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SIGNIFICANCE OF INELASTIC NUCLEAR REACTIONS AND THEIR VARYING BEHAVIOR

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Abstract

Nuclear reactions are responsible for the production of all elements in the universe that are heavier than hydrogen and are responsible for the generation of energy in nuclear reactors and in stars. Nuclear reactions are processes that occur between nuclei, as well as between nuclei and other fundamental particles, such as electrons and photons. Nuclear reactions can also occur between nuclei and other fundamental particles. Following a concise explanation of the conservation laws and a definition of the fundamental physical quantities, the following specific cases are discussed in greater detail: (a) the formation and decay of compound nuclei; (b) direct reactions; (c) photon and electron scattering; (d) heavy ion collisions; (e) the formation of a quark-gluon plasma; (f) thermonuclear reactions; and (g) reactions with radioactive beams. When it is important to do so, fundamental equations are presented in order to assist in comprehending the general characteristics of these reactions.

Introduction

Nuclear reactions are the source of a significant portion of the information that we have on the characteristics of nuclei. The outcome of an interaction in which an incoming particle is scattered off a target nucleus is dependent on a combination of three factors. These factors are the reaction mechanism, the interaction between the projectile and the target, and the internal structure of the nuclei involved. There are fundamentally two different kinds of nuclear reactions. In the first category, the initial reactant X is a single atom or nucleus that spontaneously changes by emitting one or more particles, which is to say that it undergoes a spontaneous transformation.

$$X \rightarrow b+Y$$

Radioactive decay is the name given to this type of reaction. As was made clear by the Chart of the Nuclides, the vast majority of the nuclides that are currently understood to exist are radioactive. Binary reactions are the second broad category of nuclear reactions. These reactions fall under the second broad category because they involve the interaction of two nuclear particles (nucleons, nuclei, or photons) to form different nuclear particles.

For bombarding energies below 100 MeV, nuclear reactions usually produce two products, i.e. they are of the type

$$a+X \rightarrow b+Y$$

Where a = bombarding particle

X = target (at rest in the lab. system)

b = light reaction product

Y = heavy reaction product

To shorten the notation a reaction of the type above is designated by:

X(a,b)Y

Because of the different binding energies of the nuclei involved in the reaction, one of the products is often light while the other is typically heavy. In certain circumstances, the masses of b and Y are either similar (as in the case of a spallation reaction or a fission) or the same. In the event where b is a gamma ray, we refer to the resulting reaction as a capture reaction, with Y serving as the compound nucleus. In the majority of situations in which there are the appearance of more than two products, it is possible to depict the process as a quick sequence of reactions producing just two products.

$$a+X\rightarrow b_1+Y_1$$

$$Y_1\rightarrow b_2+Y_2$$

$$Y_2\rightarrow b_3+Y_3$$

For example, see the reaction: $^4He+{}^{14}N\rightarrow{}^1H+{}^{17}O$

Take note that there is no change in the total number of neutrons and protons. At the moment, there are thousands upon thousands of different reactions that have been uncovered. Consider a nucleus with mass M colliding elastically with another nucleus. There are two different frames that can be used to classify nuclear reactions. The nucleus is initially at a state of rest in the laboratory frame, while the particle possesses energy Eo and momentum mvo. After the scattering, the energy of the particle is E1, the speed of the particle is v1 at an angle of vo, and the momentum of the nucleus recoil is MV at an angle of vo. The collision is best analysed in the centre of mass frame, where the condition of elastic scattering implies that the relative velocities only change their direction but not their magnitude. This is the most accurate representation of what happens during a collision. The definition of the centre of mass velocity is as follows:

$$\vec{v}_{C.M.}=\frac{m\vec{v}_o+M\vec{V}_o}{m+M}=\frac{m}{m+M}\vec{v}_o$$

Relative velocities in the center of mass frame are defined as

$$\vec{u}=\vec{v}-\vec{v}_{C.M.}$$

where we defined ϑ as the scattering angle in the center of mass frame, see the figures below:

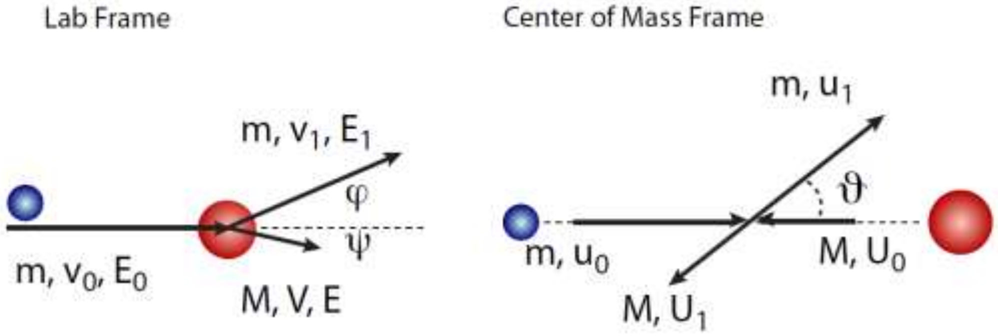

Figure (6-1): Neutron scattering from a nucleus. In left, laboratory frame, in right, center of mass frame.

Nuclear reaction

A phenomenon that happens as a result of interactions between atomic nuclei and takes place when the particles that are interacting approach one other to within distances that are on the order of nuclear dimensions (1012 cm). Even while nuclear reactions may be found in nature, the majority of the learning about these events and their application as tools has taken place in laboratory settings that are strictly regulated. The typical experimental setup involves initiating nuclear reactions by bombarding one of the interacting particles, the stationary target nucleus, with nuclear projectiles of some kind. After the reactions have begun, the reaction products and the behaviours of the reaction products are investigated. The production of pions has traditionally been considered to mark the energy border between the domains of nuclear and subnuclear (or particle) physics. The study of nuclear reactions is the most important subfield of nuclear and subnuclear (or particle) physics.

Types of nuclear interaction

Consider a collision as an example of a more generic nuclear process. In this scenario, an incoming particle impacts a particle that was previously immobile, resulting in the creation of an unknown number of finished products. The process is known as scattering if the products at the end are the same as the two particles that were present at the beginning. Whether some of the kinetic energy of the incident particle is used to raise either of the particles to an excited state determines whether the scattering is said to be elastic or inelastic. Elastic scattering occurs when the kinetic energy of the incident particle is used. A process is said to be a reaction when the resultant particles are distinct from the pair that was present at the beginning of the process.

The sort of nuclear reaction that results in the creation of two distinct end products is by far the most frequent and the one that has been subjected to the greatest amount of research. These kinds of reactions may be seen, for instance, when deuterons with a kinetic energy of a few megaelectronvolts are allowed to collide with a carbon nucleus that has a mass of 12. There is evidence of the emission of protons, neutrons, deuterons, and alpha particles, as well as processes.

$$^{2}_{1}H + ^{12}_{6}C \rightarrow ^{2}_{1}H + ^{12}_{6}C \quad (1)$$

$$^{2}_{1}H + ^{12}_{6}C \rightarrow ^{1}_{1}H + ^{13}_{6}C \quad (2)$$

$$^{2}_{1}H + ^{12}_{6}C \rightarrow ^{1}_{0}n + ^{13}_{7}N \quad (3)$$

$${}^{2}_{1}\mathrm{H}+{}^{12}_{6}\mathrm{C}\rightarrow{}^{4}_{2}\mathrm{He}+{}^{10}_{5}\mathrm{B}\tag{4}$$

are accountable. In these equations, the nuclei are represented by the standard chemical symbols; the subscripts indicate the atomic number (also known as the nuclear charge) of the nucleus, and the superscripts give the mass number of the specific isotope. Conventionally, these reactions are expressed in a compact notation that looks like this: 12C(d,d)12C, 12C(d,p)13C, 12C(d,n)13N, and 12C(d,)10B, where d represents deuteron, p represents proton, n represents neutron, and represents alpha particle. In every one of these instances, the reaction leads to the creation of a heavy residual nucleus as well as a light particle that is ejected into the atmosphere. The term "d,d" process refers to both the elastic scattering and the inelastic scattering processes that are responsible for causing the 12C nucleus to transition into one of its excited states. The other three processes are instances of nuclear transmutation or disintegration. In these events, the leftover nuclei may also be created in either their ground states or one of the numerous excited states they might assume. In this specific reaction, the many mechanisms that produce the leftover nucleus in different excited states are regarded to represent the various reaction channels. If the remaining nucleus is generated in an excited state, it will subsequently emit this excitation energy as gamma rays or, under some circumstances, electrons. This will occur if the nucleus was formed in an excited state. In the case of 13N, which was generated as a byproduct of the 12C(d,n) process, the remaining nucleus can also exist as a radioactive species. In this scenario, the remnant nucleus will go through additional alteration in line with the pattern of radioactive decay that is typical for it.

Nuclear cross section

In general, one is interested in the likelihood of the different reactions occurring as a function of the blasting energy of the impacting particle. This is because one may use this information to make predictions about what will happen. The cross section of a nuclear reaction may be thought of as a probability gauge for the reaction. Consider a reaction that is started by a beam of particles colliding with a region that has N atoms per unit area that are dispersed evenly, and a situation in which I particles per second impacting the region result in R reactions of a certain kind per second. The percentage of the region that was blasted and was able to successfully produce reaction products is called the $\frac{R}{I}$. If this is divided by the number of nuclei per unit area, the effective area or cross section $\sigma = \frac{R}{IN}$. Because it takes into account every instance of the reaction, this is what is meant when people talk about the "total cross section" for the particular reaction. The measurements correspond to those of an area, and the total cross sections can be stated in either square centimetres or barns (1 barn = 1024 cm2) The differential cross section is the likelihood that a specific reaction product will be seen at a specific angle relative to the beam direction. This probability is referred to as the differential cross section. Its measurements correspond to those of an angle solid unit per square unit (for example, barns per steradian).

Requirements for a reaction

Both the occurrence of a particular reaction and the cross section at which it is detected are dependent on a variety of parameters, some of which are not always totally understood by scientists. Nevertheless, in order for a response to take place, there are a few prerequisites that need to be satisfied first.

Coulomb barrier

In order for a reaction to take place, the two particles that are interacting must get close enough to one another to be on the order of nuclear dimensions (about 10-12 centimeters). All incident particles, with the exception of the neutron, must therefore have sufficient kinetic energy to overcome the electrostatic (Coulomb) repulsion produced by the intense electrostatic field produced by the nuclear charge. The neutron is the only incident particle that does not carry a charge. The so-called Coulomb barrier, whose magnitude is approximately given by the expression, must be met by the kinetic energy, which must be comparable to or greater than the barrier. $E_{\mathrm{Coul}} \approx \frac{Z_1 Z_2}{(A_1^{1/3}+A_2^{1/3})}$ meV, where Z and A refer to the nuclear charge and the mass number of the interacting particles 1 and 2, respectively. MeV It can be seen that while protons with kinetic energies of a few hundred kiloelectronvolts are sufficient to initiate reactions for the lightest targets, energies of many hundreds of megaelectronvolts are required to initiate reactions between heavier nuclei. This is because heavier nuclei have more electrons in their nuclei, making them more difficult to break apart. Particle accelerators of various types (such as Van de Graaff generators, cyclotrons, and linear accelerators) have been developed in order to supply energetic charged particles that can be used as projectiles in reaction studies. This has made it possible for researchers to investigate nuclear reactions induced by projectiles as light as protons and as heavy as 208Pb.

Neutrons are uncharged particles, therefore they are not rejected by the electrostatic field of the target nucleus. For some reactions, neutron energy as low as a fraction of an electronvolt are sufficient to kickstart the process. Neutrons can be obtained for the purpose of studying reactions either via the use of nuclear reactors or by the study of various nuclear processes that create neutrons as reaction products. There are in fact two more methods of manufacturing nuclear reactions that are not included in the basic description that was just presented. Under the right circumstances, electromagnetic radiation and high-energy electrons are both able to cause the nuclei of atoms to break apart. However, electromagnetic and weak nuclear forces, rather than the strong nuclear force that is responsible for nuclear interactions, cause these two types of forces to have significantly weaker interactions with nuclei than nucleons and other nuclei do.

Q value

In order for a nuclear reaction to take place, there has to be a sufficient amount of kinetic energy available to facilitate the transformation of the initial nuclear species into the products of the reaction. It is possible for the sum of the kinetic energy of the reaction products to be higher, equal to, or lower than the sum of the kinetic energies that existed before the reaction took place. The Q value for that specific reaction may be determined by calculating the difference between the two amounts. It is possible to demonstrate that the value of Q is equivalent to the difference between the masses of the reaction products and the masses of the nuclei that were there before the reaction began. Reactions that have a Q value that is positive are known as exoergic or exothermic reactions, whereas reactions that have a Q value that is negative are known as endoergic or endothermic reactions.

The Q values for reactions in which the residual nuclei are formed in their ground states are as follows: 12C(d,d)12C has a Q value of 0.0 MeV; 12C(d,p)12C has a Q value of 2.72 MeV; 12C(d,n)13N has a Q value of 0.28 MeV; and 12C(d,)10B has a Q value of 1.34 MeV. It is required for there to be a specific minimum amount of kinetic energy for reactions to take place when the Q value of the reaction is negative. There is no minimum energy requirement for reactions with positive Q values; nonetheless, the cross section for reactions triggered by charged particles is extremely low unless the energies are high enough to break the

Coulomb barrier. Reversibility may be defined in terms of the Q values of a nuclear reaction and its inverse in the sense that they are identical but have opposite signs.

Conservation laws

Experiments have shown that specific physical quantities must be the same both before and after the reaction in order for it to be considered successful. The electric charge, the number of nucleons, the energy, the linear momentum, the rotational momentum, and, in the majority of circumstances, parity are the values that are conserved. One may deduce from the conservation of charge and number of nucleons that the numbers of protons and neutrons are always preserved, with the exception of high-energy processes that result in the generation of mesons. These reactions include the production of mesons. Because the number of nucleons always stays the same, regardless of whether or not a reaction is taking place, we may assume that the statistics that control the system are unaffected. If the total number is odd, the Fermi-Dirac statistics are obeyed, and if the total number is even, the Bose-Einstein statistics are obeyed. When all of the conservation laws are considered together, they serve to place significant constraints on the kinds of reactions that can take place. In particular, the conservation of angular momentum and parity make it possible to determine the spins and parities of the states that are excited by different kinds of reactions. angular momentum; the principles of conservation in physics; parity in quantum mechanics; the laws of symmetry in quantum mechanics; quantum statistics (physics)

Reaction mechanism

The complex many-body problem of what occurs when a projectile collides with a target nucleus is not yet fully understood in its entirety. During the course of the last few decades, significant advancements have been achieved in the creation of a wide variety of reaction models. These models have had a great deal of success in characterising certain classes or types of nuclear reaction processes. In a general sense, it is possible to categorise all reactions in accordance with the time scale on which they take place and the degree to which the kinetic energy of the incoming particle is translated into the internal excitation of the products that are created. A significant portion of the observed reactions have attributes that are in agreement with those that are predicted by two reaction mechanisms. These two reaction mechanisms are at opposite ends of the spectrum represented by this generic categorization. These are the processes that underlie the development of compound nuclei as well as direct contact.

Compound nucleus formation

It was N. Bohr who first proposed the idea, but currently it is thought that the process will be broken up into two distinct stages. The initial step involves the target nucleus either absorbing the incident particle or fusing with it to create an intermediate or compound nucleus. This nucleus has a longer half-life (approximately 1016 s) when compared to the approximately 1022 s that it takes for the incident particle to travel past the target. During this period of time, the kinetic energy of the incident particle is distributed equally across all of the nucleons, and all memory of the incident particle and the target is erased. The compound nucleus is always formed in a highly excited unstable state. It is presumed to approach thermodynamic equilibrium involving all or most of the available degrees of freedom. The compound nucleus will decay, as the second step, into a variety of reaction products or through so-called exit channels. The process of decay can, in the vast majority of instances, be interpreted as the random dissipation of nucleons or light particles. Within the examples of reactions (1)–(4), the compound nucleus that is formed is 14N, and there are indicated to be four possible exit channels. When heavier targets are involved in a reaction (for instance, when A is greater than

200), one of the exit channels could be the fission channel. This is the channel through which the compound nucleus splits into two large fragments. Fission in the nucleus

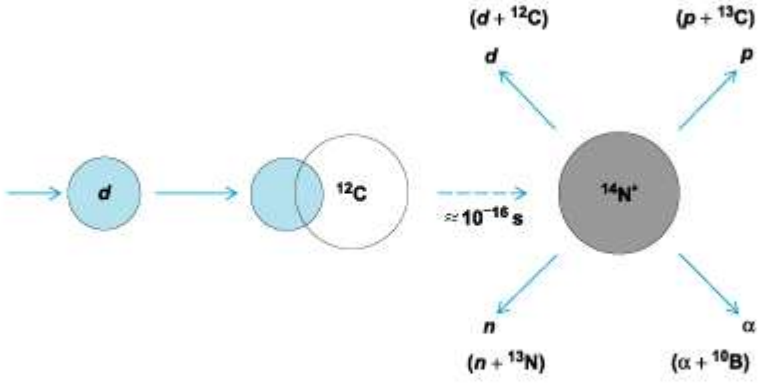

Fig. 1 Formation of the compound nucleus N after capture of the deuteron by C. Four exit channels are indicated.

The essential characteristic of the process of forming a compound nucleus or undergoing a fusion reaction is the fact that the probability of a particular reaction is dependent on two independent probabilities. These probabilities are the probability of creating the compound nucleus and the probability of disintegrating into that particular exit channel. It would appear that the mechanism is responsible for a significant portion of the reactions that take place in the vast majority of projectile-target interactions, despite the fact that certain aspects of a variety of interactions cannot be completely explained within the framework of the compound nucleus hypothesis. Fusion reactions have proven to be very helpful in a variety of spectroscopic investigations over the years. The resonance studies performed with light projectiles, such as neutrons, protons, deuterons, and alpha particles, on light target nuclei have been of particular note, as have the gamma-ray studies of reactions induced by heavy projectiles, such as 16O and 32S, on target nuclei spanning the periodic table. Both of these types of studies have been performed on light target nuclei. These studies have made a significant contribution to our understanding of the excitation energies and spins of various levels in nuclei by providing a vast amount of information.

Direct interactions

The expectations of the compound nucleus theory are strongly contradicted by the features of several reactions, which are in stark contrast to those predictions. A good number of these are consistent with the picture of a mechanism in which no long-lived intermediate system is formed, but rather a fast mechanism in which the incident particle, or some portion of it, interacts with the surface, or some nucleons on the surface, of the target nucleus. In this mechanism, there is no formation of a long-lived intermediate system. The notion of a homogenous lump of nuclear matter with distinct modes of excitation is used in models for direct processes. This concept operates to scatter the incident particle through forces that are, in the simplest situations, characterised by an ordinary spherically symmetric potential. It is possible that during the process of scattering, some of the kinetic energy will be utilised to excite the target, which will give birth to an inelastic process. Additionally, it is possible that nucleons will switch places, which would give rise to a transfer process. In general, direct reactions are presumed to include only a relatively small number of the available degrees of freedom; however, this is not always the case.

The vast majority of direct reactions are of the transfer kind, which occurs when one or more nucleons are transferred to or from the incident particle as it passes the target. This leaves the two final partners either in their ground states or in one of the various excited states that they might be in. Such transfer reactions are commonly referred to as stripping reactions or pick-up reactions, depending on whether the incident particle has lost nucleons or received nucleons as a result of the process. The (d,p) reaction is an example of a stripping reaction, in which the incident deuteron is envisioned as being stripped of its neutron as it passes the target nucleus, and the proton continues along its journey as it moves away from the nucleus (Fig. 2).

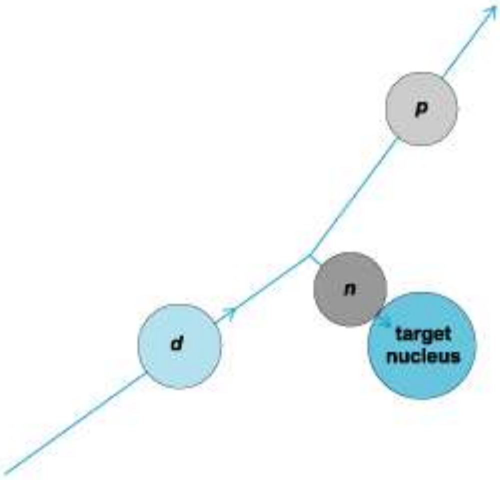

Fig. 2 A (*d*, *p*) transfer reaction.

The specifics of the reaction, including the amount of energy and angular momentum that the neutron must enter it with, are decided by the characteristics of the nucleus that will serve as the target. The amount of energy that is transferred into the target nucleus from the deuteron by the neutron is what determines the amount of energy that is transferred into the outgoing proton, which in turn helps to designate the end state that is occupied by the Q value of the reaction as a whole. At the appropriate bombarding energies, the angular distribution of the differential cross sections will not be smooth; rather, it will show a distinct pattern of maxima and minima that are indicative of the spin and parity of the final state. This information can be obtained by calculating the bombarding energies. The nuclear structures of the nuclei that are involved play a role in determining the cross section for populating a certain final state in the target nucleus. Studies of single-nucleon, two-nucleon, and four-nucleon transfer reactions, such as (d,p), (p,d), (3He,d), (t,p), and (7Li,d), have made use of this sensitivity in order to establish the validity and usefulness of the shell-model description of nuclei. Examples of these reactions include (d,p), (p,d), (3He,d), and (t,p). The use of heavier projectiles in multinucleon transfer reactions has shown to be a valuable tool in both the production of new isotopes and the accessing of nuclei that are unreachable via conventional methods.

Inelastic scattering is another type of direct response, and the information regarding the spin and parity of the excited state that it can supply can be gleaned from its angular distribution. The states that are preferentially aroused in inelastic scattering are collective in character. This is in contrast to the nature of the states that are preferentially inhabited in transfer reactions, which are those of particular single-particle or shell-model structures. Within the context of macroscopic descriptions, the states may be thought of either as oscillations in shape around a spherical mean (known as vibrations) or as rotations of a statically deformed shape. This framework allows for the states to be comprehended with the greatest degree of simplicity. The shape or deformation of the target nucleus in its various collective excitations is connected to the cross section for inelastic scattering, which is related to the shape or deformation of the target nucleus. Both a nuclear contact and an electromagnetic interaction known as Coulomb excitation can generate inelastic excitation. In the case of the latter, the target nucleus interacts with the rapidly changing electric field caused by the passage of the charged particle. When interactions between heavy projectiles take place at low bombardment energy, coulomb excitation is a crucial process that takes place. Research on the inelastic scattering of nuclei to low-lying states across the periodic table has produced visual representations of the collective properties of nuclei. The direct interaction that does not alter the state of the interacting particles is referred to as elastic scattering. The inverse-square force law between two electrically charged things provides a good description of the elastic scattering that occurs between charged particles when the bombardment energy are relatively modest. Rutherford scattering is the name given to this particular kind of operation. At higher energy, the particles enter the range of the nuclear force, and at these energies, the inverse-square characteristic of the elastic scattering begins to break down.

More complex reaction mechanisms

There are processes that can be found in the middle of direct nucleus formation and compound nucleus creation. The so-called preequilibrium emission is the greatest illustration of a process like this one. In this process, light particles are released before the kinetic energy in the compound nucleus has been distributed equally among all of the nucleons in the nucleus. Another illustration of this may be observed in the interaction of two heavy nuclei, such as 84Kr and 209Bi, where it has been shown that the chance of the creation of the composite nucleus is extremely low. According to the findings of the experiments, the nuclei contact with one another for a brief period of time before splitting apart in what seems to be a straightforward response. Even while the contact periods for these so-called highly damped or deep inelastic collisions are relatively short in comparison to those for the production of compound nuclei, they are nevertheless long enough for a significant amount of mass transfer and relative kinetic energy loss to occur.

Nuclear reaction studies

The majority of the time, the research of nuclear reactions is geared toward the long-term objective of learning more about the characteristics and composition of nuclei. These kinds of investigations often consist of two parts. During the first stage of the process, the researchers' attention is focused on the mechanism of the reaction and on determining the reliance on the nuclei that are involved. As new data from experiments are included into the specific models that have been established, such models undergo ongoing modification and improvement in order to make their predictions as accurate as possible. At this time, the process moves on to the second stage, which is characterised by the effort's concentration on the extraction of information concerning nuclei. There are further research being conducted that concentrate on response cross-section behaviours for a variety of other reasons. Both the neutron-capture reactions on heavy target nuclei that fission and the 3H(d,n)4He reaction are examples of this phenomenon. Both of these reactions are important in thermonuclear processes and continue to be studied because of their potential use as sources of energy. Because of the implications that they have for astrophysics and cosmology, research into the interactions of light nuclei at low energies has received a lot of attention recently.

Collisions of very high energy nuclei

The nucleons, which are composed of elementary particles like protons and neutrons, are not themselves elementary particles. They are each composed of clumps of quarks that are held together very securely by the transfer of gluons. In quantum chromodynamics, the theory that describes the interactions of quarks and gluons, one of the essential characteristics is that the force between quarks grows smaller when the quarks interact at greater energies. This is one of the central characteristics of the theory. It is impossible for free quarks to exist during the vast majority of nuclear processes because the interaction between quarks is so strong; quarks can only be found trapped within composite particles known as hadrons. There are many other forms of hadrons, including the unstable pions and J/p particles, which include the proton and the neutron as two examples each. Quantum chromodynamics, on the other hand, predicts that at temperatures above a critical temperature value of approximately 150 MeV (approximately 1012 K, which is approximately 105 times the temperature at the centre of the Sun), the force between the quarks in a hadon will become so weakened that it will cause the hadron to disintegrate. The phase transition described by quantum chromodynamics refers to the change that occurs when hadronic matter transforms into a plasma composed of quarks and gluons.

Following the big bang, during the first few microseconds after the event, the whole universe was filled with quark-gluon plasma and had a temperature that was higher than 150 MeV. The quantum chromodynamics phase transition took place everywhere in the cosmos when the temperature dropped below the critical point. Extreme temperatures, which are needed in order to witness the quantum chromodynamics phase transition, are difficult to achieve in the lab. The sole known way involves crashing very massive nuclei together at extremely high speeds.

Under these conditions, it is hypothesised that quark-gluon plasma will be created for the first time since the big bang as a result of detailed theoretical calculations that model the quantum chromodynamics interactions of the millions of quarks and gluons produced in such collisions. This plasma will take place in an area with a size of many times 1013 cm and will last for several times 1022 seconds until the quantum chromodynamics phase transition takes place and conventional hadrons are reconstituted.

The distribution and energy of the particles that are released as a result of the collision should contain signals that indicate the momentary presence of a quark-gluon plasma. One example of such a signature is the J/ particle, which consists of a heavy quark and a heavy antiquark as its constituent parts. The J/ particle, like any other hadron, dissociates in a quark-gluon plasma, and at the same time, the heavy quark and antiquark become separated. Heavy quarks are considerably more likely to create hadrons in association with the vastly more numerous light quarks in the plasma as it cools during the phase transition than they are to rejoin to form J/ hadrons. This is because light quarks are much more abundant than heavy quarks. The reduction in the number of J/ particles that should have been created as a result of a collision has been seen and confirmed. However, J/ hadrons may also be shattered into their component parts by repeated collisions in a hadronic environment that is both hot and dense. Therefore, the observed J/ suppression proves that such an environment has been produced, but it does not prove by itself that a quark-gluon plasma has been manufactured.

Following an unexpected quantum chromodynamics phase transition, pion waves are amplified and coherent emission of pions takes place in an idealised model. This happens as the hadronic state of matter is reestablished after the phase shift. These types of pion lasers would be very easy to detect because they would occasionally emit only electrically neutral pions or only electrically charged ones, whereas in general, different types of pions are mixed together in a uniform manner. This would make it very obvious that the lasers were producing only electrically neutral or only electrically charged pions. This result would be an unmistakable hallmark for the fleeting presence of a quark-gluon plasma in a collision between nuclei with extremely high energies.