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SPIN DETERMINATION OF HIGHLY EXCITED NUCLEI FROM LIGHT PARTICLE EMISSION STUDIES

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Among the different mechanisms involved in heavy ion reactions, deeply inelastic collisions have been studied extensively these last ten years. It is not the aim of this talk to describe in details the various features of these dissipative collisions. Several reviews of all the new aspects that appeared recently may be found in the literature. Let us recall however some of the outstanding characteristics of this process. One of the most striking features is the rapid damping of the translational kinetic energy associated with the relative motion into internal excitation energy, an indication of a large viscosity constant for nuclear matter. It has been described in term of a friction force acting between the two nuclei. This friction force might arise, for example, from the one body dissipation mechanism introduced by Blocki et al. It leads naturally to a damping of the relative motion but, due to its tangential component, it should also show up in angular momentum dissipation. It is thus clear that one should not study separately the relaxation of the two basic degrees of freedom associated respectively with energy and angular momentum. They have to be understood simultaneously and indeed we shall see later that one has to know how the excitation energy is shared between the fragments before deducing any information on the angular momentum. 

Many experiments have been devoted to this problem. Average fragment spins and/or spin alignment have been deduced from sequential fission studies, gamma ray multiplicity and circular polarisation measurements.

Angular momentum estimates from γ multiplicity measurements are however subject to some ambiguities. The first difficulty arises from the assumption which has to be made on the average multipolarity of the observed γ transitions (E2, stretched, unstretched, M1...). Also, one has to neglect (or to calculate) the angular momentum removed by light particles. Nambodiri et al. have shown very clearly the basic limitations of this method. This is indicated in Fig.1 which is a contour diagram of average γ multiplicities as a function of average angular momentum and masses (these results come from recent measurements in a number of fusion reactions). It appears clearly that for light masses (M<70), Mγ is no more sensitive to the angular momentum of the emitting system. For such light system, most of the angular momentum is indeed removed by light particle emission (mainly α-particles). The Mγ technique is thus most appropriate for medium mass systems where the competition is restricted to neutron and γ-rays. For the heaviest systems, the best method is clearly to look at sequential fission. It has led to very interesting information but this is evidently limited to products for which the fission barrier is sufficiently low. At this point, it should be stressed...
that neither of these two methods allows a simple determination of the angular momentum sharing between the two fragments.

Finally, a third method, that turned out to be the most accurate, at least for light systems (composite systems with masses lower than 100) is related to light particle emission and we shall develop its specific advantages in the next section. This talk will be centered around a complete study of the system $^{40}$Ar+$^{24}$Ni at 280 MeV. We shall try to show, through that specific example, the interest there is in studying light particle emission in DIC and more generally in any dissipative reaction.

The general motivation for particle emission studies will be given first as well as the kind of information they can presumably bring to our knowledge of heavy ion dissipative reactions. Then, the origin of the $\alpha$-particles observed in the Ar+Ni reaction will be discussed. In a third part, we present results on the angular momentum transfer as deduced from out of plane angular distributions and charged particle multiplicities. Finally, as to the general use of particle emission properties in other situations than DIC studies, we conclude by giving few examples where it may already be foreseen that such methods would be most advantageous.


Light particles emitted in a heavy ion collision may be considered as test particles to probe the evolution of the reaction. Their characteristics, energy and angular distribution, should indeed reflect the degree of equilibrium of the colliding system. In principle, they can be emitted at any stage of the reaction. Fast, knock-out particles may arise at the very beginning of the collision. One would then expect typical properties of a one-step direct reaction. They can also be emitted some time afterwards when a composite system is clearly formed between the two interacting nuclei, during the approach of the thermodynamical equilibrium in the system. This fast particle emission has been observed in several systems at rather high relative energies. It has been suggested that some hot spot has been formed during the collision, which implies that high temperatures are localised in some restricted part of the composite system. The associated particle emission time would then be so short that emission could actually occur before the scission of the composite system. That kind of emission can thus reveal the nature of the early stage of the energy and angular momentum dissipation.

Looking now at larger interaction time, many degrees of freedom of the composite system should have time to reach equilibrium (N/Z ratio, relative motion, rotational degrees) and finally, the system disrupts into two very excited fragments which are going to emit light particles ($n,p,\alpha$) and $\gamma$-rays or even to fission for very heavy products. These secondary particles have well defined characteristics related not only to the excitation energy but also to the angular momentum of the emitting nucleus. As we are interested in this conference to the behaviour of nuclei at high angular momentum, it may seem worthwhile to recall briefly the effects of high angular momentum on the deexcitation stage of the nucleus.

First, it is well known that high spin states will favor $\alpha$-particle emission. This is simply because they can carry away a large amount of orbital angular momentum as compared to other light particles.

Fig. 2. shows for example the orbital angular momentum removed by $\alpha$-particles as a function of the intrinsic spin $J$ for various emitting fragments excited to 60 MeV.
tively to the emission of other particles. Thomas and Grover and Gilat have discussed extensively the spin dependence of n, p, and α emission probabilities. Let us just show as an example the result of a GROG12 calculation for the emission probability of n, p, α as a function of the angular momentum of the 62Cu nucleus excited at 54 MeV (fig.3). It is clear from this plot that measurement of p or α multiplicities or even better \( \frac{N_p}{N_\alpha} \) may lead to a rather accurate spin determination. This requires of course extensive evaporation calculation as well as, if possible, calibration measurements.

Besides this effect on total emission probability, high spins in the emitter will also show up in the spatial distribution of the evaporated particles. To explain these effects, let us consider the particular situation of deeply inelastic collisions. Assume that the composite system is formed for a single incoming partial wave. In the limit of long interaction time, because of the tangential friction, the entire composite system will rotate rigidly with a spin J and at the time of scission, the classical picture is similar to the one encountered in fission. The two fragments will be emitted preferentially in a plane perpendicular to J and moreover as the composite system was rigidly rotating, they will appear with intrinsic spin parallel to J, that is perpendicular to the detection plane. In the same way, fragments will then evaporate particles with a maximum located in a plane perpendicular to their intrinsic spin directions. Accordingly, when one imposes experimentally a detection plane, one defines also the direction of angular momentum in the entrance channel and of the spins of the fragments issued from the collision (this is of course the ideal case of complete alignment of the fragments). Finally, the angular distribution of light particles emitted by the aligned nuclei should be isotropic in the reaction plane but should show an out-of-plane anisotropy which is directly related to the angular momentum of the emitting fragments. This problem was first considered by Ericson and Strutinski twenty years ago. More recently, it has been discussed by Dissing and Catchen et al. It may also be noticed that these properties have already been used in compound studies to determine the critical angular momentum for fusion.

The last point which is worth to be stressed concerns the kinetic energy of the emitted particles. Classically, when a rigid body is rotating, the particle emitted from the surface gets an extra initial velocity \( V_\theta \) equal to the surface velocity of the nucleus and the direction of emission. This spin-off effect will then be maximum in the detection plane perpendicular to J. It corresponds to an additional energy \( \Delta E \) equal to

\[
\Delta E = \frac{1}{2} m J^2 R^2 \sin^2 \psi
\]

(2)

where \( m \) is the particle mass.

Resulting additional α-particle energies as a function of the angular momentum of the emitter are shown in fig.4 for three different nuclei (V, Cu, Br) excited at 60 MeV. It is clearly seen that it could be an alternative approach to the angular momentum of

Fig. 3. Relative emission probabilities of neutrons, protons, and α-particles and multiplicity ratio \( \frac{N_p}{N_\alpha} \) from 62Cu fragments at \( \langle E^* \rangle = 54 \) MeV.

Fig. 4. Additional centrifugal energies (due to spin-off effect) as a function of the intrinsic spin of various emitters.
the fragments in deeply inelastic collisions.

However, whereas spin determinations that may be obtained from total particle multiplicities (see above) are independent on any assumption on the alignment of the DIC fragment, this is clearly not the case for the last two properties (out of plane anisotropy and spatial dependence of the average energies). In fact, it is hoped that comparison between these various methods may lead to a determination of both the average spin and the alignment of the emitter. Anyhow, for any of these various estimates to be meaningful, it is clear that the light particles must come from a secondary evaporation process. This implies that one has first to experimentally check that the excited fragments are in thermodynamical equilibrium and that some properties which are not spin dependent reflect correctly this equilibrium.

2. The 280 MeV \( ^{58}\text{Ni} \rightarrow ^{208}\text{Pb} \) experiment. The origin of particle emission.

Many reasons pointed to that specific reaction as a good candidate to look at particle emission. Particle inclusive experiments\(^{40,41}\), fragment-fragment coincidence studies\(^{42}\) and \(\gamma\)-ray multiplicity measurements\(^{43}\) had already been performed on the same system. These previous experiments have indicated the possible existence of an important cross-section for charged particle emission. Moreover, the evaporation residue cross-section \(\sigma_{\text{ER}}\) was also measured\(^{44}\). It indicated the existence of a rather large cross-section for compound nucleus formation.

From the measurement of \(\sigma_{\text{ER}}\) and \(\sigma_{\text{DIC}}\) one is able to define a very narrow window of initial angular momentum that leads to DIC 7462, DIC999. It is of course an ideal case to study the angular momentum transfer, much better than in heavier systems where most of the partial waves contribute to the deeply inelastic channel.

The experimental set up has been described elsewhere\(^{25}\). However, it should be noted that in these experiments, both in plane and out of plane angular distributions of protons and \(\alpha\)-particles were measured in coincidence with DIC fragments detected at \(\Psi=30^\circ\) (in plane angle). As this angle was much larger than the grazing angle, only the DIC leading to a total energy dissipation were considered.

As it has been pointed out before, a necessary condition to apply the statistical theory to the de-excitation of DIC fragments is to identify precisely the different emission sources which could be for instance the composite system or the fragment themselves. It is then very useful to express the experimental results in terms of an invariant cross-section plot as a function of the parallel and transverse velocities \((V_{\parallel}, V_{\perp})\). The invariant cross-section may be defined by

\[
\sigma_I = \frac{d^2\sigma}{dp_\perp dp_\parallel} \propto \frac{1}{p} \frac{d^2\sigma}{dp_\perp dp_\parallel} \tag{3}
\]

where \(p\) is the linear momentum of the light detected particle (\(\alpha\) or proton). The important point is that \(\sigma_I\) is invariant in a Galilean transformation since it corresponds to a simple translation in the \(p_{\perp}\) space. The iso-contour lines corresponding to a single isotropic source will appear, in this representation, as circles centered around the tip of the velocity vector characterizing the source. Fig.5 shows an example of this kind of representation for \(\alpha\)-particles in coincidence with a light fragment \(Z=16\). Labels on the

\[\text{Fig.5. Invariant cross-section plot for } \alpha\text{-particles in coincidence with fragments of charge } Z=16.\]

The size of the dots is an increasing function of \(\sigma_I\). Arrows give the mean recoil for the detected fragment \((P_{Z=16})\), and its assumed two-body reaction complementary \(P_{Z=16}\) comp. Solid circles correspond to evaporation emission. (mean linear momentum) from the detected fragment (upper circle) and from its complement (lower circle). Dashed circles indicate the experimental detection thresholds.
axis represent α-particle momentum in unit of 0.1 GeV/c in place of velocity \( p = m a V \).

In any direction, the maximum of the distribution coincides with what is expected when considering evaporation from two moving sources (the two DIC fragments with average recoil velocity \( V_z \) and \( V_{z\text{ comp.}} \)). These maxima are symbolized by the full line circles in the plot, whereas the dashed line circles simply indicate the experimental detection thresholds. One should notice also that at forward angles, when the two velocity circles overlap, there is a clear pile up of the cross-section leading to a very strong asymmetry of the α-particle spectra with respect to the beam axis. Average velocities seemed to be in rather good agreement with preferential emission from the light fragment \((Z=16)\) at \(+10^\circ\) and by the heavy one at \(-10^\circ\). Another interesting point is that, by an appropriate choice of the in-plane angle (for example \(±60^\circ\)) where to make the out-of-plane distribution, one selects almost uniquely a single source (the light fragment at \(+60^\circ\) and the heavy one at \(-60^\circ\)). This is of course a great advantage of the light particle measurements over the other methods such as the \(\gamma\) multiplicity technique.

To check more quantitatively the evaporative origin of the light particle, a two dimensional fit of the invariant distributions has been performed. For this fit, it was assumed that two isotropic sources were contributing to the α emission. The shape of the light particle energy spectrum was assumed to be of a shifted Maxwell type:

\[
P(E)dE \propto \frac{E-B}{T} \exp \left(-\frac{(E-B)}{T}\right)
\]

where \( T \) is the nuclear temperature and \( B \) an effective threshold energy. This crude equation, which neglects penetrability effects has been convoluted with a Gaussian distribution to improve the fit at low energy near the threshold for α-particle emission.

Recoil effects have been taken into account explicitly when the α-particle was emitted by the detected fragment. For each source, there were then three parameters: the barrier \( B \), the temperature \( T \) and the intensity.

The conclusion of this fit shows very clearly that the data can be nicely explained by an isotropic emission from the two fully accelerated fragments in statistical equilibrium, with one exception at forward angles where it definitely remains an other component corresponding to high energy α-particles. Comparison with experiment is shown in fig.6 for α-particle in coincidence with \(Z=16\) at three different emission angles. At \(-55^\circ\) a pure α emission from the heavy undetected fragment is observed. At \(55^\circ\) it corresponds mainly to an α-emission from the detected fragment although it remains a low energy contribution from the complementary fragment. And finally at \(-10^\circ\), when the two components are strongly mixed, an additional pre-equilibrium component appears with a rather high mean kinetic energy.

Temperatures deduced from the fit are the same for the two complementary fragments, which is expected if thermodynamical equilibrium has been reached in the composite system before scission.
3. The spin of DIC fragments deduced from out-of-plane angular distributions of α-particles.

As the statistical origin of the light particles has been well established (if one excepts the very forward angles), we mentioned before that the out-of-plane distributions should present an anisotropy that characterizes the angular momentum of the emitting fragment and its degree of alignment. We shall just recall here the basic equation which expresses the probability for a particle, with an orbital angular momentum \( \ell \) and energy \( E \) to be emitted by a nucleus with spin \( I \) at a given angle \( \theta \) with respect to the direction of this spin \( I \)

\[
W_\ell(I_\alpha \theta) \propto \frac{J_\ell(\ell+1/2)(\ell+1/2)}{J_0} \tag{5}
\]

\( J_0 \) is the zeroth order associated Bessel function and \( J_\ell \) and \( T \) are the moment of inertia and temperature of the residual nucleus.

This equation may be applied directly to out-of-plane anisotropy if one uses average values of \( E \) and \( \ell \). Alternatively it is possible to integrate over all possible \( k \)-values and energies of the emitted particle. Using the sharp cut-off approximation for the transmission coefficients, the following expression can be obtained:

\[
W_\ell(I_\alpha \theta) \propto \frac{\mu_\alpha^2 (I+1/2)^2 \sin^2 \theta}{2\mu \Omega} \tag{6}
\]

\( \mu_\alpha^2 \), the relative moment of inertia of the particle at the nuclear surface, enters via the effect of the centrifugal barrier on the transmission coefficients. It is important to keep in mind that this relation implies a complete alignment of the spin of the emitting nucleus and a first step α emission.

The out-of-plane measurements have been performed at +60° and -60°, that is in a region where only one fragment is contributing to the emission. Some of the results are plotted in fig.6 in the rest frame of the corresponding emitting fragment. Solid curves are least square fits of the experimental data assuming \( W_\ell(I_\alpha \theta) \propto \exp(-\alpha \sin^2 \theta) \). In comparison with α-particles, proton out-of-plane distributions are quite flat. This is in agreement with the fact that a proton cannot remove as much angular momentum as an α-particle does. Experimental α anisotropies have been converted in DIC fragment spins using equation (6). The nuclear temperature \( T \) has been obtained from the energy spectra \( (T \approx 2.7 \text{ MeV}) \). The moment of inertia \( \Omega \) has been taken equal to the rigid body value with \( r_o = 1.2 \text{ fm} \). \( u_\alpha R^2 \) was evaluated following Mac Mahan and Alexander:

\[
u_\alpha R^2 = u_\alpha (r_o A^2 H + R_o)^2 \quad r_o = 1.42 \text{ fm} \quad R_o = 2.53 \text{ fm}
\]

Resulting values of \( I_{\text{rms}} \) are presented in fig.8 and compared to the prediction of a classical sticking model for two possible shapes of the composite system at scission. The sticking hypothesis seems to be a reasonable assumption as we are looking at completely damped events. A mean interaction time of \( 10^{-16} \) s can be estimated, much larger than the angular momentum relaxation time for the same system which is about \( 3 \times 10^{-23} \) s. The sticking limit leads simply to

\[
I_1 = \frac{J_1}{J_1+J_2+10^{-16} \text{ s}} I_0
\]

\( J_1 \) and \( J_2 \) refer to the moment of inertia of each separate fragment. As the angular momentum window that leads to DIC is very narrow, it is a good approximation to choose a single average value \( I_0 = 86h \).
Experimental results are in clear disagreement with a sticking hypothesis between spherical nuclei. In fact, this is not surprising, as when one tries to reproduce the experimental average kinetic energies of the fragments, taking into account the Coulomb potential and also the centrifugal term, one is led to include deformation effects. By matching the fragment deformation (assuming ellipsoidal shapes) to the average energy results and assuming again a sticking limit, one gets the second curve (solid line in fig.8) which is in good agreement with the experimental data but, may be, for the heaviest products (Z>37). A possible explanation could be a fractionation. If one assumes that the largest mass asymmetries come from the lowest l waves (l~75%M) the sticking hypothesis for deformed nuclei would then lead to I=24h instead of 26h for Z=36h. However, as we have already said, equation (6) which is used to get I = RMS does not take into account a possible misalignment of the fragment angular momentum. In a way, values deduced from equation (7) are to be considered as lower limits of the actual angular momenta. A consistent interpretation of both the average kinetic energies and the out-of-plane anisotropies is nevertheless a good indication of a rather strong alignment.

A better check of this should evidently come from an independent spin estimate from the total a-particle and proton multiplicities which are not sensitive to the alignment but this is the subject of the next section.

4. The spin of DIC fragments deduced from particle multiplicities.

As it has been pointed out before in section 1,
the emission probability of α-particles is predicted to increase very rapidly with increasing spin of the emitter. As protons follow the opposite trend, multiplicity ratio \( \frac{M_{\text{H}}}{M_{\text{p}}} \) is thus strongly correlated with spin (see fig.3). Fig.9 shows very clearly what has been observed in two series of experiments concerning \(^{75}\text{Br}\) and \(^{117}\text{Te}\) compound nuclei\(^{38,39,49}\). This plot, extracted from the work of Catchen et al.\(^{31}\) shows the experimental multiplicity ratio \( \frac{M_{\text{H}}}{M_{\text{p}}} \) as a function of the average spin value in the entrance channel (for \( \ell \)-waves leading to compound nucleus formation). In the right side of the figure is shown the calculated value of \( \frac{M_{\text{H}}}{M_{\text{p}}} \) deduced from 1st step particle emission. As the calculation corresponds to single spins, the predicted curve is much steeper. This is exactly the initial condition in DIC where very excited fragments have a rather narrow spin distribution (at least for light systems). Accordingly, experimental results of Miller et al.\(^{49}\) on \(^{75}\text{Br}\) do not seem to be directly usable for our purpose. We shall need to rely on a statistical model calculation to extract a correspondence between spins and multiplicity ratio that applies to our experimental situation.

Fortunately, the previous \(^{75}\text{Br}\) compound nucleus experiment has led to extensive and successful statistical model calculations by Gilat and Grover\(^{50}\). This allows us to know rather precisely the parameters to be used in the Br region, which corresponds to the heaviest DIC fragments in the \( \text{Ar} + \text{Ni} \) reaction. Consequently, statistical model parameters (mainly level densities, moment of inertia and shell effects due to the vicinity of the 28\( p \) closed shell) have not been taken as free parameters in the calculation but fixed at the values determined by Gilat. The only real free parameter was the initial spin of the emitter.

The initial distribution in excitation energy of the primary fragments has been deduced from single and coincidence measurements of the DIC fragments. It has been assumed that, for a given product, the ratio of the two first moments were the same for both the kinetic energy and the excitation energy distributions (i.e. in this case \( \frac{<E>}{\text{FWHM}} = 3.75 \)). The initial conditions of excitation energy and angular momentum are shown in fig.10 for the \(^{75}\text{Br}\) product in the \((E^*,J)\) plane. On the same plot, appear the isoprobability contours for α-emission. It is clearly seen that a small error in the width of the \( E^* \) distribution does not affect the α emission. Another remark concerns the place of the α emission along the evaporation chain. This is an important point as in the out-of-plane analysis, it was implicitly assumed that α emission takes place at the first step. Calculations in the \( Z=30-36 \) region show that first chance α emission contributes for more than 40% of the total α cross-section. Adding the \( 2\alpha \) and \( 3\alpha \) channels (which barely change the angular momentum of the emitter before α emission), this figure increases to about 65% (and to 80% with \( 4\alpha \)). This justifies somewhat our previous assumption in section 3.
Complete calculations, including all the possible deexcitation channels, have been performed for three nuclei only (Z=23, 29 and 35). For all other charges, and to save computer time, only partial calculations have been made (including α, nα, pα and pα channels). The resulting cross-sections were then empirically corrected for the missing yield on the base of the three complete calculations. In fig.11 emission probabilities for each particle and emission width ratio $M_p/M_\alpha$ are plotted as a function of J for $^{75}\text{Br}$ (1st step calculation). Dots correspond to calculated ratios $M_p/M_\alpha$ deduced from complete calculation as the dashed curve is related to the same calculation for the first step.

A last remark should be made on the primary mass distribution for each charge. Although the calculation corresponds to the most probable mass ratio, that is the one which minimizes the potential energy of the system for a given charge asymmetry ($N/Z$ equilibrium), it does take into account the different particle emission width of the two neighbouring isotopes.

A good test of this type of calculation is that it should not only reproduce $p\alpha$ and $\alpha$ multiplicities but also the experimental energy spectra. Fig.12 shows the resulting calculated $\alpha$-spectrum for Z=29 (complete calculation). The agreement with the experimental one (histogram) is fairly good. Unfortunately, the shape of the energy spectrum is not sensitive enough to the average angular momentum to determine it this way. This is seen in fig.13 where the experimental $\alpha$-spectrum for Z=35 is compared to complete calculations with three different spins of the emitter (J=15, 21, 24$^\text{th}$). These three values give all a reasonably good agreement with the experiment. However a much better statistics might have allowed a possible
spin determination from the shape of the energy spectra.

Much more precise information should be obtained from the particle multiplicities. For example, it is seen from fig. 11 that in the region of interest (J = 16-36), \( \alpha \) multiplicity increases by about 13\% every 2\( \hbar \) and that at the same time \( M/M_0 \) decreases by 20\%. Using the spin determination obtained from the out-of-plane anisotropy, we have computed both the proton and the \( \alpha \)-particle multiplicities for all heavy emitters. The results are displayed in fig. 14 and compared to the experiment.

![Fig. 14. Calculated (solid curves) and experimental p and \( \alpha \)-particle multiplicities as a function of the charge of the emitting nucleus.](image)

The agreement is reasonable in the region \( Z = 28-36 \) but is not so good for lower \( Z \). This last case is most probably related to our choice of the statistical model parameters. We have indeed a good confidence in the parameters for the high \( Z \) region but there is no special reason why they should also work in the region \( Z = 20-25 \) where the influence of the 20\( \hbar \) shell has to be taken into account properly. If we then restrict the comparison to the region \( Z = 28-36 \), we can nevertheless notice that, on average, the predicted \( \alpha \)-particle multiplicities are a bit too high whereas the opposite trend is found for the protons. This could easily be corrected for by decreasing slowly the initial spin of the fragments. Particle multiplicity estimate will then tend to be 2 or 3\( \hbar \) units lower than the anisotropy one.

A possible explanation could be an overestimate of the moment of inertia of the residual nucleus in equation (7), as some \( \alpha \)-particles may come from a \( \nu \) or \( \rho \) channel. However, considering the model uncertainties, it is probably better not to take the above difference too seriously. In fact both methods give very similar results and this is a clear signature of a strong alignment of the angular momentum transferred in this reaction. Identical conclusions have been reached in heavier systems using sequential fission method\(^{12}\). This is also the result that theoretical investigation of angular momentum dissipation on the basis of Fokker Planck equation leads to\(^{46,51}\).

Finally, this experiment may be compared to a \( \gamma \)-multiplicity measurement on the same system by Bock et al.\(^{43}\). This is done in fig. 15 and it shows that particle results are lying well above the \( \gamma \)-multiplicity data. The difference corresponds to angular momentum removed by the light particles, which has not been taken into account in the \( \gamma \)-multiplicity measurements. It is well accounted for by the statistical model using the experimental particle multiplicities.

![Fig. 15. Sum of the spins of the two complementary fragments as deduced from the out-of-plane data compared with those deduced from \( \gamma \)-multiplicity measurements of ref. 43.](image)
5. Conclusion.

Charged particle studies in coincidence with deeply inelastic fragments appear to be a very powerful tool for studying energy dissipation as well as angular momentum transfer. Combining the different emission properties (angular distributions, energy spectra, particle multiplicities), it has been possible to measure rather precisely the angular momentum transfer. A good agreement with the sticking limit has been obtained. Moreover, the degree of alignment of the DIC fragments was found to be very strong.

At least, for light systems, light charged particle measurement should be preferred to the γ-technique as they are more directly connected with the fragment initial spin of the emitter. Moreover, this method is the only one that gives a precise measurement of the individual spin of both complementary fragments.

Systematic studies are still needed to increase our knowledge of DIC. For example, there are still very few experiments on the time evolution of angular momentum dissipation as might be obtained by studying also the fluctuations and/or the energy dissipation.

More generally, we tried in this paper to show through a specific experiment how powerful the use of charged particle emission can be to study any dissipation mechanism. Indeed, all what has been described in this paper on spin determination may be applied to any nucleus in statistical equilibrium. From this point of view, it is surprising that only very few such experiments have been performed in compound nucleus studies where protons and α-particles together with γ-coincidences could be of a great help to know very precisely the entry states.

In the same spirit, particle particle angular correlations can also be very sensitive to the angular momentum of the emitter and it seems possible to select this way, continuum states with high angular momenta. As a last example, let us consider the problem of the possible existence of a l-window in fusion reactions. TDHF calculations predict an increase of the l minimum and a narrowing of the l-window itself with increasing energy. This is a typical case where an excitation function of particle multiplicities might very simply give the answer as to the existence of such l limitation.

Finally, coming back to DIC reactions, it is worth to stress again that, for light systems, a rather narrow window of angular momenta contributes to this process as opposed to fusion reactions where the compound nucleus is formed with a very wide angular momentum distribution. This should be kept in mind in high spin state studies as it should be possible to take advantage of this situation where the entrance channel is well defined with respect to the angular momentum.

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