

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past decade, based on energy loss and momentum measurements from the Time Projection Chamber (TPC) [17, 18] and the velocity provided by TOF, the STAR Collaboration has made inclusive e^+e^- pair measurements with high e^+ and e^- purities [19–23]. However, these dilepton measurements always face long-standing challenges due to statistical limitations, not only because of the rarity of e^+e^- pair production but also because they suffer from an extremely low signal-to-background ratio. Dileptons from hadronic decay and pollution from open heavy flavor semi-leptonic decays predominantly introduce large backgrounds. The Beam Energy Scan (BES) program at RHIC provides opportunities to study this rare probe across a wide range of collision energies, where the open charm decay decreases as the collision energy diminishes from the top energy at RHIC. In the BES-Phase I, clear in-medium ρ^0 broadening spectra have been observed [23, 24], although with limited precision. As one of the key observables that drive the planned data collection luminosities, measurements of dielectrons were enabled in the BES-Phase II program with reasonable statistics [25]. In addition to thermal dileptons, dileptons from photon-photon interactions, such as the Breit-Wheeler process, have been measured in ultra-peripheral collisions [26, 27].

As illustrated in Fig. 1, temperatures were derived by fitting the invariant mass spectra of thermal dielectrons across different ranges, each corresponding to a distinct period in the evolution of the QGP. Assuming that the dielectron continuum from QGP thermal radiation can be directly described by a function with a mass term ($M^{3/2}$) multiplied by the Boltzmann factor ($e^{-M/k_B T}$), the temperature in the intermediate mass range can be extracted. In the low mass range, where $\rho^0 \rightarrow e^+e^-$ decay plays a dominant role, a function combining the ρ^0 spectral term (relativistic Breit-Wigner function multiplied by the Boltzmann factor) and the QGP thermal radiation term was used. Around 170 MeV and 280 MeV were achieved for in-medium ρ^0 dominance and QGP dominance regions, which correspond to 2.0×10^{12} K and 3.2×10^{12} K, respectively. This trillion-degree temperature is hundreds of thousands of times higher than that of the Sun's core, confirming that the medium created in relativistic heavy-ion collisions exists in an extremely hot state on the Fermi scale.

One interesting observation is that, when compared with the results of the NA60 experiment [28], the ρ^0 -like region reveals intriguing temperatures. Across collision systems ranging from Au+Au to In+In, and collision energies from 54.4 to 17.3 GeV, the calculated temperatures are comparable. While in the higher mass region, where the QGP is dominant, the temperature measured by STAR is higher than that measured by NA60. Given that the temperature obtained from the HADES experiment at a similar mass range is significantly below T_c in Au+Au collisions at 2.42 GeV [29], this suggests that the QGP created at RHIC is hotter than

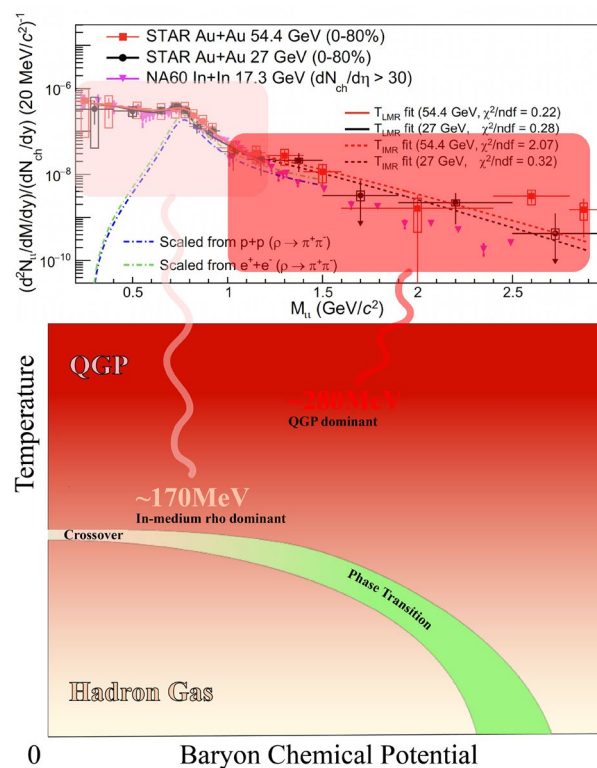


Fig. 1 A brief layout of QCD phase diagram, showing the corresponding area where the temperatures were extracted by thermal dielectrons in different mass ranges. The dielectron continuum and fitting plot in the figure are from Ref. [14]

that from NA60; however, they then reach a similar temperature close to the phase boundary. From the QGP temperature perspective, experimental physicists have discovered new evidence of behavior related to the phase boundary for the first time.

An intriguing element is that this team, using a steady and gradual methodology, is extending the research on dielectrons to energies down to 7.7 GeV by analyzing data from the BES-Phase II program [30]. The research is moving toward to a critical area of the QCD phase diagram, marked by rapid changes in the baryon chemical potential. This will improve our understanding of the factors affecting the medium's thermal radiation. To approach the possible Critical End Point (CEP), upcoming experiments at NICA [31] and FAIR [32] will push dilepton research into the domain of quark-baryon matter, where penetrating probes are crucial for exploring the properties of this kind of matter. Recently, AI techniques have demonstrated potential in nuclear physics, see eg. Refs. [3, 4, 33–38]. Especially in studies involving extremely low signal-to-background ratios and rare signals, further AI applications will be beneficial for research on electromagnetic probes.

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