Nuclear Reactions - Laws and Principals

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Abstract: ***Nuclear reactions generate energy in nuclear reactors, in stars, and are responsible for the existence of all elements heavier than hydrogen in the universe. Nuclear reactions denote reactions between nuclei, and between nuclei and other fundamental particles, such as electrons and photons. A short description of the conservation laws and the definition of basic physical quantities is presented, followed by a more detailed account of specific cases. Whenever necessary, basic equations are introduced to help understand general properties of these reactions.***

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1. Introduction

Nuclear reactions generate energy in nuclear reactors, in stars, and are responsible for the existence of all elements heavier than hydrogen in the universe. Nuclear reactions denote reactions between nuclei, and between nuclei and other fundamental particles, such as electrons and photons. A short description of the conservation laws and the definition of basic physical quantities is presented, followed by a more detailed account of specific cases: (a) formation and decay of compound nuclei; (b)direct reactions; (c) photon and electron scattering; (d) heavy ion collisions; (e) formation of a quark-gluon plasma; (f) thermonuclear reactions; (g) and reactions with radioactive beams. Whenever necessary, basic equations are introduced to help understand general properties of these reactions.

The collision of two nuclei can give place to a nuclear reaction and, similarly to a chemical reaction, the final products can be different from the initial ones. This process happens when a target is bombarded by particles coming from an accelerator or from a radioactive substance. It was in the latter way that Rutherford observed, in 1919, the first nuclear reaction produced in laboratory,

$$^{7}\alpha + ^{14}\overset{8}{N} \rightarrow ^{17}O + p, \qquad (1)$$

Using α-particles from a 214Bi sample. As in eq. 1, other reactions were induced using α- particles, the only projectile available initially. With the development of accelerators around 1930, the possibilities multiplied by changing the energy and mass of the projectile. Today it is possible to bombard a target with protons of energy greater than 1 T eV ($1TeV=10^{12}eV=$ 1.602 x 10^{-7} joules) and beams of particles as heavy as uranium are available for study of reactions with heavy ions.

Sometimes we can have more than two final products in a reaction, as in

$$p+^{14}N \rightarrow ^{7}Be+2\alpha,$$
$$p+^{23}Na \rightarrow ^{22}Ne+p+n, \qquad (2)$$

or just one, as in the capture reaction $p + ^{27}Al \rightarrow ^{28}Si^{*}$ where the asterisk indicates an excited state, which usually decays emitting -radiation. Under special circumstances, more than two reactants is possible. Thus, for example, the reaction $\alpha+\alpha+\alpha$ –>^{12}C can take place in the overheated plasma of stellar interiors. The initial and final products can also be identical. This case characterizes a process which can be elastic, a sinp $+^{16}O \rightarrow p +^{16}O$, where there is only transfer of kinetic energy between projectile and target, or inelastic, as in $n+^{16}O \rightarrow n+^{16}O^{*}$ where part of the kinetic energy of the system is used in the excitation of 16O.

Naturally, nuclear reactions are not limited to nuclei. They could involve any type of particle, and also radiation.

Thus, the reactions

$$\gamma+^{63}Cu \rightarrow ^{62}Ni+p,$$
$$\gamma+^{233}U \rightarrow ^{90}Rb+^{141}Cs+2n, \qquad (3)$$

are examples of nuclear processes induced by gamma radiation. Unlike a chemical reaction, the resulting products of nuclear reaction are not determined univocally: starting from two or more reactants there can exist dozens of Final products with an unlimited number of available quantum states. As an example, the collision of a deuteron with238U can give place, among others, to the following reactions:

$$\begin{aligned} d + ^{238}U &\rightarrow ^{240}Np + \gamma, \\ &\rightarrow ^{239}Np + n, \\ &\rightarrow ^{239}U + p, \\ &\rightarrow ^{237}U + t. \end{aligned} \qquad (4)$$

In the first of them the deuteron is absorbed by the uranium, forming an excited nucleus of 240Np that de-excites by emitting a Ɣ-ray. The two following are examples of stripping reactions, in which a nucleon is transferred from the projectile to the target. The last one exemplifies the inverse process: the deuteron captures a neutron from the target and emerges out as 3H (tritium). This is denoted as a pick-up reaction. Another possibility would-be, in the first reaction, those 240Np fissions instead of emitting a Ɣ -ray, contributing with dozens of possible final products for the reaction.

Each reaction branch, with well defined quantum states of the participants, is known as channel. In 4, for the entrance channel d + 238U, there are four possible exit channels. Notice that a different exit channel would be reached if some of the final products were in an excited state. The probability that a nuclear reaction takes place through a certain exit channel depends on the energy of the incident particle and is measured by the cross section for that channel.

In high energies collisions, the nuclei fragment and particles that were not initially present are produced (for instance, pions, kaons, etc.). The reactions proceed through an intermediate phase in which the nuclear matter is compressed. At very high energies the quarks and gluons inside nucleons become "free'' for a short time forming the quark-gluon plasma. The study of high energy reactions with nuclei is very important for a better understanding of what happens during spectacular stellar explosions (supernovae) and in the interior of compact stars, as for instance, neutron stars. The study of nuclear reactions at high energies allows to obtain information on the equation of state of nuclear matter.

2. Basic Principles

a) Conservation laws

Several conservation laws contribute to restrict the possible processes in a nuclear reaction.

1) Baryonic number - There is no experimental evidence of processes in which nucleons are created or destroyed without the creation or destruction of corresponding ant nucleons. The application of this principle to low energy reactions is still more restrictive. Below the threshold for the production of mesons (~ 140 MeV), no process related to the nuclear forces is capable to transform proton into a neutron and vice-versa, and processes governed by the weak force (responsible for the β-emission of nuclei) are very slow in relation to the times involved in nuclear reactions (~10^{-22} to 10^{-16}s). In thisway, we can speak separately of proton and neutron conservation, which should show up with same amounts in both sides of a nuclear reaction.
2) **Charge**
This is a general conservation principle in physics, valid in any circumstance. In purely nuclear reactions it is computed making the sum of the atomic numbers, which should be identical, at both sides of the reaction.
3) **Energy and linear momentum**
These are two of the most applied principles in the study of the kinematics of reactions. Through them, angles and velocities are related to the initial parameters of the problem.
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5) **Total angular momentum –**
Total angular momentum is always a constant of motion. In the reaction

$$^{10}\mathrm{B} + {}^{4}\mathrm{He} \rightarrow {}^{1}\mathrm{H} + {}^{13}\mathrm{C}, \qquad (5)$$

^{10}B has I = 3 in the ground state, whereas the α-particle has zero angular momentum. If it is captured in an s- wave (li = 0), the intermediate compound nucleus is in a state with Ic = 3. Both final products have intrinsic angular momenta equal to 1/2. Hence, their sum is 0 or1. Therefore, the relative angular momentum of the final products will be lf = 2, 3 or 4.

6) **Parity**
is always conserved in reactions governed by the nuclear interaction. In the previous example, 10B,4He and the proton have equal parities, while 13C has odd parity. Therefore, if li = 0, we necessarily have lf = 3. Thus, the orbital momentum of the Final products of eq. 5 is determined by the joint conservation of the total angular momentum and of the parity.

b) Kinematics

We consider a typical reaction, in which the projectile and the target A gives place to two products, b and B. This can also be expressed in the notation that we used so far, a + A → b + B; or even in a more compact notation, A(a,b)B: Often, a and b are light nuclei and A and B, heavy ones; the nucleus b being emitted at an angle θ and itsenergy registered in the laboratory system. The recoilingnucleus B has usually a short range and cannot leave the target. It is convenient to introduce the Q-value of their action which measures the energy gained (or lost) due to the difference between the initial and final masses:

$$Q = (m_a + m_A - m_b - m_B)c^2. \qquad (6)$$

Using energy and momentum conservation in the reaction, one gets:

$$Q| = E_b\left(1+\frac{m_b}{m_B}\right) - E_a\left(1-\frac{m_a}{m_B}\right) - \frac{2}{m_B}\sqrt{m_a m_b E_a E_b}\cos\theta. \qquad (7)$$

From this relation one obtains that, when Q is negative, an energy threshold exists for the incident particle,
Et, as a function of the angleθ, below which nuclei b are not observed in that angle:

$$E_t = \frac{-Q m_B(m_B + m_b)}{m_a m_b \cos^2\theta + (m_B + m_b)(m_B - m_a)}. \qquad (8)$$

This example shows the power of conservation laws in the analysis of nuclear reactions.

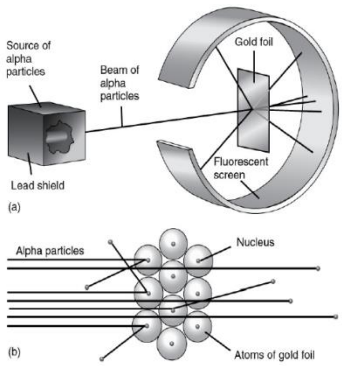

Figure 1: (Top) Rutherford's scattering experiment with α-particles scattering on a gold foil. (Bottom) Microscopic interpretation of the experimental results.

3. Statistical Reactions

a) Compound nucleus

When a low energy neutron (< 50 MeV) enters the range of nuclear forces it can be scattered or begin a series of collisions with the nucleons. The products of these collisions, including the incident particle, will continue in their course, leading to new collisions and new changes of energy. During this process one or more particles can be emitted and they form with the residual nucleus the products of a reaction that is known as pre-equilibrium. At low energies, the largest probability is the continuation of the process so that the initial energy is distributed among all nucleons, with no emitted particle. The final nucleus with A + 1 nucleons has an excitation energy equal to the kinetic energy of the incident neutron plus the binding energy the neutron has in the new, highly unstable, nucleus. It can, among other processes, emit a neutron with the same or smaller energy to the one absorbed. The de-excitation process is not necessarily immediate and the excited nucleus can live a relatively long time.

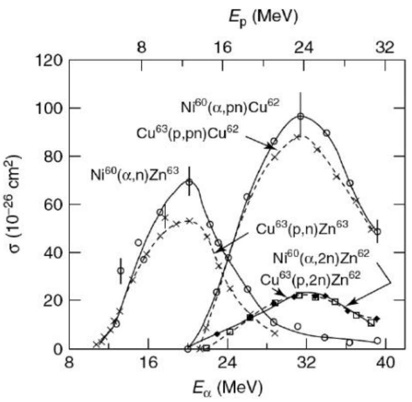

Figure 4: Cross sections for the reactions. The scales of the upper axis (energy of the protons) and lower axis (energy of the α-particle) were adjusted to correspond to the same excitation energy of the compound nucleus. We say that there is, in this situation, the formation of a compound nucleus as intermediary stage of the reaction. In the final stage the compound nucleus can evaporate one or more particles, fission, etc. In our notation, for the most common situation in which two final products are formed (the evaporated particle plus the residual nucleus or two fission fragments, etc.) we write:

$$a + A \to C^* \to B + b,$$

The asterisk indicating that the compound nucleus C is in an excited state.

b) Energy spectrum of neutrons

The energy distribution of neutrons emitted by a compound nucleus has the aspect of the curve as shown in figure, Only the low energy part obeys 31 and the reason is simple: the emission of a low energy neutron leaves the residual nucleus with a large excitation energy, and the level density is very high. The large density of final states turns the problem tractable with the statistical model that leads to 31. In the opposite situation are the low energy states of the residual nucleus. These isolated states appear as peaks in the tail of the distribution. When the emission is of a proton or of another charged particle, the form of figure 31 is distorted, the part of low energy of the spectrum being suppressed partially by the Coulomb barrier.

c) Resonances

To understand why there are resonances, we shall use again the simple model of a single particle subject to a square-well potential. We know that inside the well the Schrödinger equation only admits solution for a discrete group of values of energy, E1, E2,... En. A particle is confined to the interior of the well by reflections that it has at the surface of the well. In these reflections the wave that represents the particle should be in phase beforehand after the reflection and this only happens for a finite group of energies. Outside the well the Schrodinger equation does not impose restrictions and the energy can have any value. But we know, from the study of the passage of a beam of particles through a potential step, that the discontinuity of the potential at the step provokes reflection even when the total energy of the particles is larger than the step, a situation where classically there would not be any difficulty for the passage of the particles. This reflection is partial and it becomes larger the closer the energy is closer to the height of the potential step. We can say that a particle with energy slightly positive is almost as confined as a particle inside the well. From this fact results the existence of almost bound states of positive energy known as **quasi-stationary states or resonances.**

These resonances appear as peaks in the excitation function, a peak at a given energy meaning that the energy coincides with a given resonance of the nucleus. The existence of resonances can also be inferred from the properties of the wave function. We consider only Elastic scattering, with the other channels closed. The external and internal wave functions are both sine functions, the first with wave number k = $\sqrt{\frac{2mE}{h}}$ and thesecond with K = $\sqrt{2m(E - V0}$/h If E is small and V0is about -35 MeV, we have K >> k. The internal and external parts should join at r = R with continuous function and derivatives. As the internal frequency is much larger than the external one, the internal amplitude is quite reduced. Only at the proximity of the situation in which the derivative is zero there is a perfect matching between both and the internal amplitude is identical to the external one. The energy for which this happens is exactly the energy of resonance.

Resonances appear in the excitation function at relatively low energies, where the number of open channels is not very large and it is possible that to return to the entrance channel. To arrive at an expression of the cross-section that describes a resonance, we rewrite as,

$$u_l \sim \exp(-iKr) + b\,\exp(iKr)\,, \qquad (r < R),$$

this time containing a second part which takes into consideration the part of the wave that returns. This second part allows the existence of resonant scattering, where the incident particle is re-emitted with the same energy that it entered, after forming the compound nucleus. The complex amplitude b is always smaller than one, because there are no creation of particles in the region < R in eq.

4. Heavy Ion Reactions

a) Types and properties

Heavy ion reactions (with A > 4) can be separated into 3 major categories.

1) Due to their large charge, two heavy nuclei feel a strong mutual Coulomb repulsion. To produce a nuclear reaction the projectile needs enough energy to overcome the Coulomb barrier. For a very heavy target, as 238U, it is necessary about 5 MeV per nucleon. Then the wavelength of the projectile is small compared with the dimensions of the nuclei and classical and semi-classical methods become useful in the description of the reaction.
2) The projectile carries a large amount of angular momentum and a good part of it can be transferred to the target in the reaction. Rotational bands with several dozens of units of angular momentum can be created. In fact, heavy ion reactions are the best suited to feed high spin levels.
3) Direct reactions and formation of compound nucleus are also common processes in reactions with heavy ions. But some peculiarities of these are not found in reactions with projectile nucleons. One of these processes can be understood as intermediate between a direct reaction and the formation of a compound nucleus. Fusion does not occur but projectile and target pass a relatively long time under the mutual action of the nuclear forces. Nuclear matter is exchanged between both and there is a strong heating of the two nuclei, with a large transfer of kinetic energy to the internal degrees of freedom. These are the deep inelastic collisions.

The kind of process that prevails depends upon the distance of closest approach d between the projectile and target. If this distance is sufficiently large only the long range Coulomb interaction acts and, for a classical Hyperbolic trajectory, d is related to the impact parameter b and to the energy E of the projectile by $d = [a/2 + [\left(\frac{a}{2}\right)^2)] + b^2]^2$ where a is the distance of closest approach in a head-on collision. It is this is relatedto E by $a = Z1Z2e^2/4\pi E0E$.Experimentally, the variable under control is the energy E of the projectile and, for E sufficiently large, d can be small enough to enter the range of nuclear forces. Collisions near this limit are called grazing collisions and are characterized by values of bgraz and dgraz. Assuming that there is always reaction when b < bgraz, the reaction cross section α r can be determined geometrically by $\alpha r = \pi b^2$ graz: The experimental determination of αr allows to establish the value dgras = $0.5+1.36(A1_3^1 + A2_3^1)$ showing that the distance of grazing collision is somewhat larger than that deduced from two touching spheres (1.36 fm > r0 = 1.2 fm).

When the impact parameter is close to bgraz one expects nuclear reactions of short duration, without the contribution of the compound nucleus formation. Such reactions are elastic and inelastic scattering and transfer of few nucleons. When the incident energy is sufficiently high, small values of b can lead to the projectile penetrating the target. Depending on the energy and on the involved masses, the reaction can end in one of the processes below:

a) **Fusion-** is the preferred process when one has light nuclei and low energy. There is the formation of a highly excited compound nucleus that decays by evaporation of particles and γ-radiation emission, leading to a cold residual nucleus. If the energy in the CM is close to the Coulomb barrier energy the cross section of compound nucleus formation starting from two nuclei is practically equal to the reaction cross section.
b) **Fission-** When the compound nucleus is heavy the fission process competes strongly with the evaporation of particles in each stage of the evaporation process. A very heavy compound nucleus with a large excitation energy has a very small probability of arriving to a cold residual nucleus without fission at some stage of the de-excitation. The role of the angular momentum *l* transmitted to the target nucleus is also essential. The fission barrier decreases with the increase of *l* and for a critical value *l*crit the barrier ceases to exist. A nucleus with angular momentum greater than *l*crit suffers immediate fission and this is also a limiting factor in the production of super heavy elements.
c) **Deep inelastic collision (DIC) -** is a phenomenon characteristic of reactions involving very heavy nuclei (A > 40) and with an incident energy of 1 MeV to 3 MeV above the Coulomb barrier. In DIC the projectile and the target spend some time under mutual action, exchanging masses and energy but without arriving to the formation of a compound nucleus. The projectile escapes after transferring part of its energy and angular momentum to its internal degrees of freedom and to the target, with values reaching 100 MeV and 50~.

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