New Reaction Mechanism in Heavy Ion Reaction

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Abstract

We propose a new mechanism in nuclear reactions where fusion is accompanied by light particle emission (in the early stage of nuclear reaction), decay by multi fragmentation or fission of the fused system. This mechanism was suggested by the existing experimental data obtained in nuclear reactions for fission, deep inelastic transfer, fusion, compound nucleus decay, gamma spectroscopy multi fragmentation, etc. We want only, by an iterative procedure, obtain new and more insights for collective nuclear forces, or new properties of nuclear matter and finally for the nuclear forces. We underline some of nuclear reactions characteristics, and based on these experimental evidences we give two postulates which define the nuclear interaction between two heavy ions (two pieces of nuclear matter). With these two axioms, we are able to understand in a frame of the new reaction mechanism, the experimental data obtained in nuclear reactions induced by heavy ions like: subcoulombian (subbarrier) fusion, superdeformation, fire balls, nuclear deformation in spectroscopy studies, deep inelastic reactions, etc.
We mention that all of our efforts is to make a separate analysis, as much as it is possible, for nuclear forces, pure nuclear one. The superposition of " *the well known electromagnetic interaction* " with nuclear interaction one may not be a simply addition of the two fields (of different nature).

1 Concerning Fission

In May 1939 Bohr and Wheeler have been capable to give an explanation of fission phenomena (natural fission or induced by the low energies neutrons) based on the Liquid Drop Model of the nucleus. With some improvements this theory is guiding experimental researches and theoretical developments in our days.

After 40 years, in the 80'ties, the old Kramers'/1/ ideas on the existence and importance of the friction in the nuclear fission phenomena (with direct consequence in longer life time for fission), was successfully used to explain the continuously rising dependence of the neutron (light particle in general n, p, alphas) multiplicity's function on the bombarding energy of the projectile /2,3/. Experimental data was well fitted with

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fission lifetime as long as: 10^{-20} s (we remember that nuclear characteristic time is 10^{-23} s). This give us first indication that the nuclei decaying by fission phenomena " *don't have much of excitation energy* ".

2 Time Reversal

For strong interaction between the nucleons our knowledge is incomplete. The strong interaction is not fully known. The trial-and-error process of determining appropriate phenomenological forms for the interaction entails starting from the simplest forms and adding complications only as they are required by experimental evidence. The time reversal invariance, as well as other symmetry arguments, is used as a "natural" guiding principle in formulating model interactions. This assumption places severe restrictions on the form of the interactions to be considered and thereby reduces the ambiguities that must be faced in exploring them

In general, for all nuclear reactions, the time symmetry is accepted. In the statistical calculations of evaporated particles like neutrons, protons, alphas, etc. the inverse cross sections /4/ of this evaporation, it means cross sections for reaction between these particles and corresponding nuclei are used. This supposed equality between $\sigma_{ab} = \sigma_{ba}$ is direct consequence of time symmetry. The fusion and the fission phenomena are believed to belong to this class of nuclear reactions, with good time reversal.

We can write the relation between transition probabilities for in and out channels : $\rho_1 P_{12} = \rho_2 P_{21}$ where ρ_i is the density of a(b) the states , P is the probability, Principe of detailed equilibrium. In the terms of Compound Nucleus introduced by N. Bohr in 1936 it means that there is no relation between initial and final stage of reaction.

3 Deep Inelastic Transfer Reactions (DITR)

When two nuclei collide at an energy well above the Coulomb Barrier ($B_c = 1.44 * Z_1 * Z_2 / R$ MeV, $R = (1.225 * (A_1^{1/3} + A_2^{1/3}) + 2)$ fm, a new system of two nuclei, a Double Nuclear System (DNS) is formed /5/. This new nuclear object has a fragile and a very short life (of the order of 10^{-20} s). His stability result in dynamical equilibrium between strong attractive nuclear forces and (apparently moderate) repulsive forces Colombian and centrifugal (and may be other forces). The DNS can evolve to: elastic, inelastic, transfer, compound or others kind of reactions channels.

In DITR only projectile with an angular moment close to grazing ($l = l_g$) are involved. Many isotopes of different elements (fragments) are observed in the out-going channel of DITR, these products have a combined statistical and direct characteristics.

The neutron rich isotopes appearance are favoured in DITR and isotopes far from stability line such as ^{20}C were measured in the reaction ^{22}Ne (174 MeV) + ^{232}Th /6/. In this case, the excitation energy (thermal one) of ^{20}C after the separation of the nucleus mother was not more than four MeV and not fifteen like different models predicts, otherwise ^{20}C would disappear (by decay) due to neutron evaporation (B_n = .4 MeV). This means that ^{20}C was formed **cold**, in contradiction with the statistical predictions, where the excitation energy should be proportional to the mass, $E^*(^{20}C) = 6\text{-}7$ MeV. We do not know why, but it is but it is an experimental fact :

- the excitation energy is not distributed proportionally to the mass in this case. A trivial explanation is so called zero solution : the excitation energy (thermal) of the system is very small, at the instant of the ^{20}C birth.

Another striking feature for DITR is the Qgg dependence /7/; that is the experimental cross section for the DITR products take the form :

$$\sigma = K(A,Z) * \exp((Q_{gg} + \delta) / T) \qquad (1)$$

were Q_{gg} is the energy spent for mass reconstruction $Q_{gg} = (M_1 + M_2 - M_3 - M_4)*c^2$ and δ is the energy necessary to break the pairs involved in the transfer, T the temperature (parameter) of the system. This rule was well verified in many experiments (for different combinations Projectile (P) + Target (T), for different bombarding energies, different angles of measurements, etc.). The function K(A,Z) was experimentally determined for few reaction with ^{40}Ar. Bondorf and all. /8/ suggested a crude explanation in statistical equilibrium terms:

$$\sigma = \sigma^{\circ} * \rho \qquad (2)$$

$$\rho = \exp(-\Delta U / T) \qquad (3)$$

$$\Delta U = \Delta E_r + \Delta E_c + Q_{gg} + \delta_p + \delta_n \qquad (4)$$

For a given Z :

- the variation of rotational energy between initial and final state $\Delta E_r \sim 1$ MeV
- the variation of Colombian energy between initial and final state $\Delta E_c \sim 0.5$ MeV
- the mass reconstruction energy $Qgg = (M_1 + M_2 - M_3 - M_4)*c^2$ and the energy used to break the transferred pairs $\delta = \delta_p + \delta_n$ are of the same order of magnitude (10 - 30) MeV, so, by neglecting the small energies ΔE_r and ΔE_c in the expression (3) we obtain the Qgg dependence (1).

A similar systematic, "*isospin systematic*", was inferred /9/ from four different experimental data (reaction induced by ^{40}Ar projectile) by studying the dependence of the integrated cross sections on the isospin of the light partner $t = (N_3 - Z_3)/2$ (where the usual convention of binary reaction was conserved $1 + 2 \rightarrow 3 + 4$, 3 being projectile like partner), on the form :

$$\sigma_{\text{experimental}} = F(Z_3) * \exp(\alpha * Z_3 * t) \qquad (5)$$

In /9/ was found that the proportional factor $F = K(Z_3)$ in the relation :

$$\sigma e_{experimental} = K(Z_3) * \exp((Q_{gg} + \delta) / T) \qquad (6)$$

is exponentially dependant on Z_3, and in a logarithmic scale the $K(Z_3)$ is a perfect straight line over almost 22 order of magnitude.

In the DITR for the usual 5 - 15 MeV*A bombarding energies, there are many problems without clear, complete, solutions like mass, charge, isospin, and energy equilibration. Many authors succeed to explain some of the trains of experimental data in the frame of Bohr compound nuclear model /10/. for the DITR phenomena is not clear that the basic ansatz frame of Bohr compound nuclear model (the statistical equilibration of all the degree of freedom °). is totally valid.

4 Light Particle Emission

In the nuclear reactions with heavy ions abundant light particles, neutrons, protons, alphas, etc., are encountered. To explain this copious production of light particles, many mechanisms were imagined and some of them are supposed to be identified. Most of these mechanisms are of a statistical nature. Even with very complex coincidence measurements, it is very difficult to distinguish between these mechanisms.

Two of them are of particular interest (for us) because their estimated weight in total measured cross section of light particles seems to us to be well underestimated :

- the so called DNS-light-particles belonging to the DITR products /11/, with both direct and statistical properties and with the same origins (interpretation) as all other DITR products.

- the so called preequilibrium light particles, with more °direct° properties are rather well explained by the exciton model /12/. But, many characteristics, like the position of their emission, or the cause of their evaporation are not very clear.

5 About Fusion

We can image a nuclear reaction process in three stages : -a fusion (approaching), - an evolution, and - a decay. It is very difficult to define each of them and especially the fusion one. All our efforts try to clarify a little more this first stage the approaching. Many measurements for fusion cross section in heavy ions reaction are now available; however, these experimental data contain obvious information for all stages mentioned previously, not only about fusion part. In general, to extract some information the nuclear physicist develop a theoretical model, (with reasonable physical meaning) and compare the theoretical predictions for a given phenomena with experimental results. (It is clear that we have to have some good feelings because we don't know the nuclear (collective) forces). There are many theories (of geometrical nature) which give a rather ° *good fit*° in the comparison with experimental cross section for fusion. These kinds of models suppose a statistical equilibrium of all degrees of freedom of the compound nucleus formed (almost instantaneously) in the collision of the two nuclei, it means almost nothing at this stage of approaching (fusion); the evolution of the exiting system °*compound nucleus*° is also reduced to zero and all the attention is concentrated on the decay of (postulated) hot nuclear matter, the evaporation processes. With this kind of statistical calculations we can estimate roughly almost all the processes (x n, y p, z alpha, fission, cluster emission, etc,). None of them are able to calculate the subcolumbian fusion cross sections or transferred angular momentum, etc. For two cases of $^{12}C+^{12}C$ and ^{100}Mo + ^{100}Mo where for bombarding energies lower as $E = B_c - 0.5*Z_p$ the fusion cross section is few order higher than theoretical compound nucleus statistical calculations. For $^{12}C+^{12}C$ the measured cross sections for fused system are measurable even at as low as 3 MeV in the laboratory system. The distance between the centres of the colliding nuclei can be easy estimated to be in the range of 15-25 fm. The usual °classical° °tunnel phenomena° is helping (helpful) in theoretical calculations.

6 About Super Deformed Nuclei and Super Deformed Bands

The shape of the nucleus in its ground state is a sphere or near sphere. This is the result of indirect measurements or of theoretical calculations. The departure from the spherical shape is named deformation. To quantify its value we try to simulate the shape of the nucleus by an axial symmetric spheroid of revolution :

$$r = r_0 * (1 + \beta * Y_2(\vartheta)) \qquad (7)$$

-where $\beta = (a-b)/a$; a, b, b being the three axes of the spheroid nucleus. The normal values for $\beta \sim 0.1 - 0.3$.

In 1962 Polikanof et al. /13/ measured an unusually, short fission lifetime, an isomer of few microseconds, for the fission induced by ^{22}Ne at 174 MeV on ^{232}Th. To explain this results a few more crossing reactions have been measured and Polikanof /13/ concluded that the fission of a the system can proceed through an isomeric state. Because the fission is a continuous changing of the shape of the nucleus, they named this isomer state : shape isomer, fission isomer, a state where the nucleus has a bigger deformation beta ~0.6 or roughly twice the natural deformation of the ground state of the nucleus.

It is believed that compound nucleus has a spherical shape at the creation and by decaying through the fission channel is continuously changing the shape starting with the sphere by graduate deformation into the spheroidal shape, its passing through a gantere (halter) configuration in a way to reach a final, two separate pieces of nuclear matter, two new nuclei (we will not discuss about the characteristics of these pieces - excitation energy, rotational energy, etc.).

Recently, by 1985-6, the continuous and discrete gamma spectroscopy furnished experimental evidence of electromagnetic transitions between states of the nucleus with deformation estimate to be approx. 0.6 (very similar to the deformation for shape isomer estimate by the Strutinsky/14/ method). By using a ball of many (16-45) Ge detectors many authors put in evidence chains of many (up to 19) discrete gamma rays transition of E_2 nature (super intense relative $B(E_2)$.) with the energies ;

$$E_n = E_0 + n\,\varepsilon \tag{8}$$

where E_0 is the energy of the zero energy of the superdeform sequence of the (n-1) gamma and ε (epsilon) is the average distance between the two adjacent gamma ray of SD chain. The n for some chains (more than 200 chains are known over the all Mendeleev table) experimental detected can be as large as 19. These strange, very regular gamma, are electromagnetic transitions of E_2 nature (in general) with $B(E_2)$ thousands times larger than normal.

The deduced deformations, is approximately beta app. 0.6 for a spheroidal shape. The theoretical calculation for Routhian (the hamiltonian in the system of reference related to the rotating nucleus) or so called Total Routian Surfaces (TRS) , with the same shall correction and Strutinsky method, explain this phenomena and predict the nuclei where this phenomena should appear and provide the values for the deformation in agreement with experimental findings. Like in the case of the isomeric fission, SDB it believed to appear when the evolution of compound nucleus toward a spheroidal shape reach the deformation where the equilibrium between different forces put forward the deexcitation of the nucleus by discrete (continuum) gamma named Super Deformed Bands. At the end of the chain SDB it is believed that the nucleus is going back to the natural (spherical) deformation through the gamma transition. These Linking Transitions (LT) have been investigated through many (hundreds) experiments over the world in the last six, seven years. Only few cases present clear LT formed of three or four big energy (2- 3 MeV) transitions. This absence of linking transition; the link between the last excited state of the SD chain and the states of normal deformed nucleus, is probably due to the many passes (chains of gamma transitions) very fragmented. Th nuclear physicists hope to find LT with more powerful balls (more than 300 big Ge detectors in 2005 to detect 10 and more SD gamma in coincidence).

Some general remarks about other experimental facts in the SDB problem :

- discovered SDB only for a dozen of the nuclei, situated in few region of the Mendeleev table of the nuclei : Z = - 42(Nd) - 66(Dy) - 80(Hg).
- crossing reactions give the same results.(For the symmetrical systems the cross section for SDB is twice larger than others reactions).
- up to 6 SDB have been measured for same nuclei,
- SDB with identical energies are measured for neighbour nuclei.
- the lower spin (in the SDB chain) is 24 for Dy and 8 for Tl

- the higher spin of the last SDB excited state is 72 for Dy and 42 for Tl
- the monotone increase or decrease of the SDB transition energies are perturbed in some cases for the last six, eight transition (more precision measurements for the energies of gamma transitions, 100 eV resolution, confirm the effect)

The deformation does not change when the system is decaying through the SDB, in other words ,at the starting point of the SDB in the plane (E* , I) the system is cold, well deformed and rigid over 20 transitions (seems to be yrast).

7 About Binding Energy (BE)

The difference in mass (energy) between the theoretical (sum of nucleon mass) and experimental mass of a nucleus is named mass defect or binding energy. The actual accurate measurements of the nuclear masses for stable nuclei are in a range of few hundreds keV precision. For the known radioactive nuclei the errors in mass measurements or evaluation can reach values up to few MeV. Other few thousands theoretical predicted nuclei, not discovered up to now, the masses are estimated in the errors bars of few tens of MeV. Almost all of the theories of nuclear masses are some kind of reasonable parametrisation with a number of parameters which can vary from few tens up to few thousand parameters. In general, the mass of the new discovered nuclei is in reasonable agreement with the °theoretical° predictions.

The binding energy, together with spin, parity, isospin etc. are the characteristics well known of the nucleus, and they tell us indirectly about nuclear field, nuclear forces, nuclear structure, and about dynamics of the nuclear matter inside the nucleus.
We can calculate, by simple formulas : the binding energy for a proton, neutron, alpha, clusters and so on (B_p, B_n, B_α, $B^{14}{}_{C}$,.); therefore we have some information about an integral over the interaction of the nucleon with the nuclear field. Mathematically, we can use the inverse procedure to recover the nuclear field.

POSTULATES

Postulate I :
- when two pieces of nuclear matter are in nuclear contact (nuclear fields are superposed and a virtual pion appear) the new nuclear piece of nuclear matter is formed. This new piece of nuclear matter are the properties determined simply be the new nuclear numbers $Z = Z_1 + Z_2$ and $A = A_1 + A_2$

Postulate II :
- the nuclear field (binding energy) of a nucleus is independent of
  - his shape,
  - excitation energy,
  - quantum numbers which characterise the new piece of nuclear matter.

Based on these two postulates we propose a new mechanism of nuclear reaction between two heavy ions :

- once the new nuclear matter is formed (new nuclear field) when the two nuclei touch each other, in agreement with the first principle we have a new nucleus and therefore all his basic properties,
- the information about extra-energy is instantly spread in all nuclear field which should evolve toward the minimum of its tension by breaking the pairs by eliminating hadrons or different clusters, shouting out electromagnetic waves, gamma, fission, etc.,
- any nuclear act is covered by a formation of a new nucleus new A, Z hence new field with new properties,
- this process can be either sequential or simultaneous,
- this process stop itself when the °extra-energy° is lower than quantum rigidisation energy,
- the sequential process can be imagined so : all the way of decreasing the °extra-energy°, new nuclear field is formed with new excess-energy the system evolving toward the quantum rigid, through the cold state possible.

Therefore the new system , in this transformation, can be found in a specific

- deformation (superdeformed - for example), angular momentum traps, isospin equilibrium, etc.
- all actions can be treated like movement of information with a nuclear sped, probability, difficult to have a scale of the nuclear time for the actual understanding of nuclear interaction, but with the theory of the catastrophes may we hope to relate nuclear time with electromagnetic one, weak one and gravitational one.

Conclusion

It appears that it is impossible to excite the nucleus at high of excitation energy (like it is suppose to be done by nuclear bombardment at very high energies GeV*A); the maximal excitation energy (equilibrated one) is very small compared to the one transported by kinetic movement of the projectile; many experimental facts present indications in this direction.

- the subcolumbian fusion reaction can be understood : like a normal reaction (because the barrier change in the fusion proceeds) where the nuclear field is some kind of °catalyser° of the reaction. We don't have a real tunnel effect because we have a continuous changes of the nuclear and electromagnetic fields. The geometry (deformation) of the system changes simultaneously with the binding energy (field) and this evolution gives the impression of the tunnel effect.
- the nucleus is evoluting at near zero excitation energy by emission of °evaporative° particles, gamma (continuous one) GDR - GQR, subthreshold Kaons, pions etc. , and may change the speed of the rotation. Talking about changings we have to answer at the simplest question : how fast are this changes, and therefore we have to define some time unit (does time exist ?). I have especially avoided this question of time; in our opinion the nuclear time is not the same as the other time.

8 Conclusions

We have presented a new mechanism for nuclear reaction which takes into account two experimental facts : that the prefission neutron multiplicity increases proportionally with the bombarding energy in a nuclear reaction with heavy ions, and that the cross section for preequilibrium emitted particles are very important, up to 40-60% of the cross section of the light particles. The postulates (two) presented as start point of our calculations take into account the experimental facts, and give a new picture of the nuclear reaction. The probability of the emission of the high energy particles in the beginning of the transformation process of the new nuclear matter, is very high.

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