# Phases of nuclear matter

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*Nuclear matter exists in different forms under different conditions of temperature and pressure, just as in the case of water. The phase diagram of nuclear matter spans a vast region of temperature and density, starting with the quark–gluon phase of the early universe at high temperature to the high-density matter that exists in the core of the neutron star. Between the two extremes, at least two spectacular phase transitions occur: the quark–hadron transition and the nuclear liquid–gas phase transition. There have been predictions for two critical points corresponding to the two phase transitions. We present the phase diagram of nuclear matter, give an overview of both types of phase transitions and discuss the critical points of the phase diagram.*

**Keywords:** Critical point, nuclear matter, phase transition, water.

MATTER exists in different forms or phases. This had been known to mankind very early on, even to ancient Indian philosophers, who were of the opinion that matter is made up of five great elements or 'pancha mahabhuta', namely earth, water, wind, fire and aether. Indeed these may be identified with our present knowledge of the states of matter, as solid (earth), liquid (water), gas (air) and plasma (fire). The classical aether may be thought of as the void or vacuum. By application of external forces, it is possible for matter to change its form from one phase to another, thereby changing its physical properties. Transition from one phase to another involves an abrupt, discontinuous change in the properties (order parameter in general) of a system. The study of phase transitions of different forms of matter has attracted the attention of scientists for a long time. The question naturally arises about what to expect in the case of nuclear matter – does it also exhibit different forms when exposed to different thermodynamic conditions? The answer is yes, and in fact, the transitions between different nuclear phases exhibit some of the most spectacular examples of phase transitions.

The nucleus is a highly dense region consisting of nucleons (protons and neutrons) in its centre, and the nuclear force is responsible for binding the nucleons within the nuclei. As we probe deeper, the nucleons are found to be composed of quarks and gluons, bound by the strong interaction. The strong interaction between the quarks is mediated by massless gluons. The nuclear force is essentially the residual effect of the strong interaction, which binds the quarks together. Decades of experimental explorations and ingenious theories have led to an amazingly simple picture of the world within the atomic nucleus and the laws which govern them. The classification and behaviour of the elementary particles have so far been successfully described by the Standard Model. The theory of strong interactions, describing the interactions between quarks and gluons, is given by quantum chromodynamics (QCD). Understanding the behaviour of the nucleons in a nucleus or the quarks with the nucleon is essential for studying the phases of nuclear matter and transitions between them.

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The nucleus in its normal state exhibits liquid-like characteristics with a density of 0.17 nucleons/fm$^3$ (1 fm is $10^{-13}$ cm). When we apply energy and heat up the nuclear matter, under certain circumstances it may behave like a gas, thus making a liquid–gas phase transition[1,2]. Further application of energy results in high temperature and high density conditions where a system of deconfined quarks and gluons, called the quark–gluon plasma (QGP) may be formed[3–5]. In this article, we explore the phases of nuclear matter and transitions between them.

## Phases of water

Before starting with the nuclear matter, let us take a detour and discuss about one of the most studied forms of matter, in terms of the phases of water. Under normal conditions, water exists in one of three forms – the solid phase (ice), the liquid phase (water) and the gaseous phase (steam). At atmospheric pressure, below the freezing point (0°C), water exists in the form of ice; between 0°C and 100°C, water is a liquid, and above the boiling point of 100°C, water exists in the form of steam/gas. When heat is added at a constant rate to a mass of ice, it changes its form to water, and adding more heat changes the form to steam. Thus two distinct transitions have been observed, one when ice melts to liquid water and the other at the time of vaporization. The energies required to accomplish the phase changes are the latent heat of fusion

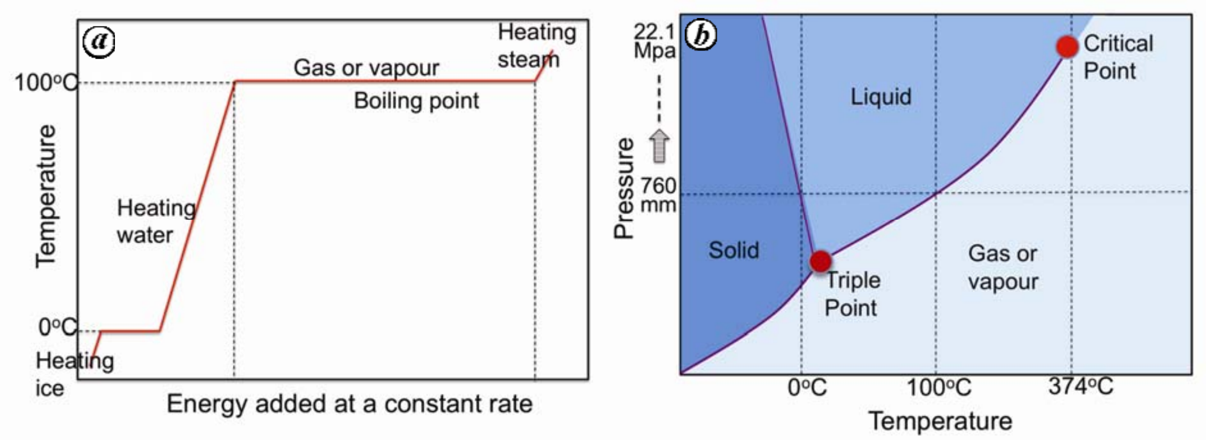


**Figure 1.** ***a***, Phase change with additional energy to the system at atmospheric pressure. ***b***, Phase diagram of water, showing the phases at various temperatures and pressures.

and latent heat of vaporization. By heating water, we reach the boiling point, but addition of more heat does not immediately lead to a rise in temperature; it has to overcome the latent heat. The temperature does not rise until all of the liquid is converted to steam. This leads to plateaus in the temperature and time (or additional energy) profile, as shown in Figure 1 *a*. The transition between the two phases with a latent heat and phase coexistence is the consequence of a first-order phase transition.

The pressure versus temperature profile of water as shown in Figure 1 *b*, has two characteristic points: (i) the triple point and (ii) the critical point. The triple point occurs at 0.01°C and a partial vapour pressure of 611.73 pascal (0.0060373 atm), where it is possible to change all of the substance to ice, water, or vapour by making arbitrarily small changes in pressure and temperature. At higher temperature, as we raise the pressure, the boiling temperature of water increases until the critical point at a pressure of 22.1 MPa (218 times atmospheric pressure) and a temperature of 374°C is reached. The critical point occurs where the first-order transition between the two phases ceases to exist, and beyond which the phase transition becomes second order or a smooth cross-over. What happens if water is further heated to a much higher temperature – in fact, if heated high enough, water, or any other substance regardless of its composition, becomes plasma-containing ions and electrons. High compression may also produce plasma states.

## The nuclear phase diagram

Under varying thermodynamic conditions, the nuclear matter behaves in an analogous manner to that of the phases of water. A schematic view of the phase diagram of nuclear matter is shown in Figure 2, in terms of baryon chemical potential ($\mu_B$) and temperature ($T$) of the system. Baryon (baryons are particles with three quarks like protons and neutrons) chemical potential here represents the net baryon number in the system. On the $T = 0$ axis, the left-hand corner is characterized by small values of baryon chemical potential, where the number of baryons and anti-baryons is approximately equal. Matter in the early universe, within a few microseconds of the big bang, corresponds to low values of $\mu_B$ and high temperature. On the $T = 0$ axis, at $\mu_B = 938$ MeV, we have the normal nuclei. One electronvolt (eV) corresponds to $1.6 \times 10^{-19}$ joule. One MeV, GeV and TeV corresponds to $10^6$, $10^9$ and $10^{12}$ times this value respectively. At higher values of $\mu_B$, we get to the matter at large baryon densities, similar to the matter that may exist in the interior of the neutron stars (a very large collection of neutrons, typically a few kilometres in diameter, which is held together by gravity). Theorists predict that a neutron star of a large enough mass could have enough density to produce a QGP. The rest of the phase diagram at finite temperature and $\mu_B$ shows distinct phase structures.

As the temperature of the nuclei is raised to a few MeV, a part of the nuclear liquid evaporates making the system behave like a gas. Similar to the case of water, the nuclear liquid has a latent heat of vaporization, and goes though a first-order phase transition. Thus the nucleus goes through a liquid–gas phase transition, as shown in the lower left corner of Figure 2. The liquid–gas phase coexistence is expected to terminate at a critical point, as shown in Figure 2. This is the predicted critical point of nuclear matter.

By further increasing the temperatures and densities, the nucleons themselves undergo phase transition. Within the nucleons, the quarks move relatively freely, and are well confined. This is known as asymptotic freedom and quark confinement. Because of this, it has never been possible to isolate and detect individual free quarks. With the application of very high temperature and pressure, it may be possible that the nucleons overlap, making the quarks deconfined for a very short time. This deconfined quark matter is called QGP. The transition from hadronic matter to a state of QGP is expected to be of first-order, ending up in a critical point, beyond which a second order or a cross-over transition may exist. This is the critical point of QCD matter.

It is a real challenge to prepare the nuclear system in order to study the different phases and the nature of the phase transitions. Large amount of energy is required to probe the scale of nucleons and quarks. The only way to expose the nucleus to a wide range of temperatures and densities is by accelerating it to high energies and colliding against a fixed target or colliding against each other. Dedicated experiments in fixed target or colliding modes are designed to measure majority of the particles emitted from such reactions. In controlled experimental environments, liquid–gas phase transitions are studied in reactions which produce temperatures from a few MeV to few tens of MeV, whereas high-energy collisions reaching to temperatures of a few hundred MeV are needed for exploring the QCD phase transitions. (As a reference, an average energy of 1 MeV corresponds to a temperature of $1.2 \times 10^{10}$ K.)

## The nuclear liquid–gas phase transition

The study of nuclear liquid–gas phase transition is important for exploring the phase boundary[6,7], to locate the critical point, and to address many important issues in nuclear astrophysics[8]. Intermediate energy (10 MeV/nucleon to 1 GeV/nucleon) nuclear reactions are ideal for these studies. Major thrusts of research at several laboratories around the world, such as the Superconducting Cyclotron at Variable Energy Cyclotron Centre (VECC), Kolkata; National Superconducting Cyclotron Laboratory at Michigan State University, USA; Cyclotron Laboratory at Texas A&M, USA, GANIL in France, LNS in Italy and GSI in Germany, are to accelerate heavy-ion beams at intermediate energies for performing experiments to explore the liquid–gas phase transition. The superconducting cyclotron at VECC (left panel, Figure 3), once commissioned, will deliver light and medium mass heavy ion beams with energy between 80 and 10 MeV/nucleon. Several experimental facilities are in place to utilize the beam from this cyclotron. Figure 3 (right panel) shows the general purpose scattering chamber (2.2 m in length and 1 m diameter) which is designed to place complex detector arrays in vacuum.

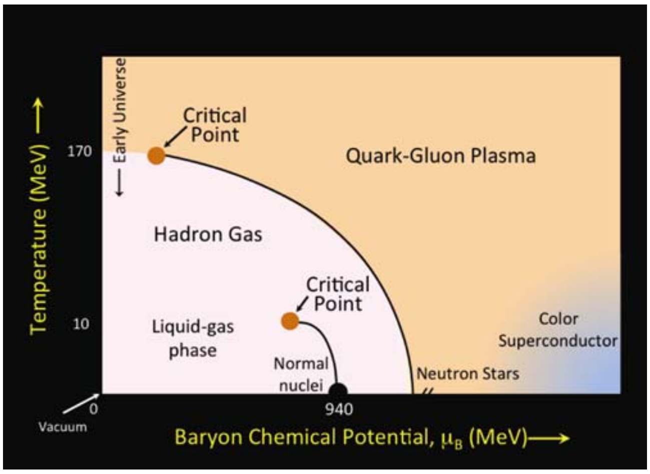


**Figure 2.** Schematic phase diagram of nuclear matter.

Several theoretical calculations suggest that infinite nuclear matter undergoes transition from a liquid to gaseous phase and supports a mixed phase equilibrium at temperatures up to about 17 MeV (ref. 9). Statistical model calculations predict a plateau in temperature when plotted as a function of excitation energy. This curve is known as a caloric curve. One of the major goals of the experiments is to construct the caloric curve and study its behaviour. But the experiments do not measure temperature directly. In fact, in collisions of the beam with the target, the matter produced at a given temperature and density does not stay in that condition for a long time. The measurements give the conditions at freeze-out, when all the interactions among the particles stop. Experimental observables are the number and energies of identified light particles, intermediate mass fragments and heavy fragments. Thermodynamic quantities such as temperature and density are derived from these observables.

For collisions at low incident energies (beam energy of less than about 10 MeV/nucleon), the dominant reaction process occurs through the formation and decay of fully equilibrated compound nucleus. The excitation energy and temperature of the compound nucleus can be deduced from the slope of the inclusive kinetic energy spectra of evaporated light nuclei. As the incident energy increases to about 20 MeV/nucleon, formation of a compound nucleus becomes unlikely, and the kinetic energy spectra are better described by the superposition of more than one source. Thus the temperatures extracted from the fits will be misleading. A more accurate method of estimation of the emission temperatures has been devised, based on the relative populations of ground and excited states of emitted intermediate mass fragments[10]. If the excited states are thermally populated and the feeding from sequential decay of heavier nuclei is not significant, these give a more accurately determined temperature compared to the slope parameters. This method, however, is more demanding as it requires coincidence measurement of decay products. A third method, requiring double yield ratio of isotope pairs, has been devised which can be extracted from single particle yields[11–13].

Caloric curve for nuclear systems[14], obtained from ‘isotope temperatures’ as a function of the total excitation energy per nucleon, is shown in Figure 4. Three distinct

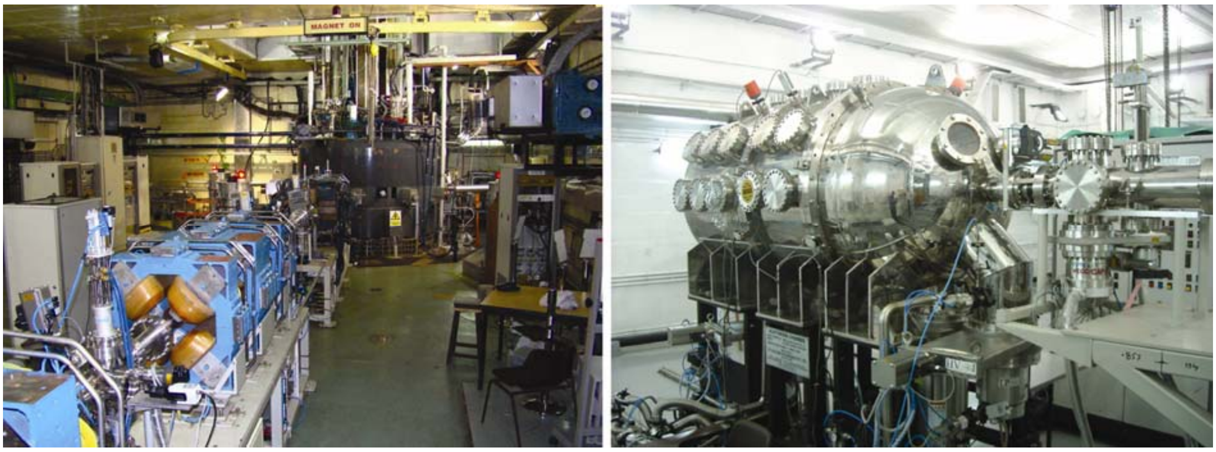

**Figure 3.** (Left) Photograph of the K-500 superconducting cyclotron along with the zero-degree beam line at the Variable Energy Cyclotron Centre, Kolkata. (Right) Photograph of a general-purpose scattering chamber in the beam line, which is designed to house complex detector arrays in vacuum.

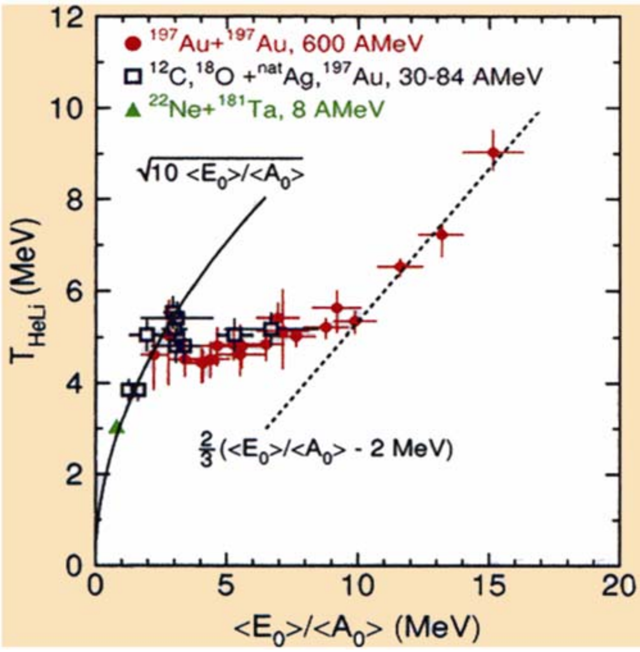


**Figure 4.** Caloric curve of nuclei determined by dependence of the isotope temperature on the excitation energy per nucleon[14].

regions are observed in the curve: At low excitation energy, we see a rise in temperature, then a plateau at an almost constant value of temperature at about 5 MeV, and then a steady rise at higher excitation energy. This shows a striking similarity with the caloric curve of water. Experimental programmes at different accelerator centres have been set up to probe the nuclear liquid–gas phase transitions in more detail.

## The QCD phase transition

Soon after the discovery of asymptotic freedom in the theory of strong interactions in 1974, for which Gross, Politzer and Wilczek received the 2004 Nobel Prize in Physics, T. D. Lee had stated that it would be intriguing to explore new phenomena by distributing high-energy or high-density nuclear matter over a relatively large volume. The name 'quark–gluon plasma' was coined by Eduard Shuryak in 1978. The idea was to use heavy ions to make a new state of matter consisting of deconfined quarks and gluons. Dedicated experimental programmes have been undertaken to search for the QCD phase transition and study QGP matter in detail.

The QCD phase transition has been explored theoretically by performing numerical simulations of QCD on the lattice at finite temperature and density. The lattice QCD-based calculations indicate that the phase transition from a hadronic state to a state of deconfined quarks and gluons occurs beyond a critical temperature ($T_c$) and a critical energy density ($\varepsilon_c$) as seen from Figure 5. The energy density is seen to exhibit the typical behaviour of a system with phase transition, where an abrupt change is observed within a very narrow temperature range around $T_c$. These calculations give a critical temperature $T_c \sim 173 \pm 15$ MeV, corresponding to the critical energy density of $\varepsilon_c \sim 0.7$ GeV/fm$^3$. Lattice QCD models predict a smooth cross-over at high $T$ and small $\mu_B$, while there are expectations for a first-order transition at smaller $T$ and larger $\mu_B$. As indicated in Figure 2, existence of the critical point has also been predicted where a sharp transition between the QGP phase and the hadronic phase first appears. Experimentally, the only way to make such a system is to collide two relativistically accelerated heavy ions (such as ions of Au on Au or Pb on Pb). In this process it is possible to compress and heat the colliding nuclei in such a way that their individual protons and neutrons overlap, creating a region of enormously high-energy density, where a relatively large number of deconfined quarks and gluons can exist for a brief time.

The quest for the search and study of QGP started about three decades ago, first with the Au beam at 1 GeV/nucleon at the Bevalac in Berkeley. The early success of the experiments in terms of bringing out the collective nature of the produced matter prompted the scientists at Brookhaven National Laboratory (BNL), New York and CERN, Geneva to make concrete programmes for the future accelerator developments for heavy ions. A series of fixed-target experiments were followed at the Alternating Gradient Synchrotron (AGS) facility of BNL and Super Proton Synchrotron (SPS) at CERN. AGS provided Si energy at 14 GeV/nucleon as well as Au at 11.7 GeV/nucleon, whereas at the SPS, the top energy has been a Pb beam at 158 GeV/nucleon. The results from the SPS experiments (NA44, NA45/CERES, NA49, NA50, NA52/NEWMASS, WA97/NA57 and WA98) led CERN to announce the creation of a new state of matter in 2000 (ref. 15).

The experiments at AGS and SPS were fixed-target experiments, where one beam of nuclei is extracted from the accelerator and made to hit a target. The next generation of experiments are performed in a collider environment. The centre-of-mass energy in the fixed-target experiment is given by $\sqrt{s} = 2m_t E$, where $m_t$ is the mass of the target and $E$ is the beam energy. In a collider, the beams are made to collide head-on, so that $\sqrt{s} = 2E$. The main advantage of a collider over a fixed-target machine is an enormous gain in the centre-of-mass energy, which is the effective energy available for particle production.

In 2000, the Relativistic Heavy Ion Collider (RHIC), a dedicated machine for QGP search, became operational at BNL, where the top beam energy has been Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV/nucleon. Note that RHIC is a collider where two independent Au beams moving in opposite directions are made to collide. The results of the last decade of data taken by the four experiments (BRAHMS, PHENIX, PHOBOS and STAR) at RHIC point to the creation of a new form of matter that behaves like a strongly interacting near-perfect liquid. The medium created at RHIC collisions is not the expected QGP, but rather a strongly coupled or strongly interacting quark–gluon plasma (sQGP)[16].

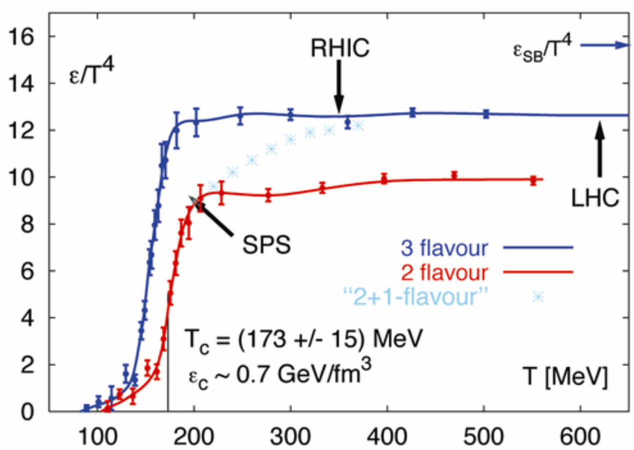


**Figure 5.** Lattice quantum chromodynamics calculations for energy density as a function of temperature.

The Large Hadron Collider (LHC) at CERN is designed to deliver Pb–Pb collisions at centre-of-mass energy of 5.5 TeV/nucleon, which is an increase of 27.5 times over the top RHIC energy. At the LHC, the ALICE[17] is a dedicated experiment for the study of QGP whereas ATLAS and CMS have excellent programmes for QGP study. Figure 6 (left panel) shows a photograph of the ALICE experiment during its construction, indicating the large scale of the experiment (26 m long, 16 m high, 16 m wide; weight: 10,000 tonnes). Over the last two years, the LHC collided Pb ions at a centre-of-mass energy, $\sqrt{s_{NN}} = 2.76$ TeV. At this energy, several tens of thousands of particles are produced in each collision (right panel, Figure 6). During the first two years of the running of the LHC, a total of about 60 million collisions were recorded. The challenge is to identify most of these tracks in each of the collisions, and from these debris identity the real signatures of the QGP to distinguish those from the hadron gas. With the advancement of sophisticated computing systems, like GRID computing, it is now possible to perform the data analysis and have the results within a reasonable span of time. First results at the LHC confirm the formation of a hot, long-lived and high-density system[18]. A large asymmetry in the back-to-back jet study confirms the formation of a very dense medium at the LHC.

Indian scientists have been at the forefront of the QGP study from early on, contributing effectively to the experimental programmes as well as theory[19]. Indian scientists have been intimately connected with the STAR and PHENIX experiments at RHIC. At the LHC, the Indian groups are involved in the ALICE and CMS experiments, contributing to the hardware detector efforts, computing and physics analysis. Figure 7 shows the two major contributions to the ALICE detector from India, in terms the Photon Multiplicity Detector (PMD) and the second station of the Muon Spectrometer. PMD has been a full Indian effort from concept to commissioning. These two detectors have been fully operational and continue to collect data, contributing to the physics programme of collective flow, chiral phase transition and quarkonia production at the LHC. The development of the MANAS chips for ALICE and high-resolution, large area silicon sensors for CMS has been quite unique.

Study of the evolution of QGP signatures from low-energy collisions at the AGS, SPS to RHIC and LHC is crucial to understand the nature of the phase transition. Most of the QGP signatures, in terms of global observables, photon production, quarkonia and jets have been studied as a function of energy. Here we present a recent compilation of the energy dependence of the inverse slope parameter ($T$) of transverse momentum spectra of kaons ($K^+$) produced in the Au–Au or Pb–Pb collisions from AGS to SPS to RHIC and LHC (Figure 8)[20]. It is

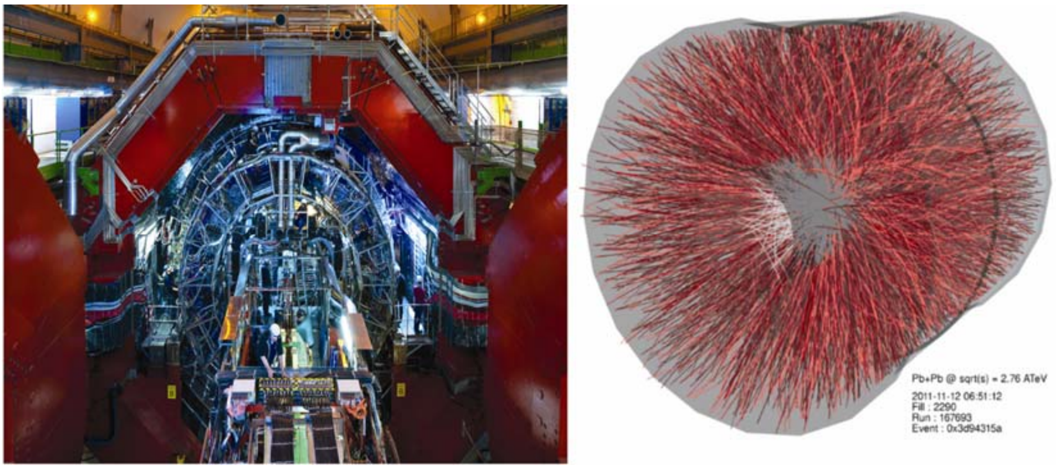


**Figure 6.** (Left) Photograph of the ALICE experiment during construction. (Right) An event display showing a large number of tracks emitted from a single Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV, measured by the ALICE experiment at the Large Hadron Collider. (Picture courtesy: A. Saba, ALICE Collaboration and CERN.)

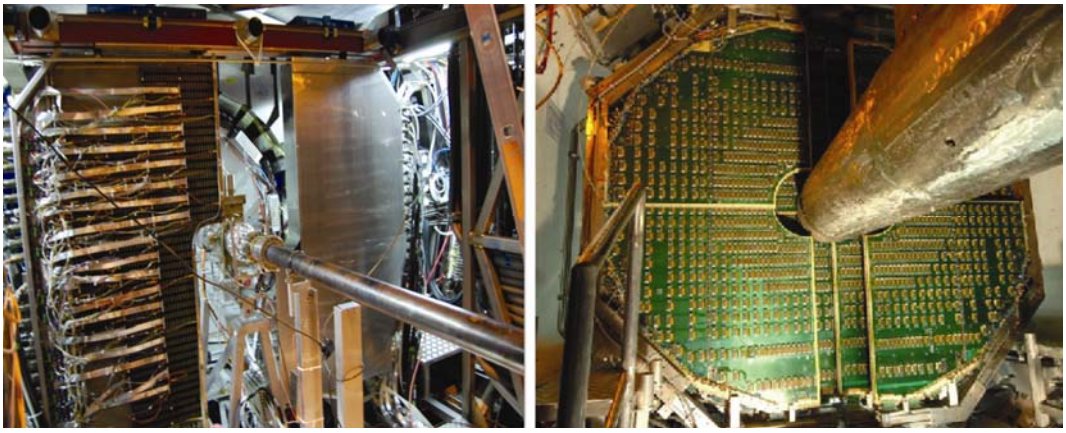

**Figure 7.** (Left) Photograph showing the Photon Multiplicity Detector. (Right) Photograph of station 2 of the Muon Spectrometer as installed in the ALICE cavern.

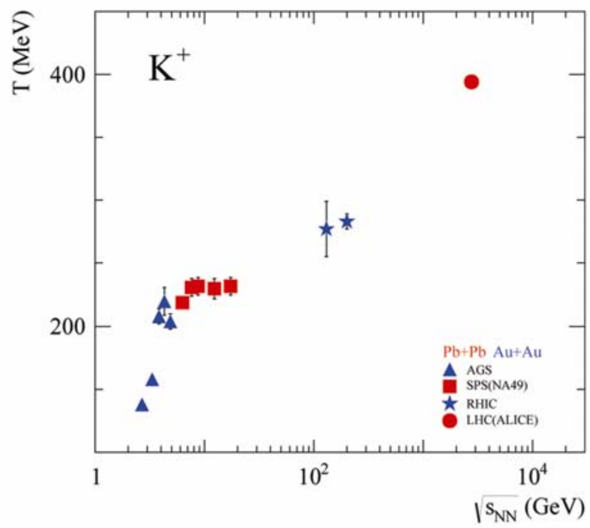


**Figure 8.** Energy dependence of the temperature derived from the spectra of kaons in central Pb + Pb (Au + Au) collisions. A step-like behaviour is observed for centre-of-mass beam energies between 10 and 100 GeV, where the transition between the confined to deconfined matter takes place[20].

observed that $T$ increases strongly with collision energy up to about 20 GeV/nucleon, followed by a region of approximately constant value at SPS energy range. This is indeed the indication of a coexisting phase of quarks and hadrons in heavy-ion collisions[21]. This behaviour is similar to that of the caloric curve, as discussed before. At higher energies, $T$ again increases with collision energy, as the early stage pressure increases with colliding energy, resulting in an increase in $T$. Several other observables exhibit similar behaviour, which is a characteristic of first-order phase transition at large $\mu_B$, ending up at the critical point.

At RHIC, the Indian scientists have initiated the search for QCD critical point by making a beam energy scan for Au–Au collisions from 5 GeV/nucleon to the top energy of 200 GeV/nucleon[22,23]. The results are expected within the next few years. In the near future, the CBM at the FAIR facility at GSI, Darmstadt, Germany will be operational, which aims to study the region of QCD critical point as well as high baryon density matter in more detail[24].

## Summary

Nuclear matter exhibits some of the most spectacular phases of matter and the transitions among these phases[25]. The study of the various phases and the nature of phase transitions have been at the forefront of scientific research for last three decades. The nuclear liquid to gas phase has been explored by low and intermediate energy nuclear reactions. Experimental results show a plateau in the caloric curve, characteristics of a first-order phase transition. There is prediction of a critical point at the end of the first-order line, which is yet to be found. The experiments with the superconducting cyclotron at VECC will shed light in this direction. At high temperature and density, the transition from hadron gas to quark–gluon plasma takes place. Dedicated experimental facilities at the BNL and CERN have been exploring the phase structure. Indian scientists have been playing an important role in these experiments, shaping the physics programme, design and fabrication of detectors, computing, data analysis and data interpretation from theoretical viewpoints. The results from RHIC and LHC indicate that the matter formed in high-energy collisions behaves like a strongly interacting near-perfect liquid. Experimental results indicate a first-order phase transition at higher baryonic chemical potential, giving hope for the existence of a critical point as has been predicted by lattice calculations. Major efforts in the search for the QCD critical point is ongoing with the beam energy scan programme at RHIC, where several signatures are being probed simultaneously. Future programmes at the FAIR facility will give access to the high density matter, and shed light on the behaviour of matter in the core of the neutron star. With the present state of affairs and planned activities, we are certain to learn and discover much more about the phases of nuclear matter in the near future.



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