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Rare cold nuclear processes – A review and some new results

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Abstract. The rare nuclear processes of cluster radioactivity, cold fission and cold fusion, studied on the basis of the quantum mechanical fragmentation theory (QMFT), are reviewed. This theory was advanced as early as in 1974–75 by the author and collaborators, first at Frankfurt and then developed both at Frankfurt and Chandigarh. The QMFT predicted all the three phenomena to occur most probable as cold processes, *prior* to their experimental observations. The success of experiments with respect to the QMFT and some new results are presented as predictions of this theory for future experiments.

Keywords. Cluster radioactivity; cold fission; cold fusion.

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1. Introduction

Cluster radioactivity, cold fission and cold fusion of nuclei for synthesizing new heavy elements are rare nuclear processes. The interesting aspect of these processes is that they are not only rare but also occur more probable as cold phenomena. The rare nature of these processes stem from the fact that these processes are masked by other competing processes. Cluster radioactivity is masked by the larger number of α-decay events, cold fission by fragments of various other velocities (hot and/or bimodal fission) and cold fusion by their specific choice of target-projectile combinations, incident bombarding energies and angular momenta. The dynamical or quantum mechanical fragmentation theory (QMFT) predicted all the three phenomena to be most probable as cold processes. These predictions were made as early as in 1974–75, *prior* to their being observed experimentally. Note that the QMFT, being a quantum mechanical theory, does not preclude the other processes, like the hot fission or hot fusion, but predict them to be less probable, as is now observed to be the case. A complete study of these three processes and related new phenomena is given in a forthcoming new book [1] edited by the author and Walter Greiner.

Cluster radioactivity is the spontaneous emission of clusters heavier than α-particle and *without* being accompanied by any neutron emission. Thus, it is a cold process (zero excitation energy) since the energy released as Q-value is completely consumed by the kinetic energy alone of the two fragments (the cluster and daughter nuclei). Fission is also the spontaneous breaking of a nucleus into two fragments (for binary fission), heavier than the ones involved in cluster radioactivity, but *with* or *without* being accompanied by neutron emission. The neutronless fission or in terms of velocities the very high *total kinetic energy* (close to the Q-value) fission, called cold fission, was first observed in 1981/82 at Grenoble, using the recoil spectrometer Lohengrin, where the kinetic energies of the fragments were also measured along with their masses and charges [2,3]. The actual neutronless fission, an equivalent of cluster radioactivity, is observed more recently in 1994 at Oak Ridge, where the neutronless as well as high neutron multiplicity fissions are observed [4]. This establishes the cold and hot fission, as well as the bi-modal fission, first observed in 1986 as two different kinetic energy distributions [5]. The observed high neutron multiplicity fission in these experiments is also associated with hyper-deformation of the fission fragments at the scission configuration [6], since the total excitation energy (difference of Q-value and total kinetic energy) can go into not only the internal excitation of the fragments but also in their deformation degree of freedom. This hyper-deformation mode is apparently the low total kinetic energy or hot deformed fission, that was first observed in 1992 at ILL [7]. Finally, the real signatures of cold fusion were first seen in the 1994 experiments at GSI, Darmstadt, where enhanced fusion cross-sections were observed at lower excitation energies, or incident energies below the barrier [8–10]. Also, hot fusion experiments are carried out more recently which result in lower fusion cross-sections [11]. For example, ^{58}Fe + ^{208}Pb and ^{34}S + ^{238}U result in the same heavy nucleus $^{265,267}_{108}$Hs emitting one or five neutrons, respectively, but the first one is a cold reaction (18 MeV excitation energy) with 19 pb of fusion cross-section and the second one a hot reaction (50 MeV excitation energy) with only 2.5 pb of fusion cross-section. It is relevant to mention here that all the transactinides $(Z < 103)$ are synthesized since 1975 using only, what can be termed as the cold fusion reactions on the basis of the QMFT. All these early experiments were made either at a single incident energy or at energies above the barrier. Thus, inspite of the use of cold fusion reactions, real signatures of cold fusion eluded detection till late 1994 when Hofmann *et al* [8] bombarded ^{208}Pb with ^{62,64}Ni at different incident energies, both above and below the barrier.

The QMFT is a unified description of all the three processes of (cold) fusion, fission and cluster radioactivity. The key result behind the three phenomena is the shell closure effect of one or both of the reaction partners for fusion or that of the decay products for fission and cluster radioactivity. Both experimentally and theoretically, for cold phenomena, one of the nucleus (or decay product) is always a *spherical* closed or nearly closed shell nucleus. Apparently, the significance of spherical closed shells raises the question of the role of *deformed* closed shells, which need to be investigated in future.

Section 2 gives briefly the essential aspects of the dynamical fragmentation theory, the QMFT. Applications of this theory to heavy ion reactions, specifically the synthesis of new heavy elements, the fission phenomenon and cluster radioactivity are reviewed in §3. This includes some new results obtained recently. Our conclusions are summarized in §4.

2. The dynamical fragmentation theory

The QMFT is based on two center shell model (TCSM), used as an average two-body potential in Strutinsky macro-microscopic method. The relevant dynamical collective coordinates are the mass and charge asymmetry coordinates

$$\eta = \frac{A_1 - A_2}{A_1 + A_2}(A = A_1 + A_2), \quad \eta_Z = \frac{Z_1 - Z_2}{Z_1 + Z_2}(Z = Z_1 + Z_2), \tag{1}$$

in addition to the commonly used coordinates of relative separation $\vec{R}$ of two nuclei (or fragments), their deformations β_i $(i = 1, 2)$ and neck parameter ε. Similarly, a neutron asymmetry coordinate can be introduced, but one need to treat only two of them as independent variables since the three are related. The limiting values of η are $0 \leq |\eta| \leq 1$ and thus allows a unified description of a few nucleon, multi-nucleon (or cluster) transfer, a large mass transfer, the complete fusion $(|\eta| = 1)$ of nuclei and the symmetric $(\eta = 0)$, asymmetric and super-asymmetric fission (equivalently the cluster radioactivity) of a nucleus or compound nucleus. The details are given in the review by Gupta and Greiner in [1].

For heavy-ion collisions, the time-dependent Schrödinger equation in η (taking motions in η and η_Z as weakly coupled)

$$H\Psi(\eta, t) = i\hbar\frac{\partial}{\partial t}\Psi(\eta, t), \tag{2}$$

is solved for $R(t)$ treated classically and the other coordinates β_1, β_2 and ε fixed by minimizing the collective potential in these coordinates. Equation (2) is solved for a number of heavy systems, showing a few nucleon to large mass transfer or no transfer at all for the initial η_i-values refering to outside or on the potential minima. This procedure, however, is very much computer-time consuming, but some simplifications have been possible.

The potentials $V(R, \eta)$ and $V(R, \eta_Z)$ show that the motions in both η and η_Z are much faster than the R-motion. This means that the potentials $V(R, \eta)$ and $V(R, \eta_Z)$ are nearly independent of the R-coordinate and hence R can be taken as a time-independent parameter. This reduces the time-dependent Schrödinger equation (2) to the stationary Schrödinger equation

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B\eta\eta}}\frac{\partial}{\partial\eta} + V_R(\eta)\right\}\Psi_R^{(\nu)}(\eta) = E_R^{(\nu)}\Psi_R^{(\nu)}(\eta), \tag{3}$$

where R is fixed at the post saddle point. This choice of R-value is justified by many good fits to both the fission and heavy-ion collision data and by an explicit, analytical solution of time-dependent Schrödinger equation in η_Z coordinate [1]. An interesting result of these calculations is that the yields ($\propto$ $|\Psi(\eta)^2$ or $|\Psi(\eta_Z)|^2$, respectively, for mass or charge distributions) are nearly insensitive to the detailed structure of the cranking masses $B_{\eta\eta}$, calculated consistently by using TCSM. In other words, the static potential $V(\eta)$ or $V(\eta_Z)$ contain all the important information of a fissioning or colliding system, given simply by the Coulomb interaction plus the sum of the ground state binding energies of two nuclei (at some critical distance R_c),

$$V(R_c, \eta, \eta_Z) = \frac{Z_1 Z_2 e^2}{R} - \sum_{i=1}^{2} B(A_i, Z_i, \beta_i) + V_{\mathrm{P}}. \tag{4}$$

The charges Z_1 and Z_2 are fixed by minimizing the potential in η_Z coordinate (which fixes β_i automatically) and then the proximity potential V_{P} is added to account for the additional attraction between nuclear surfaces. Equation (4), without V_{P}, formed the basis of our first calculation on *cold fusion* reaction valleys, which was later optimized by adding the requirements of smallest interaction barrier, largest interaction radius and non-necked (no saddle) nuclear shapes. Non-necked shapes are signatures of the cold fusion, and like the necked-in shapes are known to witness the preformation of fission fragments.

For cluster radioactivity, a model of coupled motion in $\vec{R}$ and η coordinates is developed by Malik and Gupta [17]. The decay constant λ or the decay half-life $T_{1/2}(= \ln 2/\lambda)$ is calculated as the product of cluster preformation probability P_0 (given by the solution of stationary Schrödinger equation (3)), the barrier impinging frequency ν_0 (obtained from the Q-value shared between two fragments) and the WKB barrier penetration probability P:

$$\lambda = P_0 \nu_0 P. \tag{5}$$

Further details can be seen in [1].

3. Applications

The QMFT is applied very successfully to many heavy ion reactions, the predictions of target-projectile combinations for cold synthesis of new and superheavy elements, the fission data and the exotic cluster decay process. In fact, both the phenomena of cold fission and cluster radioactivity were predicted on the basis of this theory, *prior* to their experimental observations, and the idea of cold fusion (for synthesis of new elements) was first introduced on the basis of this theory. The success of experiments in proving almost all the predictions of this theory are reviewed in ref. [1]. Here we discuss only one new result each for future experiments.

3.1 Cold fusion studies

Figure 1 shows a portion of the nuclear chart, depicting the superheavy elements beyond $Z = 103$, and the cold fusion reactions used. It is creditable to mention that all the reactions underlined in this figure were predicted on the basis of the QMFT about two decades back (see figure 2, only the even–even elements were studied [12]). Thus, the road to the centre of island of stability at $Z = 114$ seems opened. Two important points may, however, be mentioned. Firstly, the predicted neutron number $N = 184$ for the centre of island. What we have observed so far are the heavy nuclei in continuation of our earlier known chart of nuclei, near the β-stability line. Therefore, in order to reach the real island of stability predicted at $Z = 114$, $N = 184$, we have to overshoot it by means of radioactive nuclear beams. Secondly, some new relativistic mean field calculations [13] predict $Z = 120$, $N = 172$ or 184 as the major closed shells instead of $Z = 114$, $N = 184$. The QMFT predicts a possible synthesis of $Z = 120$ element by a cold fusion reaction ^{208}Pb + ^{98}Sr. The interesting point to note is that one of the reaction partners for cold fusion reactions is always the closed shell nucleus Pb.

3.2 Cold fission studies

The QMFT is known for its success to explain the symmetric as well as asymmetric mass distributions (the single-, double- and even triple-humped distributions), including the very-asymmetric case of fission valleys at large η-values, the super-asymmetric fission (an equivalent of cluster radioactivity), the charge distributions and the associated fine structure in them leading to proton odd–even effect, and the simultaneous occurrence of both the cold and normal (hot) fission modes, called the bi-modal fission.

Figure 3 illustrates the calculated isotonic and isotopic yields for fission of ^{236}U, compared with the experimental data [14]. Apparently, the calculations give experimental

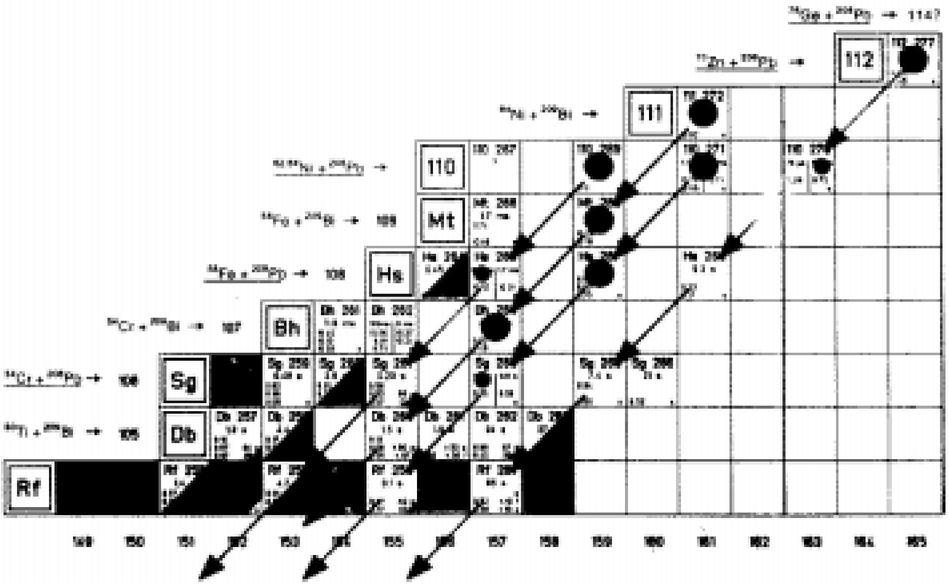

Figure 1. Nuclear chart (upper end only), along with the cold fusion reactions used to produce them (based on Münzenberg and Hofmann in [1]).

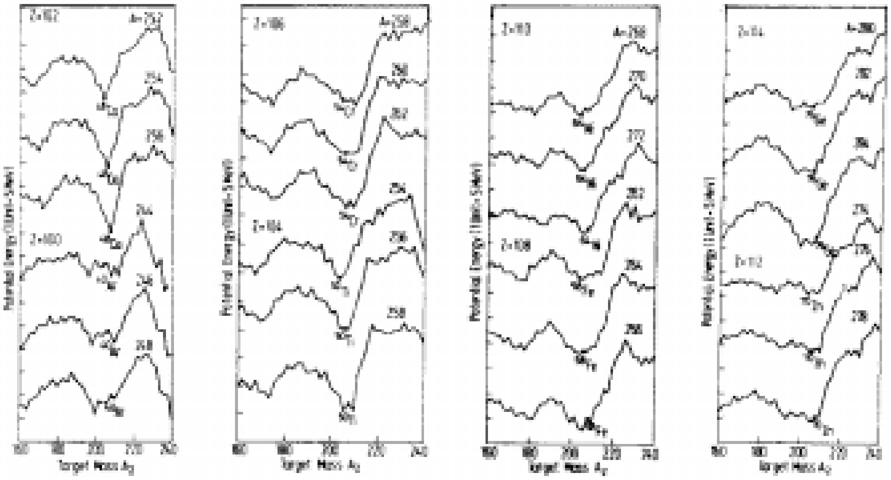

Figure 2. Calculated potential energy surfaces [12] using eq. (4).

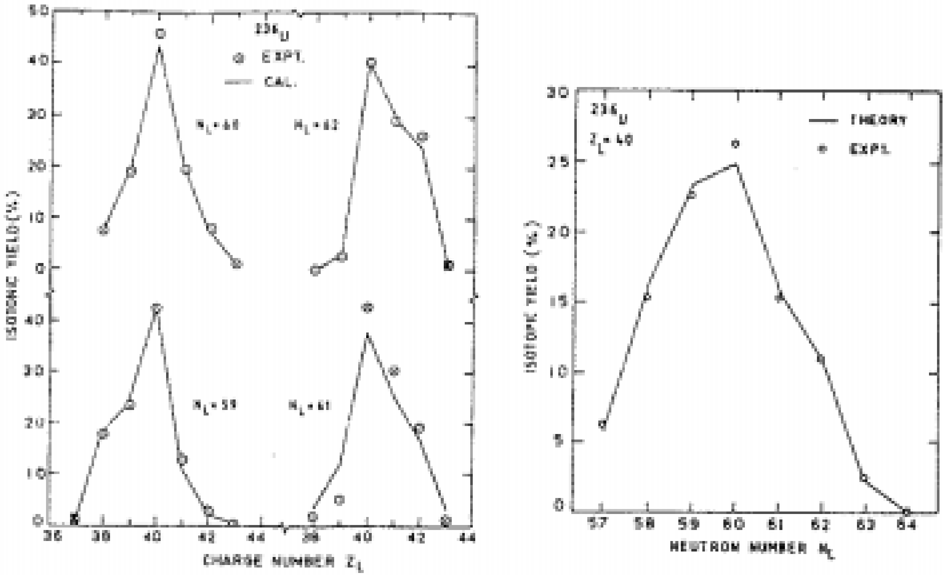

Figure 3. Percentage isotonic and isotopic yields for fission of ^{236}U.

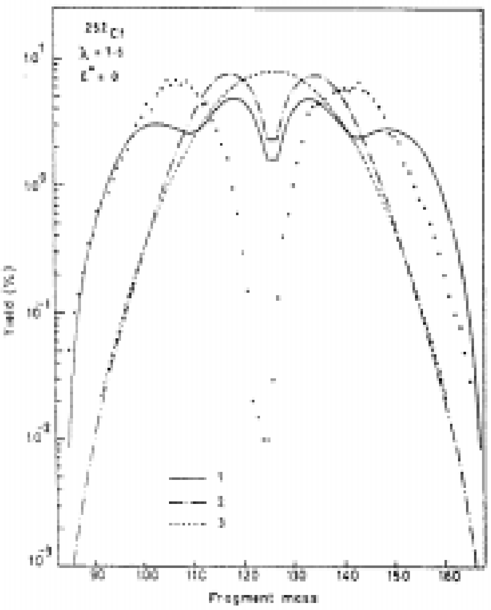

Figure 4. Fission yields of ^{252}Cf [15]. The experimental data is old. The recently observed peak at ^{132}Sn [16] was already given by the calculations.

results exactly. There is no parameter fitting in these calculations. Figure 4 gives the calculated fission yields for ^{252}Cf, [15]. The experimental data shown is the old data. The interesting result of this calculation is the appearance of a shoulder at ^{132}Sn, not there in the old data. This new mode of doubly magic ^{132}Sn fragment is now observed recently in the cold fission of ^{252}Cf [16]. Once again the closed shell effects (this time of ^{132}Sn) came into play and the theory preceded the experiments.

3.3 Cluster radioactivity

One of the important results of cluster radioactivity is that daughter nucleus is always observed to be the magic Pb or neighbouring nucleus. This has led us to predict the ^{100,132}Sn radioactivities and deformed (Os or W) daughter radioactivities (see e.g. Gupta in [1]). Table 1 presents the results of our calculation, based on the PCM of [17], for ^{249}Cf parent for which some preliminary experiments (Nice University preprint) indicate the possibility of ^{41}Sc cluster emission. Our calculations show that ^{249}Cf is not a very good parent for exotic cluster decays.

Table 1. Calculated cluster decay characteristics of ^{249}Cf. The only experimental information is the α-decay half-life log $T^{\alpha}_{1/2}$ (Expt.) = 10.04 s.

Cluster	Q-value (MeV)	Preformation probability P_0	Penetrability probability P	Decay constant λ (s^{-1})	Half-life $\log_{10} T_{1/2}$ (s)
^{4}He	6.30	8.23×10^{-01}	1.51×10^{-29}	2.92×10^{-08}	7.38
^{14}C	25.79	7.37×10^{-23}	3.51×10^{-43}	6.58×10^{-44}	43.02
^{30}Mg	69.77	5.51×10^{43}	2.41×10^{-38}	3.80×10^{-59}	58.26
^{42}S	109.42	2.07×10^{-34}	7.76×10^{-26}	4.84×10^{-38}	37.16
^{48}Ca	137.69	9.88×10^{-37}	1.14×10^{-22}	3.58×10^{-36}	36.29
^{50}Ca	136.69	5.53×10^{-38}	2.08×10^{-23}	3.56×10^{-39}	38.29
^{51}Ca	135.53	1.67×10^{-37}	3.56×10^{-24}	1.81×10^{-40}	39.58
^{52}Ca	132.66	1.89×10^{-38}	2.87×10^{-26}	1.62×10^{-43}	42.63

4. Summary

We have shown that the quantum mechanical fragmentation theory gives a unified description of the three rare processes, the cold fusion, cold fission and exotic cluster decay of nuclei. The unifying result is the closed shell effects of one or both the reaction partners or the outgoing fission or decay products. The process is most probable as cold since the shell effects are operative in full. As the system is heated, shell corrections reduce, so does the probability of their production.

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