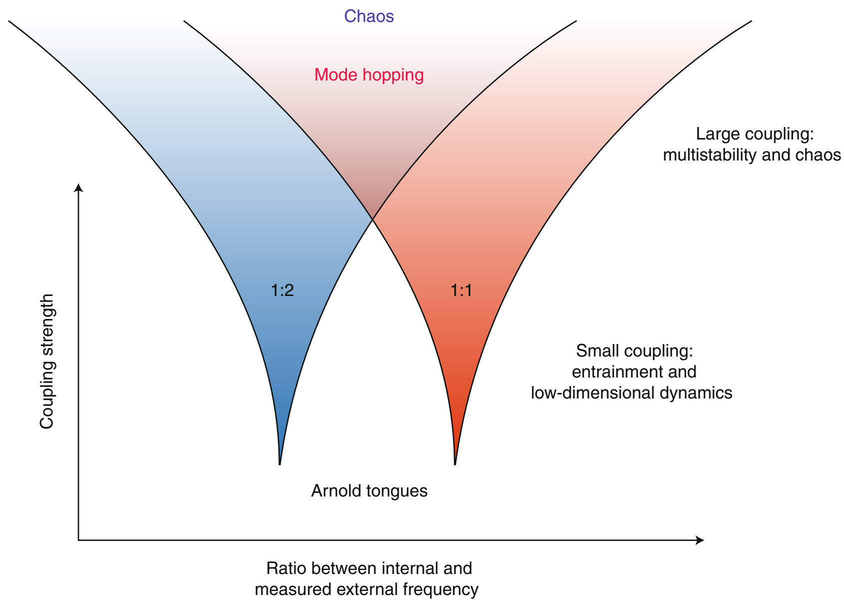

Fig. 1 | Arnold tongues represent the regions of synchronization of coupled oscillators. For small coupling strength, they describe regions of entrainment and low-dimensional dynamics, but when the interaction grows large, multistable cycles, mode hopping and chaos can occur. The 1:1 and 1:2 tongues indicate entrained states, where the numbers refer to the frequency of the external oscillator and the internal oscillator. In this way, 1:2 means that every time the external oscillator makes one rotation, the internal oscillator makes two rotations. Likewise, 1:1 means that the oscillators are synchronized in frequency.

of synchronization emerge and the ratio between the two oscillations assumes some rational number — the smaller the denominator, the larger the region of synchronization. In the parameter space spanned by the ratio of the oscillation periods and the coupling strength, these regions are known as Arnold tongues (Fig. 1). As the coupling strength between the two oscillators increases, the width of the Arnold tongue also grows. The typical set-up in a physical or biological experiment would comprise an internal oscillator (such as a wave or a variation in the protein levels in a cell) and an external oscillator controlled from outside[3,4].

The existence of these tongues in nature has been shown in numerous experiments across very different fields, from fluids to the dynamics of proteins inside cells. If the coupling strength is strong enough, the tongues can start to overlap, leading to multistable solutions and — for even stronger coupling — chaotic dynamics (Fig. 1). Synchronization thus can cause both increased order and the disappearance of order in terms of chaos, so it's natural to think that this framework might be useful for describing the complexities of living systems.

Multistable solutions have been studied in cells subjected to a cell signalling protein known as tumour necrosis factor, which induces sustained oscillations of another protein involved in the transcription of DNA into RNA. Externally affecting oscillations in the concentration of this factor results in the appearance of several overlapping Arnold tongues[3], which can induce the cell to switch between high and low production of certain genes[4]. The appearance of chaotic dynamics can similarly cause some genes to increase their production while others become silent[5].

The study carried out by Droin and colleagues demonstrates the surprising robustness of synchronization between two oscillators of very different nature. Through carefully conducted experiments, the authors have provided convincing evidence for this coupling, and by showing that the relation is conserved across different species, they have written a new chapter in the story of how nonlinear coupling mechanisms can be of fundamental importance to our understanding of living systems. ❐

Mathias L. Heltberg[1,2] and Mogens H. Jensen[1]*
[1]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. [2]Laboratoire de Physique Theorique, Ecole Normale Superieure, Paris, France.
**e-mail: mhjensen@nbi.ku.dk*

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STRONG-INTERACTION MATTER

Fireball spectroscopy

The visible mass in the Universe emerged when hadrons — the building blocks of atomic nuclei — formed from a hot fireball made of quarks and gluons. This mechanism has now been investigated in baryon-rich matter at relatively low temperatures.

Ralf Rapp

It is fascinating that temperatures that were last present a few microseconds after the Big Bang can be recreated in the laboratory by colliding atomic nuclei at high energies[1]. In these collisions, fireballs of strongly interacting or quantum chromodynamics (QCD) matter are formed. However, they only last for a short time before disintegrating into thousands of

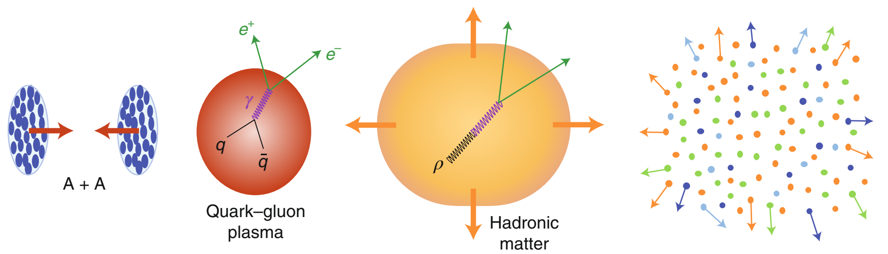

Fig. 1 | Schematic of the creation of QCD matter in the laboratory. High-energy collision of two nuclei (A) with subsequent formation of a fireball that evolves through quark–gluon plasma and hadronic matter before decoupling into hadrons. Dilepton radiation (for example, positron–electron pairs, e^+, e^-), produced via a virtual photon (γ) from quark–antiquark ($q, \bar{q}$) annihilation or ρ-meson decays, can penetrate the fireball.

hadrons, which can be observed in large particle detectors. The hot fireballs also emit real and virtual photons, which — contrary to hadrons — penetrate the QCD medium and thus carry information on the interior of the fireball (Fig. 1). Now, writing in *Nature Physics*, the HADES Collaboration reports the measurement of the di-electron spectrum from QCD matter created in gold–gold collisions at lower energies[2]. They find conditions similar to those in the final stages of a neutron-star merger, but with spectral properties akin to the early Universe.

Within the standard model of particle physics, the strong nuclear force between quarks and gluons occupies a special role. Its large interaction strength gives rise to two fundamental phenomena: the confinement of quarks and gluons into bound states (hadrons), and the generation of about 98% of the visible mass in the Universe. The mechanisms underlying these phenomena remain under intense investigation, but are generally believed to be associated with condensation phenomena, similar to the Higgs mechanism via the electroweak force. Whereas the condensation of the Higgs particle generates the bare masses of the up and down quarks at around 5 MeV c^{-2} (where c is the speed of light), the strong force binds them into protons (two up and one down quark) and neutrons (two down and one up quark) with a mass of approximately 940 MeV c^{-2}. At a pseudo-critical temperature of around 160 MeV k_B^{-1}, where k_B is the Boltzmann constant, or about 2 trillion kelvin, numerical simulations predict that hadronic matter transitions into a deconfined quark–gluon plasma[3,4], which can be created in heavy-ion collisions.

The QCD matter that emerges in these collisions emits virtual photons from which a pair of leptons — either electron–positron or muon–antimuon pairs — is created. The energies of the two leptons reflect the mass spectrum of the QCD medium. In particular, they provide direct access to the mass spectrum of mesons with spin−1, most notably the ρ meson, which is a bound state of a quark–antiquark pair with a vacuum mass of 770 MeV c^{-2}. Much like atomic spectra reveal the structure of ordinary matter, dilepton spectroscopy in heavy-ion collisions can probe the structure of QCD matter.

Pioneering precision measurements of dimuon mass spectra were carried out by the NA60 Collaboration in heavy-ion collisions at the CERN Super Proton Synchrotron at a centre-of-mass energy of 17.3 GeV per nucleon pair[5]. These studies revealed that the mass of the ρ meson in the hot fireball does not diminish, but rather melts gradually: intense rescattering of the ρ meson in the QCD medium renders its lifetime so short that — due to Heisenberg's uncertainty principle — its mass spectrum spreads out and approaches that of a quark–antiquark continuum[6]. Thus, the ρ-mass melting seems to induce a transition into a spectrum of deconfined quarks and antiquarks. This was corroborated by the characteristics of the dimuon spectrum at masses exceeding 1.5 GeV c^{-2}, signalling thermal radiation from the quark–gluon plasma at an average temperature of 205 ± 12 MeV k_B^{-1}, well above the pseudo-critical temperature. Key questions are if the mass melting is relevant for other hadrons and how it responds to varying conditions of the QCD medium.

The HADES Collaboration has now broken new ground with a precision measurement of dileptons in heavy-ion collisions at a much lower centre-of-mass energy of 2.42 GeV. The significance of this energy regime lies in a dramatically different composition of the produced medium with a much higher concentration of baryons (consisting of three quarks) than mesons, in contrast to the high-energy regime. The HADES Collaboration made the remarkable discovery that also at low energies, the ρ resonance structure in the dilepton spectrum dissolves — meaning its mass melts. In fact, the very presence of a robust thermal-radiation signal was not necessarily expected due to the much lower excess energy in the collision, but has now been firmly established. This means that frequent rescattering among the baryons in the fireball produces a locally near-thermalized medium, which shines via its electromagnetic radiation analogously to high-energy collisions. The temperature of the fireball was determined to be 70 MeV k_B^{-1}, reflecting the much reduced excess energy compared with the collisions studied by the NA60 Collaboration.

One may wonder whether at these temperatures the ρ melting remains an indicator of a transition to quark degrees of freedom. Transport models predict the baryon densities in the collision to reach around three times that of atomic nuclei. At a temperature of 70 MeV k_B^{-1}, this translates into an energy density of 0.5 GeV fm^{-3}, which is comparable to, or even larger than the energy density at the pseudo-critical temperature of 160 MeV k_B^{-1} at vanishing net baryon density when matter and antimatter exist in equal parts[4]. Thus, the baryon-rich matter produced in heavy-ion collisions at HADES energies may indeed create conditions where quark and gluon degrees of freedom are unleashed. This has intriguing implications for the presence of deconfined matter in the mergers of neutron stars, as well as in the centre of isolated neutron stars with comparable baryon densities but lower temperatures. Future precision measurements will test the mass melting in conditions similar to those that existed in the early Universe, and thereby build a bridge to the compact stellar objects that are now — 14 billion years later — observable in the sky with increasing scrutiny. ❐

Ralf Rapp
Texas A&M University, College Station, TX, USA.
e-mail: rapp@comp.tamu.edu

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