Chapter 9 Phases of Nuclear Matter

As we know, water (H_2O) can exist as ice, liquid, or steam. At atmospheric pressure and at temperatures below the 0˚C freezing point, water takes the form of ice. Between 0˚C and 100˚C at atmospheric pressure, water is a liquid. Above the boiling point of 100˚C at atmospheric pressure, water becomes the gas that we call steam. We also know that we can raise the temperature of water by heating it— that is to say by adding energy.

However, when water reaches its melting or boiling points, additional heating does not immediately lead to a temperature increase. Instead, we must overcome water's latent heats of fusion (80 kcal/kg, at the melting point) or vaporization (540 kcal/kg, at the boiling point). During the boiling process, as we add more heat more of the liquid water turns into steam. Even though heat is being added, the temperature stays at 100˚C. As long as some liquid water remains, the gas and liquid phases coexist at 100˚C. The temperature cannot rise until all of the liquid is converted to steam. This type of transition between two phases with latent heat and phase coexistence is called a "first order phase transition."

As we raise the pressure, the boiling temperature of water increases until it reaches a critical point at a pressure 218 times atmospheric pressure (22.1 Mpa) and a temperature of 374˚C is reached. There the phase coexistence stops and the phase transition becomes continuous or "second order." We can make a diagram, Fig. 9-1 that shows the states of water depending on pressure and temperature.

This diagram indicates that even at temperatures below 0 C, as the pressure increases, ice can turn into water. The diagram can be used to predict the state of H_2O at any temperature and pressure. We call the mathematical relations inferred by the chart the "equation of state" of water.

Just as the state of a collection of atoms or molecules depends on temperature and pressure, we find that the state of a nucleus depends on temperature and on the density of the nucleons. Thus we may ask what is the equation of state for nuclear matter? In their normal states of lowest energy, nuclei show liquid-like characteristics and have a density of 0.17 nucleons/fm^3. In more conventional units, this corresponds to $2.7 \times 10^{17}\text{kg/m}^3$, or 270 trillion times the density of liquid water.

In a laboratory, the only possible way to heat nuclei to significant temperatures is by colliding them with other nuclei. The temperatures reached during these collisions are astounding. In atomic physics, the electron volt (1.6×10^{-19}joules) is used as a convenient unit because it is roughly the energy scale of atomic and chemical processes. Similarly, nuclear scientists use millions of electron volts or MeV (1.6×10^{-13}joules) as a convenient energy unit because it is roughly the energy scale of nuclear processes. An average energy of 1 MeV corresponds to a temperature of 1.2×10^{10}K. The temperatures we can reach in nuclear collisions range up to 100 MeV and above— more than 200 million times the temperature at the surface of the Sun (~5,500 K)!

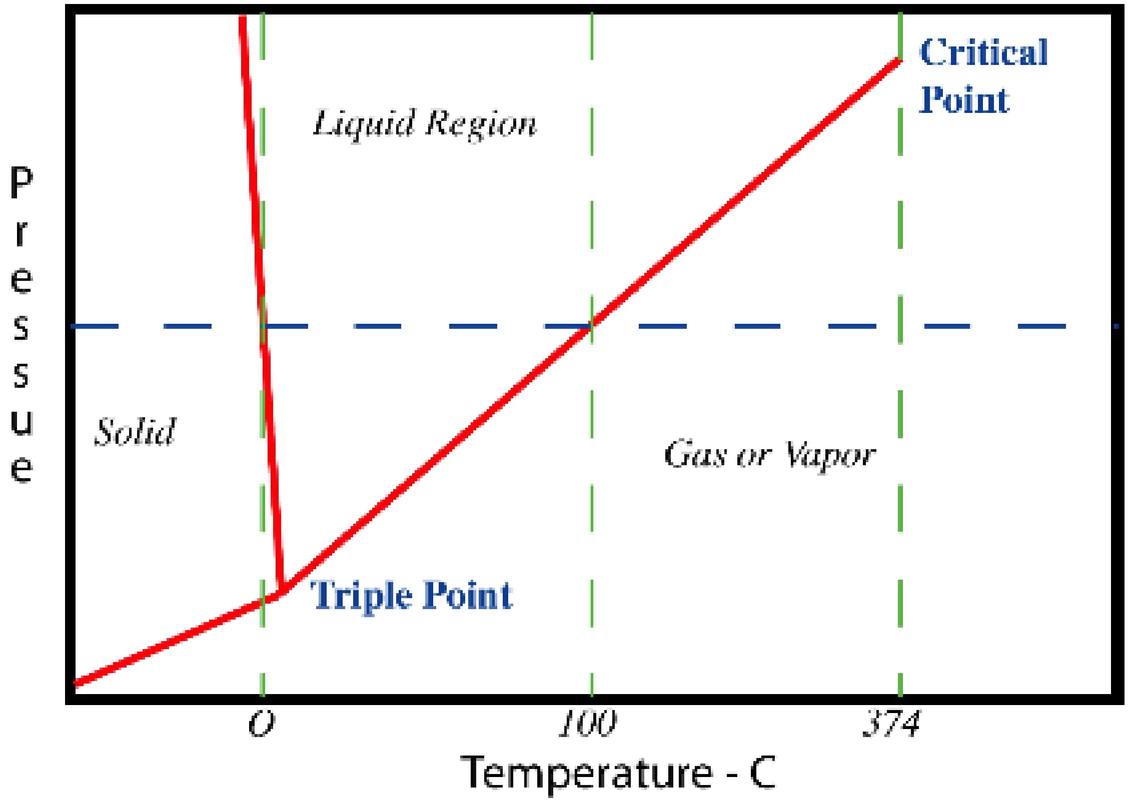

Fig. 9-1. The Phase Diagram for "water." The location of the "Triple Point" is displaced to the right to make it visible. The triple point of water is at a temperature of 0.0098 C and a pressure of 4.579 mm of mercury. The dashed horizontal line is at one atmosphere.

If we heat a nucleus to a temperature of a few MeV, some of its nuclear "liquid" will evaporate. From knowing the general form of the interactions between nucleons, we know that, just like water, the nuclear liquid also has a latent heat of vaporization, and that nuclei should undergo a first-order phase transition. This liquid-gas coexistence is also expected to terminate at a critical point, the critical point of nuclear matter. One of the major thrusts of heavy ion research at laboratories such as Michigan State University's National Superconducting Cyclotron Laboratory is to find out if these theoretical expectations are correct. Experiments try to determine at what temperature and density the critical point of nuclear matter is located.

Nuclear physicists face major challenges in their efforts to explore the nuclear equation of state and these nuclear phase transitions. We can only establish the hot and dense conditions needed for this process during heavy ion collisions. Thus we do not have the luxury of carefully preparing our sample at a given pressure, temperature and density, as is done when studying the phase diagram of water. Instead, we have only a time interval of about 10^{-21} seconds during which to conduct our experiment. To complicate things further, our sample does not stay at a given density and temperature, but rapidly expands and cools during our experiment. We also do not have any direct way of measuring the state variables (temperature, pressure, and density). We need to determine them from observables such as:

1. the abundance of isotopes,
2. the population of excited nuclear states,
3. the shapes of the energy spectra from nuclear collision remnants,
4. the production of particles such as pions.

It is also not obvious that thermal equilibrium can be established during these short time scales. Finally, there is the problem of finite particle number. When studying the phases of water, the sample usually contains very large numbers of molecules. This, again, is a luxury not enjoyed in heavy ion collisions, where the number of nucleons is at best only a few hundred. We then have to establish what signatures of a phase transition remain when so few elementary constituents are present.

Despite these challenges, progress in this field has been significant. We now have deep insights into how the thermodynamic state variables can be measured during heavy ion collisions. We are confident that thermal equilibrium can be established, have found evidence for phase coexistence, and we are beginning to pin down the critical point of the nuclear liquid-vapor phase diagram. Information about the size of fragments produced when nuclear matter is near its critical point gives essential information about the nuclear equation of state. Recent experiments on nuclear breakup are leading to improved understanding of this important question.

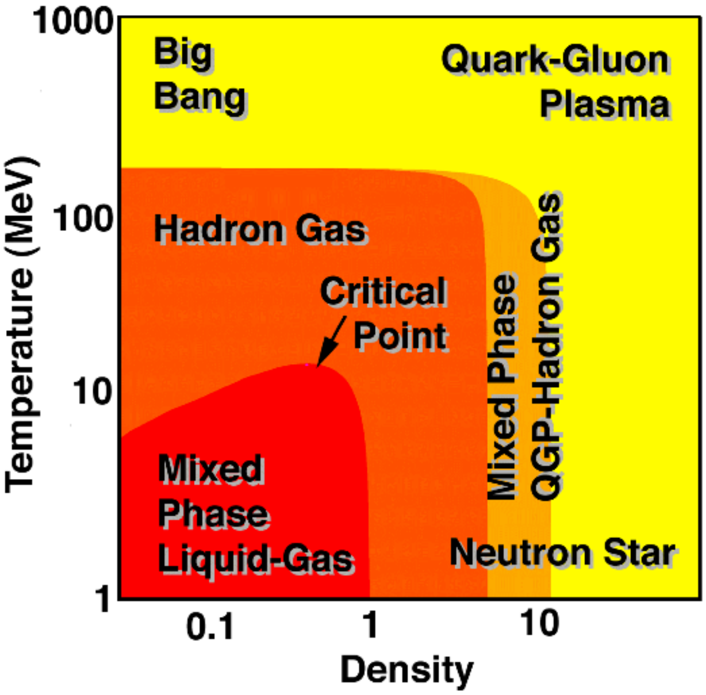

Fig. 9-2. The phase diagram for nuclear matter, as predicted theoretically. The horizontal axis shows the matter density, and the vertical axis shows the temperature. Both axes are shown in logarithmic scale, and the density is given in multiples of normal nuclear matter density. Please note that the temperature axis is the vertical one, as opposed to Fig. 9-1.

The yellow part of Figure 9-2 shows that the phase transition between the nuclear liquid and a gas of nucleons is not the only phase transition that heavy ion scientists are studying. At even higher temperatures and densities, the nucleons themselves can undergo a phase transition.

We can view each nucleon as a "bag" containing quarks and gluons. These can move relatively freely inside their own bag, but the theory says that they cannot escape from the bag— they are "confined." For this reason, we have never been able to detect individual free quarks or gluons. However, if we are able to produce an extremely dense gas of hadrons (mainly pions and nucleons), then their bags can overlap. This overlap lets the quarks and gluons from different bags mix freely and travel across the entire nuclear volume. We call this state a "quark-gluon plasma," in analogy with an atomic plasma in which electrons become unbound from atoms. From theoretical calculations, we also expect the phase transition to a quark-gluon plasma to be of first order, with a phase coexistence region.

Major research efforts at BNL (Brookhaven National Laboratory) in New York and at CERN (Conseil Europeen pour la Recherché Nucleaire) in Switzerland are directed toward establishing the conditions for creating this phase transition and observing its signatures. The Relativistic Heavy Ion Collider (RHIC), which began operation in the year 2000, has as its main mission the study of this exotic and unique phase transition in the nuclear equation of state. It accelerates two counter-circulating beams of gold nuclei, each at speeds extremely close to the speed of light. The machine then steers the gold nuclei so that they collide inside the experimental detectors.

All of the theoretical and experimental challenges described above are also present when studying the transition to the quark-gluon plasma. In addition, there is another, possibly even more severe obstacle to overcome— the quark-gluon plasma cannot survive longer than a few times 10^{-22} seconds. After that, the density and temperature reached during a heavy ion collision fall to values that force quarks and gluons to recombine into hadrons (strongly interaction particles, particularly p mesons) again. The number of hadrons produced in relativistic heavy ion collisions is staggering. For every nucleon that was initially contained in the two colliding gold nuclei, there can be more than 50 pions produced during each RHIC collision. This amounts to several thousands of hadrons emerging from each relativistic heavy ion collision, as shown in Fig. 9-4. The essential problem for the nuclear scientist is then to distinguish between those hadrons that were created from the ashes of the quark-gluon plasma and those that might be created in a dense gas composed only of hadrons.

Figure 9-4 shows a single collision of one of the new detectors (STAR) at RHIC. Each line represents a particle that is tracked and measured in the magnetic field of the detector, with the colors indicating different particle momenta. The detector measures the thousands of particles produced by the collision. Analysis of these data is like an attempt to "put Humpty-Dumpty together again"— to see if the collision showed any evidence that a quark-gluon plasma had been formed. Message carried by energetic particles produced in the early stages of the collision and by later particles produced in the evolving fireball must be carefully interpreted to understand the physics of the collision process.

What is the purpose of studying the nuclear matter phase diagram? The answer is that we need this information to understand the early history of our universe, and to understand high-density objects, called "neutron stars" in our present-day universe.

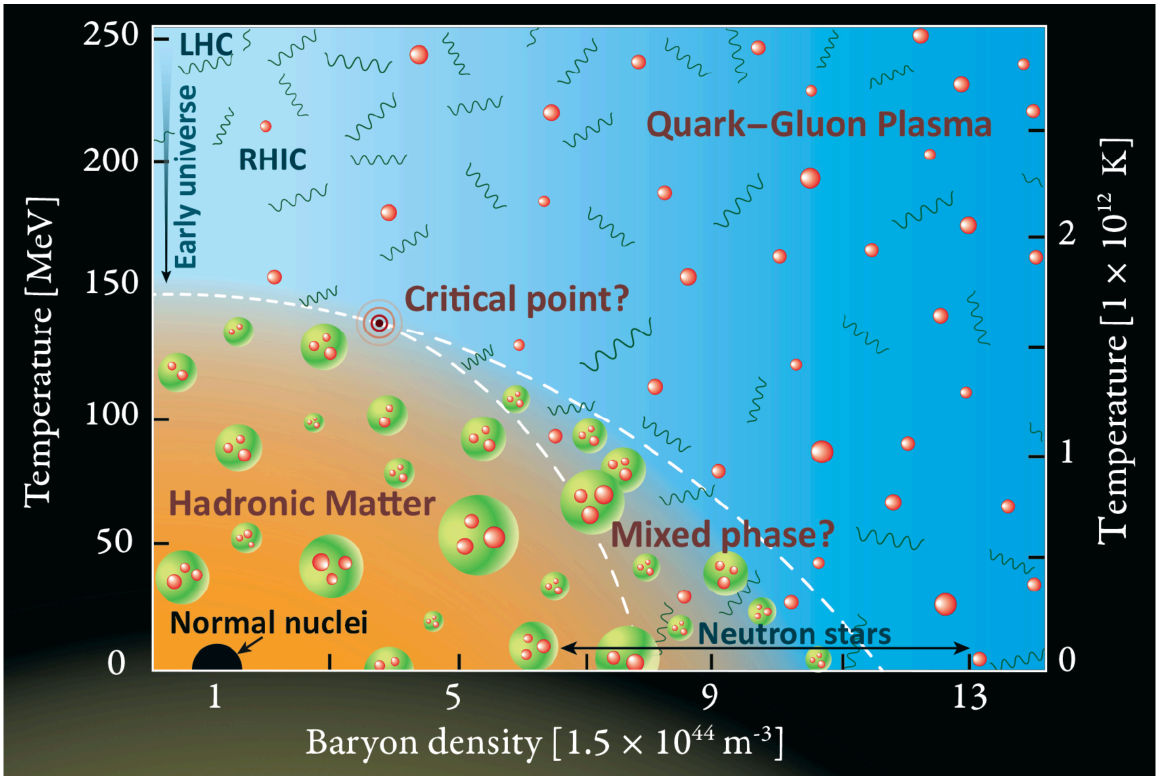

Fig. 9-3. This is a similar phase diagram as drawn in Fig. 9-2. A representation of the quarks is shown in the hadron gas area. The mixed phased region shows the existence of both hadrons and quarks and gluons. The quark-gluon plasma region shows the existence of quarks and gluons.

In the upper left corner of Figs. 9-2 and 9-3 is a region labeled "Early Universe". In the first microsecond after the Big Bang, the entire universe should have been in the state indicated there. Heavy ion collisions at Brookhaven National Laboratory at the RHIC facility, which recently began operation, and at the Large Hadron Collider (LHC) facility currently being constructed at CERN in Geneva, Switzerland will create dense matter and antimatter in about equal quantities. These accelerators can produce conditions similar to those of our early universe.

Figures 9-2 and 9-3 also show a region labeled "neutron star". When a massive star undergoes a supernova explosion, a core of iron nuclei remains. Gravity brings the nuclei together. The short-range nuclear repulsive force is not strong enough to keep the nuclei apart. As the core collapses, the individual nucleons separate from the nucleus. The protons become neutrons by inverse beta decay. Therefore, the neutron star is very large collection of neutrons, typically a few kilometers in diameter, which is held together by gravity. Some theorists predict that a neutron star of a large enough mass could be of high enough density to produce a quark-gluon plasma. The high-density end of the neutron star region indicates this region.

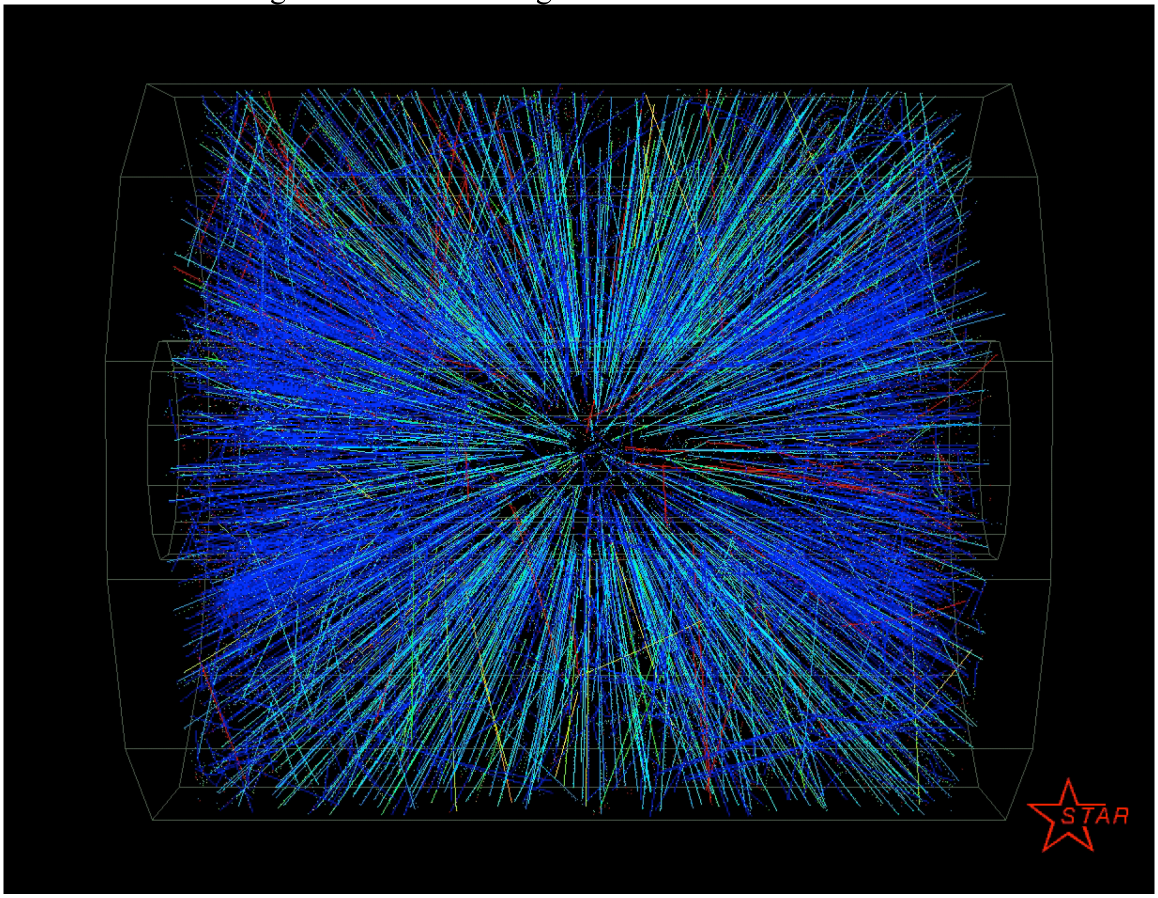

Fig. 9-4. This picture shows a collision between two gold nuclei in the STAR detector at the RHIC accelerator. Each line represents the path of a particle produced in the collision. It is recorded electronically, and the mass and momentum of each particle corresponding to each track is assigned by sophisticated computer software.

Thus, the study of the nuclear equation of state is connected to the initial phases of the early Universe, to ultra-violent stellar explosions, and to experiments around the world. These laboratories bring nuclei, which are traveling almost at the speed of light, into violent collisions to perhaps produce a state of matter in which quarks and gluons, if only briefly, become free particles. Exciting and surprising results have already began to emerge from RHIC. When the higher energy LHC facility comes into operation around 2007, we can expect even more unanticipated discoveries. These accelerators can produce states of matter in the laboratory that have not existed since the first microsecond of the Big Bang.

Web Sites:

RHIC- The Relativistic Heavy Ion Collider
https://www.bnl.gov/rhic/ — From this site you can find information about RHIC and the four experiments that are being done there.

ALICE – A Large Ion Collider Experiment
https://home.cern/about/experiments/alice — ALICE is the only dedicated heavy ion experiment at the LHC facility at CERN. It is scheduled to go into operation around 2007.