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To cite this version:
H. Morinaga. DIRECT VS. COMPOUND PROCESSES PRODUCTION AND DE-EXCITATION OF HIGH ANGULAR MOMENTUM STATES. Journal de Physique Colloques, 1972, 33 (C5), pp.C5-103-C5-110. <10.1051/jphyscol:1972508>. <jpa-00215110>

HAL Id: jpa-00215110
https://hal.archives-ouvertes.fr/jpa-00215110
Submitted on 1 Jan 1972

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DIRECT VS. COMPOUND PROCESSES
PRODUCTION AND DE-EXCITATION OF HIGH ANGULAR MOMENTUM STATES

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Résumé - On discute les caractéristiques des réactions induites par des ions lourds sans parallélisme direct avec les réactions induites par des projectiles légers. La forme des noyaux hautement excités est discutée à ce sujet. En outre, on présente des exemples d'application en spectroscopie nucléaire des réactions induites par des ions lourds.

Abstract - Specific features of heavy ion reactions, which have not direct parallelism in the reactions with light projectiles is discussed. In this connection, the shape of nuclei at high excitation is discussed. Also examples of the use of heavy ion reactions for nuclear spectroscopy are given.

I - INTRODUCTION

Reactions between heavy nuclei, or more precisely, between complex nuclei reveal many interesting features and recently very much attention has been paid to the study of the so-called heavy ion reactions from various points of view. Actually, the history of acceleration of heavy ions is not so new. For example, very high energy $^{12}$C ions had been accelerated by cosmic ray physicists in Chicago already twenty years ago [1]. Strangely enough, not much attention was paid to the beam except for calibration of nuclear emulsions. Probably, we were not so well prepared to be interested in such extreme novelty.

The reason why one is interested in heavy ion physics so much seems to be due to the fact that we have now certain ways to look at the phenomena. One can at least classify phenomena well enough to organize sessions. - like Coulomb excitation, one nucleon transfer, two nucleon transfer, elastic scattering, optical model parameters, and so on. Those concepts are well defined and one can at least talk about various parameters and the interplay between various mechanisms.

Indeed, the face of heavy ion reactions is very many-sided. We can see almost every "physics" developed with lighter projectile also occurring with heavy ion reactions. The extension of a concept developed in nucleon-nuclear collision to heavy ion collision often seems rather tricky and problematic, a typical example is probably the optical potential in heavy ion collisions. How far can one push certain concepts and how far can one parametrize a phenomenon without being too much criticized is already a bold experiment.

Since I am not an expert in neither of those established directions, I should rather not review the development of those main lines which, I am sure, most of you are already familiar with, but rather like to look at two problems connected with the heavy ion reactions in which I have my own problems and then, finally, just in order not to be a snob, I'd like to show you the usefulness of heavy ion reactions as a spectroscopic tool: an example that one can use a tool even without understanding the precise functioning of this tool.

II - DIRECT PROCESSES

Typical direct processes are the elastic scattering, the Coulomb excitation and various transfer reactions. They are by now well parametrized in the standard way as used in light ion physics.
There are, however, two new processes which are more characteristic of heavy ion collisions but not so well studied, and I should like to draw your attention on them. The first is what we might call the scattering vibrational state and corresponds to the giant resonance in nucleon-nuclear collisions.

If two heavy ions collide each other and if we assume that the viscosity of nuclear matter is small, there is a chance that the compound system comes back to the incident channel and causes elastic scattering. We can immediately guess that such compound elastic channel is small but in certain cases it may not be ignored. The grazing collision of two heavy ions may be regarded in this way since the $\ell$ dependent imaginary optical potential above has some critical $\ell$ expected to be small.

Actually, the most interesting case in the heavy ion collisions such as $^{12}$C-$^{12}$C or $^{16}$O-$^{16}$O occurs for low angular momentum collisions. A description for such a collision opposite to the optical model, where the exit channel (in which well defined separate particles travel towards each other) is described exactly, is to consider the total system. The latter describes better the situation when the system is amalgamated although the asymptotic behavior is less practically defined.

We can understand such considerations somewhat analogous to the unified theory of nuclear reactions of nucleon-nuclear collisions, which is developed by Bloch, Feshbach and others [2,3] and called usually the shell model theory of nuclear reactions. In this theory both bound states and scattering states of single nucleons in a finite well are considered and both bound levels and scattering levels are obtained after the inclusion of residual interactions. The result is the appearance of the doorway states or intermediate structure which give fine structure to the giant resonance, namely a single nucleon scattering state. In this description a state is expanded according to the descending order of simplicity as $1p$, $2p-1h$, $3p-2h$, ... and so on.

It is obvious that such an expansion is inconvenient for the description of heavy ion collision or fission phenomena. It would be best to start with just an opposite description which we might call "collective model theory of nuclear reactions" [4]. Parallel to the shell model theory of nuclear reactions we assume the collective potential to be not a simple harmonic oscillator but a finite well — naturally the coordinates are not $x,y,z$ of the particle but collective coordinates (4) and the quanta are bosons. Now, permanent oscillations are not allowed and corresponding to the scattering nucleon state, the scattering vibrational states appear. Refinement of the theory including interaction of those bosons will lead to the splitting of the simple scattering vibrational states to the doorway states.

It would be very interesting if the width of those intermediate resonances could be estimated. But it will not be so easy. We could, however, look at experimental results and see if there are any phenomena which may be the indication of such a narrow doorway state. The most suspicious candidate is the old Bromley molecular state: a narrow and low spin state whose outgoing channels show definite sign of correlation.

Another possibility of investigating such collective modes in high excitation may be considered again from the analogy to the nucleon-nuclear collision. The loose coupling in the descending order of hierarchy of $1p$, $2p-1h$ ... is seen in the existence of the pre-compound decay in the nucleon-nuclear collision even in the regions where the narrow resonance in the ingoing channel is already smeared out. In the case of heavy ion collision there are definitely indications that compound elastic is higher than the statistical value. But this may be due to higher spin part with low $\omega$. A more interesting observation would be that of a pre-compound gamma decay, which should have rather large enhancement if such scattering vibrational state is not immediately damped. Comparison of $(p,\gamma)$, $(d,\gamma)$ ($H_1,\gamma$) at the same excitation and same input angular momentum should be highly interesting.

The second category of the processes which was not much discussed is a process in which two ions touch each other but do not form compound nucleus. The super high energy reaction with multi GeV is naturally one example but also even at low energies high angular momentum hinders the system to form compound nucleus. We shall discuss this process together with the compound nucleus formation in the next section.
III - COMPOUND PROCESSES

There is no doubt that the ordinary type of compound nucleus can be formed by the collision of heavy nuclei. Indeed, under typical conditions - above barrier but not too high energy - the main process is found to be the compound nucleus formation and successive evaporation of protons, neutrons and alphas. The branching ratios in the evaporation process may differ from the case of reaction with light projectiles, but they are properly accounted for by solely taking into account the higher input angular momentum.

A serious deviation from the normal compound nuclear formation cross section formula happens at higher incident energy. The compound nucleus formation cross section decreases seriously because of the fact that the high angular momentum collision cannot lead to the formation of the compound nucleus. The ratio of measured compound cross section to the value (1) is a very interesting quantity. I shall discuss it somewhat more in detail in the next section.

The considerations given in the previous section let us suspect that there must be some pre-compound phenomena in heavy ion reactions. How do these phenomena show up is an interesting subject of speculation? Except for a very high energy collision, the collision is most likely to be adiabatic, since the velocity of nucleons at the Fermi surface is still much faster than the mutual velocity of ions at the collision. This will assure the constancy of the density of nuclear matter, that is, the rather well defined instantaneous shape with constant volume. Therefore, it is expected that at first the nucleus is moving rather like an ameba, which will enhance the emission probability of larger object than \( \alpha \)-particles. Also there may be effects on the effective Coulomb barrier for proton and alpha particles.

IV - THE COHEN-PLASIL-SWIATECKI CALCULATION

How big the cross section is for forming a compound nucleus in higher energy collisions where the high angular momentum hinders the formation, may be discussed not from the optical model approach but rather again from the stability calculation of the total system.

The stability calculation of a rotating liquid drop has been a classical astrophysical problem. The oblate shape of the sun may be calculated by taking into account three energies - surface energy, rotational energy and the gravitational energy. Such equilibrium shape calculation may be transformed for discussing the rotating nuclei just by changing parameters and changing the sign of the gravitational energy.

The calculation was done ten years ago by Cohen, Plasil and Swiatecki [5]. They found that for slow rotation, all stars, light nuclei, and heavy nuclei prefer oblate shape but when the angular momentum is increased, this shape becomes unstable and, in heavy nuclei goes over to fission. Stars, and light nuclei, however, go first over to rotating ellipsoid then later to fission. Recently, a very interesting experiment to see the limit of the angular momentum was reported by Pühlhofer and Diamond [6]. The general behaviour is reproduced although the experimental cross section is smaller. We could think of various reasons but one of them may be the fact that the theoretical value uses the surface tension parameter obtained from the ground state which could be larger than the value for the hot nucleus. Also it has been noticed in a photo-fission study that the surface tension should be taken smaller, in order to account for lower photo-fission thresholds of lighter nuclei than the theoretical estimates [7].

An unsatisfying aspect of the C.P.S. calculation for nuclei is the fact that it is a completely classical calculation. Therefore, at lower frequencies one gets rotation around the symmetry axis which is tricky to interpret in quantum mechanics. How far we can use the analogy between the rotation of the sun and the star becomes problematic. The only way to understand the angular momentum around the symmetry axis is to give the angular momentum to the single particles rather than the total rotation, which is meaningless if there is symmetry around the angular momentum axis.

This problem is actually not fictitious but lies very close to our experimental laboratories. We have seen a serious disturbance to the rotational
ground state band of rare earth nuclei at \( I = 14 \) to 20 \[8\]. Recently, there was a small meeting in Stockholm, where this phenomenon was thoroughly discussed. The interpretation is not unique and there are two lines of theories, namely, one is to assume breaking of one pair \[9\] and the other assumes total disappearance of the pairing correlation \[10\]. Anyway, it seems to us that after angular momentum of 14 or 20, the pair gets broken. This phase transition, however, does not correspond to any phase transition in the classical calculation and should take place before the classical phase transition. Kumar calculates \( J \) and \( \beta \) as a function of \( I \) and observes a sudden increase of \( \beta \) at the transition \( (I = 14) \) and at this point \( \beta \) decreases \[11\]. This suggests a transition from a prolate to a more oblate shape. If it goes immediately to the oblate star, it is still a problem. Experiment to see the yrast structure and the gamma transitions in this region should be extremely interesting.

V - HIGH SPIN STATES IN LIGHT NUCLEI

Just for comparison, the properties of high spin states in light nuclei is interesting and instructive. A case well studied both experimentally and theoretically, is the ground state band of \( ^{20}\)Ne. Although there exists some discrepancy of the opinion in the case of the structure of the \( 8^+ \) state \[12\], we might tentatively take the lowest \( 8^+ \) as a member of the ground band. Both theoretically and experimentally, E2 transition probabilities decrease considerably as the spin is increased. And according to the calculation of Arima \[13\], the deformation deduced from the E2 transition probability assuming a cigar shape decreases in the higher member of the band, which is opposite to what is expected from energy spacing that show the increase of moment of inertia. It is similar to the tendency in heavy nuclei and suggests that there are some similar physics behind the situations although in light nuclei we cannot talk about the pairing correlation.

It is interesting, in the case of \( ^{20}\)Ne, to look at the microscopical wave function. The lower states \( 0^+, 2^+, 4^+ \) contain large mixture of s, d, which is essential for a cigar shape deformation. But higher spin states contain no s components whose interference is essential to cause the deformation. For example, the \( 8^+ \) state is a completely stretched state without s, which means that the angular momentum is aligned to the \( Z \) axis. That is, the angular momentum is along the symmetry axis and this is a pancake high angular momentum state but no collective rotation. This situation causes the reduction of the E2 transition probability.

VI - NUCLEAR RING

Rotating stars, higher spin states in heavy nuclei and also high spin states in light nuclei suggest the need to consider an oblate object where angular momentum is parallel to the symmetry axis. Also the qualitative success of the C.P.S. calculation shows that at certain high angular momentum the nuclei may have a sun shape. How the transition from one structure to another takes place may be complicated. Therefore, we might first try to describe a high spin oblate state (not rotational – but rotating in a classical sense). In Nilsson’s scheme we take the oblate side and we take a three dimensional plot \((E, \delta, m)\). Then if we look at the diagram of \((E, m)\) for fixed negative \( \delta \) it will be as shown in Fig. 1.

![Fig. 1. The Nilsson diagram](Image)

The extreme case of large deformation is like Fig. 2. Now if there is an \( s \) type correlation we
i expect that the extreme case will become a "nuclear ring" whose thickness is the thickness of the alpha particle. The nuclear potential is not any more the harmonic oscillator (Fig.3), but it is a ring. For the $\phi$ direction we must allow the particles to be in different $m$ state.

![E-m diagram for a ring.](image)

Fig.2: E - m diagram for a ring.

Such rings are not completely a joke. As much as $^8\text{Be}$ is a chain (the smallest chain) $^{12}\text{C}$ ground state is considered to be a ring (the smallest ring). Recent Hartree Fock calculations suggest it [14]. The 6.06 MeV $^{16}\text{O}$ state is probably the next ring [15]. The chain lies much higher ($\sim 16$ MeV). Those data suggest that there are differences of $5\sim 10$ MeV between chain and ring. Incidentally, such a nuclear ring with fixed length is classically stable.

Of course, such an extreme structure would not show up in the experiment so easily and if there is any chance to see it, it will be in light nuclei. $^{20}\text{Ne}$, $^{24}\text{Mg}$ are the next candidates and the chain may lie some $10\sim 20$ MeV high. But those energy ranges are already being looked at extensively.

Such rings are expected to have more alpha type structure, just like chains, than spheres, because there are more surfaces. I should also mention that for a ring, the $\ell \sim n$ force should become hardly important because of the shape of the nuclear potential. So, better pairing or quarteting is expected. Then the ring can have any angular momentum while for a ring $S \geq 0$, $I = \Sigma \ell$. Looking for such a ring at $A \sim 20$ must be a very interesting experiment.

VII - NUCLEAR SPECTROSCOPY WITH HEAVY ION REACTIONS

Heavy ion reactions give unique opportunity for nuclear spectroscopy. The multipole Coulomb excitation gives us opportunity to reach very high spin states. Transfer reactions have been used extensively due to their selective character. Those reactions are being understood rather quickly. But I shall not talk about them since there is a talk by George Morisson.

Somewhat more interesting is the availability of compound reaction for some specific spectroscopical purpose. An interesting example has been found by the Saclay group [16]. They observed high energy residual states in $^{24}\text{Mg}$ by $^{16}\text{O}(^{12}\text{C},a)^{24}\text{Mg}$.
reaction and from the analysis of excitation function they were successful to show that they are statistical alphas to high spin states whose intensities are fit by Hauser-Feshbach analysis. The analysis leads to the discovery of the lowest $10^+$ and probably $12^+$ states after adjusting the parameters to known $8^+$ intensities.

The gamma spectroscopy of the heavy ion collision is, according to my opinion, one of the most fruitful domains of application of heavy ion accelerators. Compared with its powerfulness the field is not so much exploited. Therefore, I should like to account for this field briefly with some examples from our laboratory in München.

No matter what target one irradiates with whatever beam, one gets γ-rays. They are the Coulomb excitations of both the target and beam, γ-rays following transfer reaction and γ-rays following the evaporation of light particles $(p,n,a)$ from the compound nucleus. In a heavy nucleus, the main mode is the neutron evaporation and typically one sees the yrast line up to some transition point. For deformed rare earth even-even nuclei the rotational band is seen to some $20^+$ or so, then after that we do not see much. For lighter nuclei the competition of the p or a emission is strong or dominant, but this tendency already starts around the rare earth region because the collision of a heavy ion usually leads to the very neutron deficient side.

One can measure the following properties of those rays:

1. Excitation functions
2. Cross bombardment properties
3. Comparison with the γ-rays following activities produced by the beam
4. The shape of the line of the Doppler-shift
5. Angular distribution
6. Lifetime with pulsed beam
7. Lifetime with the recoil distance methods
8. Polarization
9. Y-Y coincidence
10. Charged particle-γ coincidence
11. Coincidence with neutrons.

The measurements are usually done with high resolution germanium diodes and the heavy ion is advantageous because of the small neutron yield.

Such richness of the heavy ion γ-spectroscopy gives us opportunity to do very much spectroscopical work with it. Usually with heavy ions we can study the yrast side, that is the high spin side better, but the opportunity is not limited to the high spin states.

As an example, I shall show you our recent work on the level scheme of $^{48}$V [16], The nucleus $^{48}$V may be reached by various methods and in the last decade there are many spectroscopical works using particle spectroscopy. Much work
using magnetic spectrometer is available for observing the levels in this odd-odd nucleus. They are \(^{(2)\text{He},p}\), \(^{(2)\text{He},d}\) \((p,n)\) counter ratio measurements, \((p,t)\) reaction on \(^{50}\text{Cr}\), where analogue states of \(^{48}\text{V}\) are observed, \((d,a)\) and also decay of \(^{48}\text{Cr}\). But till half a year ago when we looked at the \(\gamma\) spectra in this nucleus only three lower levels had known spin parity. Fig.4 indicates our \(\gamma\)-decay results. Here the reaction employed was \(^{40}\text{Ca}(^{10}\text{B},2p)^{48}\text{V}\) reaction at 25 MeV \(^{10}\text{B}\) energy. Originally experiment was planned for finding ground bands of \(^{48}\text{Ca}\) and the running time was about 20 hours for the \(\gamma-\gamma\) coincidence which yielded most important information. Of course, the information from particle spectroscopy was fully used. But it is surprising to know, how efficient the heavy ion reaction \(\gamma\) spectroscopy is. Also the energy values are much more precisely determined by the \(\gamma\)-spectroscopy.

For doing such gamma spectroscopy it is not too important to know the strange reaction mechanisms, But rather the fact that we see structure of nuclei so well, will lead to the next step where new interesting phenomena will show up.

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DISCUSSION

K. BLEULER (Bonn)

I would like to draw some attention on a recent work of Professors Stephens and Diamond (Berkeley): levels schemes of heavier even-odd nuclei are successfully interpreted by assuming a high spin \((13/2)\) single-particle state coupled to a rotating core. Would such a structure correspond to your ideas? One might assume that even 2 or more single-particle states would contribute to the large angular momentum in the critical region.

H. MORINAGA (Munich)

Not completely yet. But the diversion is to become oblate, since a part of the angular momentum is decoupled from the rotating core.

G. RIPKA (Saclay)

I hate to sound philosophic, but I have seen recently so many curves plotting moments of inertia or excitation energies in terms of angular momentum, or its square or of the frequency ... that I wonder: frankly, what does it matter what you plot? Does anybody really
care if the curve buckles up or not? Why not simply calculate the distortion and (or) phase changes in the nucleus and see if the spectrum agrees with experiment? Is there any physics favoring one parametrization rather than another?

H. MORINAGA (Munich)

I don't think that any particular fancy plot has very deep theoretical meaning.