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THE ROLE OF THREE-BODY COULOMB FIELDS VERSUS FINAL STATE INTERACTIONS IN THE DECAY OF $^{12}C - \alpha - {}^{12}C$

(invited talk)

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Specific three-body decays such as $P + T \rightarrow A + m + A$ have been thoroughly studied in the region of $Y_m = Y_{cm}$; $\theta_L = 0$, as defined in a rapidity plot fig. 1. The purpose of the experiments is to probe the complex dynamical aspects of some H. I. collisions by observing the distribution of small velocities of m in the final state. This is a step toward the high degree of multiplicity which characterizes the dissociations in relativistic H.I. collisions ; it is also a rather difficult attempt at low energy because three-body cross-sections are very small compared to the ones of prominant binary processes.

We began the study of $^{16}O + ^{12}C \rightarrow ^{12}C + \alpha + ^{12}C$ with the aim of probing aligned or quasi-aligned shapes which could describe the structure of high excited states in ^{28}Si. The experiments were carried out at Saclay with the Tandem Van de Graaff. The simple and naive starting idea of such experiments was to evidence these exotic configurations by detection of α particles emitted at rest [1].

In fig. 1 the three-body configuration A-m-A qualitatively explains how m (or α) can be emitted far below the two-body Coulomb repulsion $m + |2A|^*$ (or $\alpha + ^{24}Mg^*$). Thus, any enhancement in the inclusive α spectrum <u>taken at zero degrees</u> is a way to evidence the most probable shape involved. This argument, really valid for negligible cm velocities, was used as a signature of the quasi-aligned configuration $^{12}C - \alpha - ^{12}C$ ($V_\alpha = V_{cm}$).

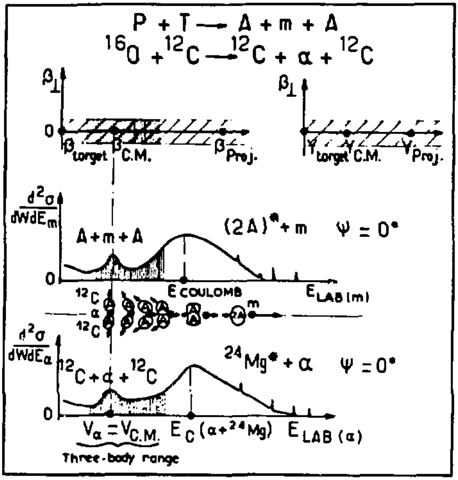

Fig. 1 : Qualitative representation of the collision process which yields α particles in the range of low cm velocities. The α particles are expected at zero degrees with $\beta_\alpha = \beta_{cm}$.

Fig. 2 shows a typical inclusive α spectrum obtained with the QDDD of Saclay, set at zero degrees. It is quite clear that a peak does emerge at $\beta_\alpha = \beta_{cm}$: an excitation function for such events has been published [1].

In this work we would rather pay attention to the origin of such α particles and compare the role of sequential decays (or two-body final state interactions) as well as the role of three-body Coulomb distorsions. This discussion is also based on experimental results which refer to exclusive measurements due to a well-known method in three-body reactions. This method consists of considering m(or α) as a missing mass in the detection of the associate fragments in coincidence. Contrary to inclusive measurements, this is a powerful means to study the dissociation, particularly for the α emission at zero degrees, since no counter has to be set in the beam path.

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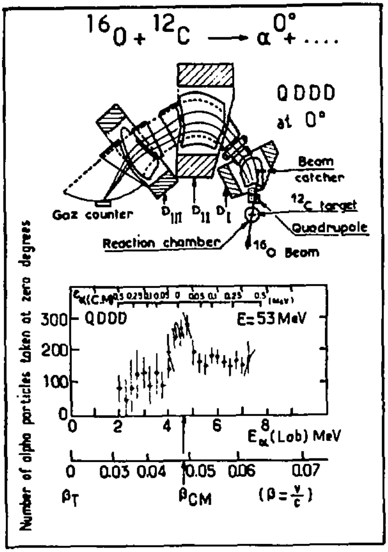


Fig. 2 : Inclusive α spectrum recorded at zero degrees with the QDDD of Saclay. Each point of the spectrum is obtained with a specific Bρ value and normalised by a parasitic Rutherford scattering on Au.

Fig. 3 shows a typical coincidence plot relative to the detection of the ^{12}C nuclei and the relevant α velocities which are easily deduced from kinematics.

The main features of the experimental data are :

i) an accumulation of events in region (a) ($Y_\alpha = Y_{cm}$), as already observed in inclusive measurements at 0°. The observation selects here the transverse velocities in this region (symmetric detection).

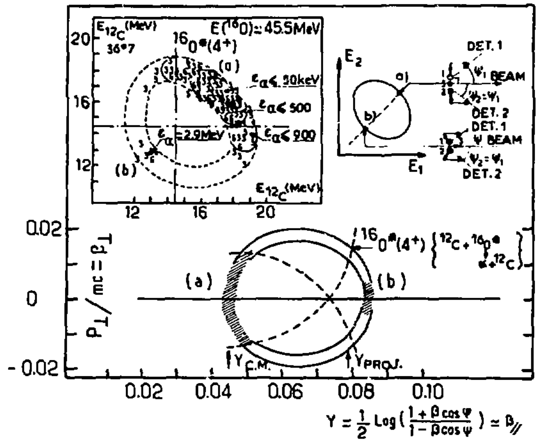


Fig. 3 : ^{12}C - ^{12}C coincidence data recorded at $E(^{16}O)$ = 45.5 MeV. The angles are chosen in such a way that the α emission can be observed in the vicinity of $Y_\alpha = Y_{c.m.}$. The exclusive measurement allows to observe the α emission in the only region defined by the contour in the rapidity plot.

ii) an accumulation of events in region (b) that we define as follows : the two ^{12}C's have a symmetric recoil and educe the α particle at zero degrees (see the rapidity plot). The α energy is about 3 MeV (perhaps fortuitously the α velocity is comparable to the projectile velocity).

iii) an empty zone out of zero degrees, along the kinematically allowed contour. What is not particularly observed, is the sequential decay due to the formation of $^{16}O^*(\alpha - {}^{12}C)$ or $^{24}Mg^*({}^{12}C - {}^{12}C)$. Concerning the formation of $^{16}O^*(4^+$; 10.3 MeV), our experimental results are inconsistent with the occurence of such a two-body final state, observed in other conditions of detection [2, 3].

More generally, in this range of incident energies, and for the specific observations we chose (small α velocities), the well- known mechanisms of three-body reactions, such as sequential or statistical decays, are not able to account for the date. Fig. 4 gives an illustration of such an inadequacy.

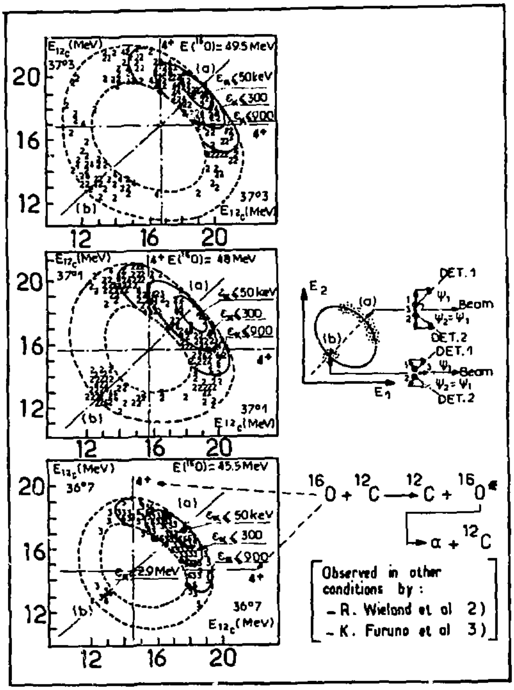


Fig. 4 : Inadequacy of the sequential process (straight lines), involving the 4^+ state (10.3 MeV) of ^{16}O, to explain the typical accumulations in regions (a) and (b). A same negative conclusion could be obtained with a ^{24}Mg state.

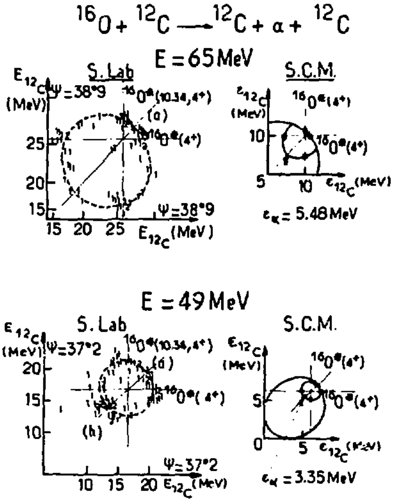


Fig. 5 : Difference between the coincidence plots obtained at 65 and 49 MeV. The relevant observation in the Dalitz plot is shown on the right. We are able to distinguish two different mechanisms which give rise to the same emission at rest in (a). The sequential decay is clearly observed at 65 MeV.

To give more contrast to this new kind of α emission, characterized by an accumulation along the bisectrix of the plot, fig. 5 shows two opposite results obtained at 65 and 49 MeV. In this experiment, the conditions were exactly the same (only the angles were slightly corrected to observe $\gamma_\alpha = \gamma_{cm}$). It is quite clear that the two-body final state interaction α - ^{12}C ⇒ $^{16}O(4^+)$ is observed at 65 MeV whereas it is not at 49 MeV. In both cases there is emission at rest of the α particle (region (a)) but the processes are different. Qualitatively, negligible α velocities could be explained at 65 MeV by an α emission which balances the recoiling velocity of $^{16}O^*(4^+)$; the emission is thus apparently at rest. On the contrary, at 49 MeV, the α emission seems to be due to a direct decay which actually leaves the α particle at rest.

This difference of α emission is worth discussing in the framework of quasi-molecular states because these states are commonly described in two ways :

i) a binary representation [4-6], in which one of the two interacting incident cores may be in one of its intrinsic states. The example shown here could be an excitation of ^{16}O in the unbound 4^+ state.

ii) a ternary representation [7-8] of the type A – α – A (here $^{12}C - \alpha - {}^{12}C$). H.J. Wiebicke, at this conference, gives a theoretical approach to the description of such molecular states. It is worth noting that stretched configurations should favour

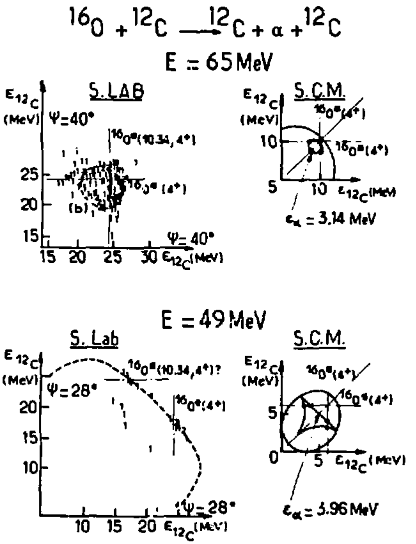


Fig. 6 : Coincidence events at two different incident energies and angles such that $Y_\alpha \neq Y_{cm}$. Small α energies are selected by the detection at 65 MeV (and an accumulation of events is observed in (b)) ; larger α energies are selected at 49 MeV where the sequential decay seems to be present.

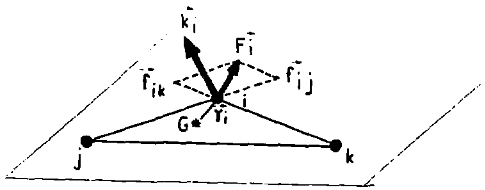
m - A (or α - ^{12}C) interactions ; on the contrary, in the triangular cases, the removal of m (α) from aligament should permit the A - A (^{12}C - ^{12}C) final state interaction. Our results, which refer to $^{16}O^*$ (α - ^{12}C) or to small α velocities, are, in both cases, rather related to stretched configurations. Triangular configurations, which are expected at lower incident energies[8], should be searched for α particles of long range (and more probably in the two-body decay α + $^{24}Mg^*$).

Thus, these two kinds of molecular structures seem to be clearly signed in the results given fig. 5. At 65 MeV, the sequential decay signature could be assigned to an initial two-body configuration, when at 49 MeV, the three-body structure would be more probably evidenced in the original accumulation in regions (a) and (b).
In fact, the experimental situation is not so clear when other exclusive measurements are carried out in different conditions of detection (observation out of $Y_\alpha = Y_{cm}$). For instance, fig. 6 gives a rather confusing and misleading result, since an opposite conclusion to the previous one (fig. 5) can be drawn ; now, the sequential decay seems to appear clearly at 49 MeV and an accumulation of a few events in (b) (previously defined) is observed at 65 MeV.

Interpretation of the results

To summarize the experimental data, it seems that a coexistence or a competition of two decays is observed according to the conditions of detections. To give a quantitative interpretation to such results we assume that the molecular configuration is decaying under the influence of the Coulomb fields due to the distribution of charges involved (analogy with Coulomb distorsion studies of pion emission in relativistic collisions [9] or with ternary fission). The three Coulomb trajectories can be computed when initial conditions at scission are defined in the phase-space. The relevant equations we used, and one of the initial conditions we considered in detail, are shown fig. 7.

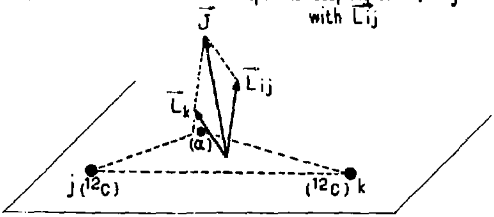
The initial conditions are defined as follows : first, a coupling between two particles is assumed to have a specific angular momentum value ; for instance we may consider $m_i - m_j \equiv m - A \equiv \alpha - {}^{12}C$ with the angular momentum $\vec{L}_{ij}$; then, this angular momentum is coupled to $\vec{L}_k$, the angular momentum of the third particle $m_k \equiv A \equiv {}^{12}C$, to give the final $\vec{J}$ value. The L_{ij} and L_k values evolve with time, J is checked to be constant. The example which will be discussed, refers to the following initial values : J = 14 (spin of the molecular resonance observed in elastic scattering), $L_{ij}(\alpha - {}^{12}C) = 4$ (analogy with the 4 state of ^{16}O ; in fact, a sum over different L_{ij} values could be performed also).



Newton's second law $\vec{F}_i = m_i \frac{d^2\vec{r}_i}{dt^2} = \vec{f}_{ij}(r_{ij}) + \vec{f}_{ik}(r_{ik}) \equiv$ 18 coupled differential equations of 1st order

$$\begin{cases} \text{conservation of momenta} & \sum \vec{k}_i = 0 \\ \text{Phase space relation} & \sum \varepsilon_i = \varepsilon_T - \sum V_{jk}(r_{jk}) \quad \left(\varepsilon_T = \frac{T\ E_0}{P+T} + Q\right) \\ \text{conservation of the total angular momentum} & \sum \vec{r}_i \wedge \vec{k}_i = \vec{J}\hbar = \sum \vec{\ell}_i \hbar \end{cases}$$

Initial conditions : ———→ specific coupling of $m_i - m_j$ with $\vec{L}_{ij}$



$$|\vec{L}_{ij}\hbar| = \left|\vec{r}_{ji} \wedge \frac{m_j\vec{k}_i - m_i\vec{k}_j}{m_i + m_j}\right| = \text{constant}$$

$$\vec{L}_{ij} + \vec{L}_k = \vec{J} = \sum \vec{\ell}_i, \text{and} \quad \vec{L}_k = \frac{\sum m_i}{m_i + m_j}\vec{\ell}_k$$

Fig. 7 : Equations and initial conditions used in the calculation of the Coulomb break-up of the three-body configuration.

Then, this choice allows to define the initial conditions in the phase-space. Fig. 8 particularly shows the closest location of the α particle irrespective to the core it is coupled with. The example chosen here is a parallel coupling of $\vec{L}_{ij}$ and $\vec{L}_k$; an anti-parallel coupling and intermediate configurations in space give less tight configurations. Depending upon the distance of the third cluster $[{}^{12}C(2)]$, we obtain a more or less deformed circle : the deformation is really efficient in the axial region. Starting with a distribution of α locations and the relevant velocities, the final asymptotic velocities are computed. The simplest way of representing the results is to plot the asymptotic ${}^{12}C$ energies in the Dalitz diagram and compare with the experiment. Such ${}^{12}C$ - ${}^{12}C$ energy distributions are rather more complex than the usual straight lines which characterize the sequential decay ; however, the Coulomb loci may quite well simulate the sequential decay in some parts, as shown in the Dalitz plot, at ϵ_1 = 5.6 MeV $[{}^{16}O^{*}(4^{+})]$. This result shows that an observation inside the Dalitz plot may disentangle pure final state interactions from Coulomb effects. Concerning our experiments, they are mainly probing the axial region of the initial structure and are very sensitive to such a Coulomb effect ; this is shown by the correspondance between the heavy lines in the structure and the heavy parts in the Dalitz plot where the small energies are due to quasi-aligned configurations ; the asymmetry of the Coulomb locus is due to the asymmetry of the relative velocities and Coulomb forces when the α particle is considered on one side or the other of the in-plane configuration axis ; of course, a final symmetry is achieved by considering $\vec{J}$ and $\vec{L}_{ij}$ in the opposite direction. The calculations show that the Coulomb effects are mostly expected in stretched configurations where the α particle is strongly perturbed when emitted from the axial region. On the contrary, well inside the Dalitz plot, the calculations may not be valid anymore because nuclear distances may be reached.

Finally, the effect of the incident energy can be observed in fig. 9 when the same set of initial conditions(r_{12} = 14fm, J = 14, L_{ij}(α - ${}^{12}C$) = 4) is kept. It can be seen that the Coulomb locus (r_{12} = 14fm) is out of the experimental observation ; to reach the small α velocities we need to tight the structure more (r_{12} = 10fm). The heavy lines give the correspondance between the initial α locations and the final energies. Once more the kinematic locations, due to the Coulomb effects, fit the experimental accumulations of fig. 5 and fig. 6 at 65 MeV ; namely, a straight part, as expected with the two-body final state α - ${}^{12}C$ = ${}^{16}O(4^{+})$, and an accumulation close to $\epsilon_1 = \epsilon_2$ (region (b) observed in fig. 6). The asymmetrical configurations involve very small distances α - ${}^{12}C$, giving much less validity to the existence of a Coulomb locus inside the Dalitz plot. Only the axial region is in the reasonable range of Coulomb effects and is connected with the experiment.

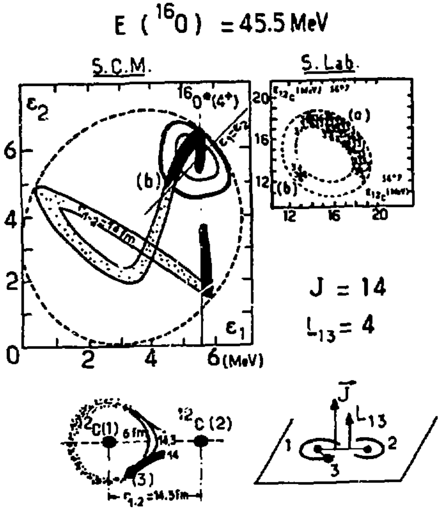


Fig. 8 : Bottom left, the initial configurations of the three clusters when a parallel coupling $\vec{L}_{ij} + \vec{L}_k$ is assumed. The experimental data are given above with the relevant locus which is drawn in the Dalitz plot. Finally, the Coulomb locus, due to the evolution of the three clusters, is represented by the complex dotted and heavy curve ; the heavy parts are due to initial axial locations of the α particle ; the dotted parts are due to more asymmetrical initial configurations (dots in the configuration).

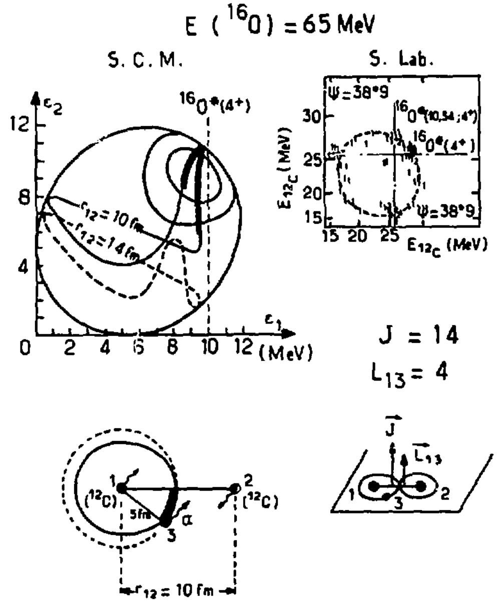


Fig. 9 : Calculations of the Coulomb break-up at 65 MeV. The J and L_{ij} values are the same as in fig. 8. Only r_{12} must be decreased to yield the α particles whith small velocities (experimental observation).

In conclusion it seems that a coexistence of stretched configurations has been probed by the experiments. Classical calculations of the Coulomb break-up and relatively simple initial assumptions show that the Coulomb effects are really sensitive to such configurations ; They also give a natural explanation of the experimental accumulations which are found in the Dalitz plot. According to the initial conditions in the phase space, the Coulomb signature can either be clearly distinguished from a sequential decay or in kinematic overlap with a two-body final state interaction which is then strongly enhanced compared to others. More generally such three-body emissions may be of some interest :

- in the study of the complex distributions of charges involved in a collision since, contrary to binary processes, the Coulomb fields are very sensitive to three-body configurations.

- in the study of central collisions and light particle emission at zero degrees. The missing mass technique suits very well the study of the emission near $Y_m = Y_{projectile}$ or Y_{cm} or Y_{Target} for favourable Q values.

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