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HIGH ENERGY NUCLEAR EXCITATIONS

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Résumé - Nous étudions dans quelle mesure certaines structures observées à haute énergie d'excitation peuvent être identifiées à l'aide d'un modèle simple décrivant les excitations élémentaires du noyau. La discussion s'appuie sur la réponse linéaire calculée à l'approximation R.P.A. avec différents champs extérieurs. Pour les structures à très haute énergie d'excitation (> 50 MeV) qui ont été détectées dans des collisions entre ions lourds et qui ne peuvent s'interpréter de cette façon, nous tentons de trouver une explication dans un éventuel mécanisme de réaction.

Abstract - The main purpose of this talk is to see whether a simple description of the nuclear excitations permits one to characterize some of the high energy structures recently observed. The discussion is based on the linear response to different external fields calculated using the Random Phase Approximation. For those structures in heavy ion collisions at excitation energies above 50 MeV which cannot be explained with such a simple approach, we discuss a possible mechanism for this heavy ion scattering.

I - INTRODUCTION

The past decade has seen much effort put into the investigation of giant resonances in nuclei using different probes and covering a wide range of energies. These investigations provide a large body of experimental data showing great richness in the nuclear response for energies far above the particle emission threshold. Besides the most studied resonances belonging to 1 $\hbar\omega$ and 2 $\hbar\omega$, new resonances of different multipolarities and nature (isovector quadrupole, squeezing mode, high energy octupole resonance) have been observed /1,2,3/. More recently (α,α') scattering experiments /4/ on different nuclei indicate the presence of multipole strength above 200 $A^{-1/3}$ MeV which corresponds to 40 MeV in the ^{208}Pb. Finally, heavy ion collisions, initially ^{40}Ca on ^{40}Ca at 400 MeV /5/, and very recently ^{36}Ar and ^{20}Ne on ^{208}Pb show regularly spaced structure in the cross section up to excitation energies around 100 MeV. The position of these high energy structures does not depend on the nature of the projectile which unambiguously demonstrates that they can be associated with the excitation of the target only /6/.

Theoretically, one knows very little about the high frequency components of giant resonances. In a time dependent Hartree-Fock approach, Flocard and Weiss /7/ have done a ^{40}Ca + ^{40}Ca calculation at 400 MeV laboratory energy and grazing impact. Subsequently they analysed the vibration pattern in one of the outgoing ^{40}Ca nuclei by studying the Fourrier transform of the time evolution of the matter density multipoles which led directly to the response function. Their main result is that some collective strength lies around 50 MeV for all the multipoles included in the calculation. The explanation put forward is that these excitations are due either to the non-linearity of the T.D.H.F. equations or to the anharmonicities of the collective motion.

On the other hand, the possibility that these excitations are of one-particle-one-hole content was doubtful after the Van Giai calculation /8/. He calculated the centroid positions of high multipoles in a simple particle-hole approximation and found that, for high J , centroids shift to lower energies.

Both theoretical investigations mentioned above consider the response function to the multipole operator $r^J Y_{JM}(\theta,\varphi)$ which is the limit $q \to o$ of the full operator $j_J(qr) Y_{JM}(\theta,\varphi)$. This would be perfectly legitimate provided that the response does not depend crucially on the momentum transfer q. However, as it will be emphasized in this talk, the use of the full operator and the study of the response function as a function of momentum transfer q is necessary. More generally, according to the reference /9/, it will be seen that it is of great importance to study the response function for external fields with different radial shapes.

In the first part of this talk, our main purpose is to see whether or not a simple description of the nuclear excitations provides an explanation of some of the observed high energy structures up to around 50 MeV.

For those structures at higher energies, which cannot be interpreted with such simple approach, we shall comment on a simple model of heavy ion collision.

II - STUDY OF THE LINEAR RESPONSE FOR DIFFERENT FIELDS

1) Some definitions

In this part, the linear response of the nucleus to different arbitrary external fields is considered as a simple means of investigation, providing qualitative information on the location and the identification of possible structures. It must be emphasized that the comparison of the theoretical predictions presented below with scattering data is not necessarily exact since one uses external fields which can differ from the effective fields arising in a precise experimental situation. However, when we use the operator $j_J(qr) Y_{JM}(\theta,\varphi)$ the response is directly comparable to electron scattering data provided that the plane wave Born approximation is justified.

One uses the linear response theory because it is a convenient tool to extract all information concerning the behaviour of the nucleus under the influence of a weak external field "F". In fact, the imaginary part of the response function " $\chi(\omega)$ ", restricted to positive frequency ($\omega > 0$), defines the so-called dynamical form factor $S(\omega)$:

$$S(\omega) = \mathrm{Im}.\chi(\omega>0) = \sum_N |\langle N|F|0\rangle|^2 \, \delta(\omega-\omega_{N0})$$

This quantity furnishes a direct measure of the excitation spectrum of density fluctuations.

Here we have assumed a discrete spectrum, but the generalization to the continuum case is straigthforward. In principle, the states $|N\rangle$ are exact eigenstates and ω_{N0} represents the excitation energy measured with respect to the ground state. In many applications the excited states $|N\rangle$ are approximated by the solutions of an R.P.A. calculation or sometimes by simple particle-hole wave functions. According to its definition the trend of $S(\omega)$ is governed by the transition matrix element

$$\langle N|F|0\rangle = \int F(\bar{r})\, \rho_N(r)\, d\bar{r}$$

where $\rho_N(r)$ is the transition density. It represents the distribution of the nucleons which participate in the excitation of state

$$\rho_N(r) = \langle N | \psi^+(r)\, \psi(r) | 0 \rangle$$

In the R.P.A. this quantity takes the simple form :

$$\rho_N(r) = \sum_{ph} X^N_{ph}\, \varphi^*_p(r)\, \varphi_h(r) + Y^N_{ph}\, \varphi^*_h(r)\, \varphi_p(r)$$

(N denotes the set of indices i, π, J : π parity, J the angular momentum, i distinguishes different states of same J, π).

In order to study the collectivity of a particular mode, it is convenient to consider the first moments of the dynamical form factor defined as :

$$m_k(F) = \int S_F(\omega)\, \omega^k d\omega = \sum \omega^k_N |\langle N | F | 0 \rangle|^2$$

Restricting ourselves for the moment to m_1 , one sees immediately that it can be rewritten as

$$m_1(F) = \frac{1}{2} \langle 0 | [[H, F], F] | 0 \rangle$$

Now, if the operator F commutes with the potential occuring in the definition of H , we have the identity

$$m_1(F) = \frac{\hbar^2}{2m} \langle 0 | |\nabla F|^2 | 0 \rangle$$

The equality

$$\sum \omega_N |\langle N | F | 0 \rangle|^2 = \frac{\hbar^2}{2m} \langle 0 | |\nabla F|^2 | 0 \rangle$$

is known as the energy-weighted sum rule (EWSR). The E.W.S.R. remains true even when approximating the states $|N\rangle$ by the R.P.A. solutions. According to Thouless's theorem one has to calculate the right hand side in the Hartree-Fock ground state. The percentage of the sum rule exhausted by some particular mode $|N\rangle$ is defined as :

$$\omega_N |\langle N | F | 0 \rangle|^2 / m_1(F)$$

It gives an indication on the collective nature of the transition.

Other quantities of interest are the different prescriptions $(m_3/m_1)^{1/2}$, $(m_1/m_{-1})^{1/2}$ and $(m_{-1}/m_{-3})^{1/2}$ for the centroid energy.

When a mode exhausts all the E.W.S.R., all these prescriptions lead to the same answer. Otherwise, they differ and give an indication on the concentration of the strength.

2) Results

J. Dechargé et al. /10,11/ have calculated the energy-weighted sum rule for ^{40}Ca and ^{208}Pb using the operator $j_J(qr)\,Y_{JM}(\Omega)$ relevant to the electromagnetic processes. Note that the E.W.S.R. is q independent only in the long wavelength limit ($q \rightarrow o$). The E.W.S.R. has been evaluated making use of the R.P.A. states expanded using the particle-hole solutions of a Hartree-Fock calculation. These calculations were performed in an $N_0 = 12$ harmonic oscillator shells for ^{208}Pb and $N_0 = 10$ for ^{40}Ca. Since the continuum was not treated exactly, the authors have checked the completeness of their basis by comparing the values of the two sides of equation 1 defining the E.W.S.R. They conclude that the particle-hole basis is sufficient for the reconstruction of the E.W.S.R. up to $q \backsim 1.2\ fm^{-1}$ for all multipoles and parities (J , π) considered. Such a comparison is shown in Fig.1.

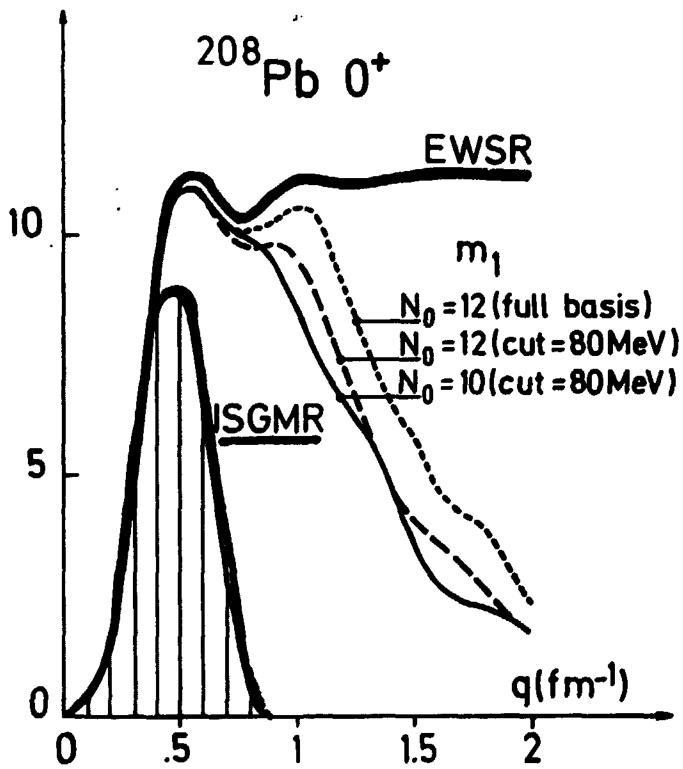

Fig. 1 - Double commutator EWSR (q) is compared to the first moment of the $J^\pi = 0^+$ response function $m_1(q)$ to the electric transition operator, in ^{208}Pb. Full and dashed lines represent the $N_0 = 10$ and $N_0 = 12$ basis, respectively with cut-off, 80 MeV ; the dotted line gives the full $N_0 = 12$ basis (no cut-off). The shaded area is the contribution of the 14.6 MeV ISGMR to $m_1(q)$.

In Fig. 2 the individual R.P.A. energy-weighted strengths for ^{40}Ca have been summed in energy bins of 5 MeV. The q-dependence is seen to be quite dramatic. The single-peaked, low-energy resonances 0^+ and 2^+ at $q \rightarrow 0$ disappear almost completely at $q = 1.2\ fm^{-1}$ and the maximum of the strength lies around 60 MeV. For 4^+, already at $q \rightarrow 0$, the response shows two peaks (15 - 20 and 40 - 45). For $q = 1.2\ fm^{-1}$, the strength shifts appreciably toward higher energy. States which are not shown here, namely 3^- and 5^-, behave similarly to the 4^+ state. In view of these results, one can conclude that some collective strength exists at high energy (40 - 60 MeV) already at $q \rightarrow 0$ for high multipoles 3^-, 4^+, 5^+ and 6^+.

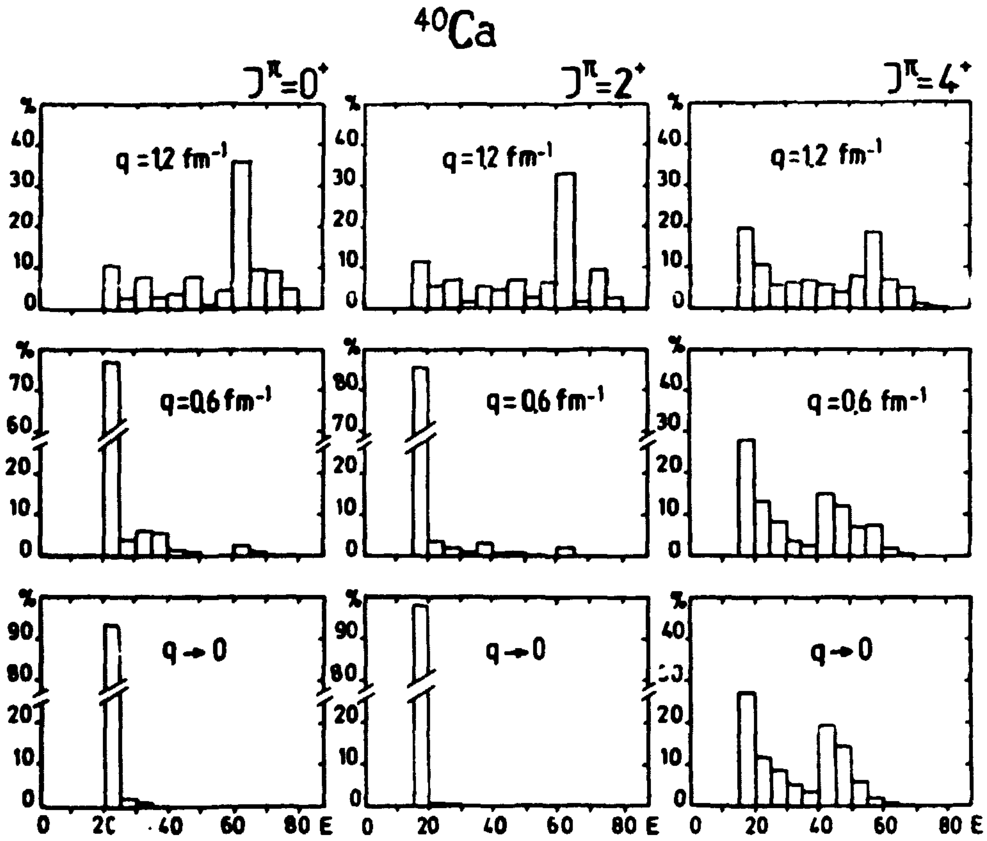

Fig. 2 - RPA response to $j_J(qr)$ operator for q = 0, 0.6, and 1.2 fm^{-1} is grouped in energy binds of 5 MeV. The height of columns represents percent of $m_I(q)$. $J^\pi = 0^+$, 2^+, and 4^+ are shown.

However more strikingly, depending on the excitation operator and, in particular, on momentum transfer, the low multipolarities shift the strength toward the same region of energies. On the other hand, for these excitations lying between 40 and 60 MeV, the strength never exceeds 20% of the sum rule, and as emphasized in Fig. 3, it is widely spread. Consequently, in view of the present results one cannot really attribute a collective nature to such excitations.

S.A. Fayans et al. /9/ have studied the strength distribution of high multipolarity excitations in the continuum for the two external fields $j_J(qr) Y_{JM}(\Omega)$ and $\partial U/\partial r$ ($U(r)$ the self-consistent field) using a finite Woods-Saxon potential. Their conclusion is very similar at least when they use the field $j_J(qr) Y_{JM}(\Omega)$. The distributions of strength shift to high energy around 50 MeV at q = 1 fm^{-1} and they predict some structures for multipolarities $J < 6$. As for the field $\partial U/\partial r$, the essential difference with $j_J(qr) Y_{JM}(\Omega)$ concerns the high multipolarities $J > 6$ whose distributions shift rapidly to much higher energy.

Finally, the same discussion applies to the strength distributions of the ^{208}Pb. Again one observes that all multipolarities shift around $\sim$ 50 MeV for q = 1.2 fm^{-1} (see Fig. 4).

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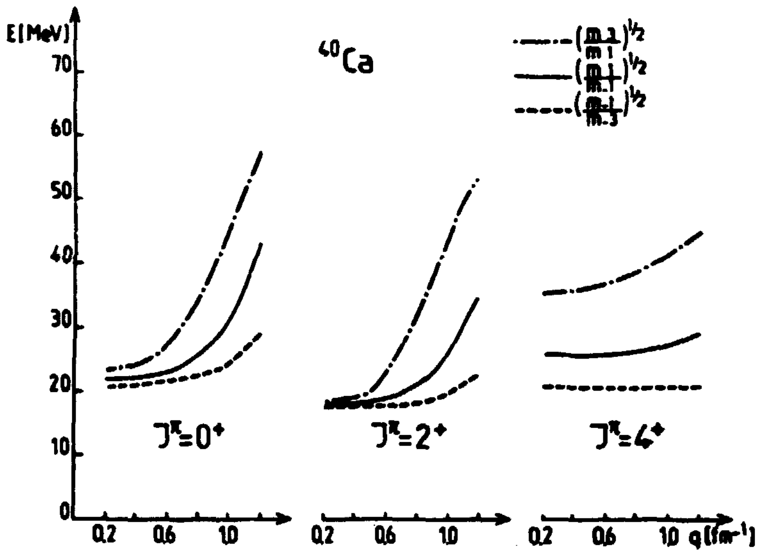


Fig. 3. - Three different prescriptions for the centroid energy as a function of q are drawn. $(m_3/m_1)^{1/2}$, $(m_1/m_{-1})^{1/2}$, and $(m_{-1}/m_{-3})^{1/2}$ are represented by dash-dotted lines, full lines, and dashed lines, respectively.

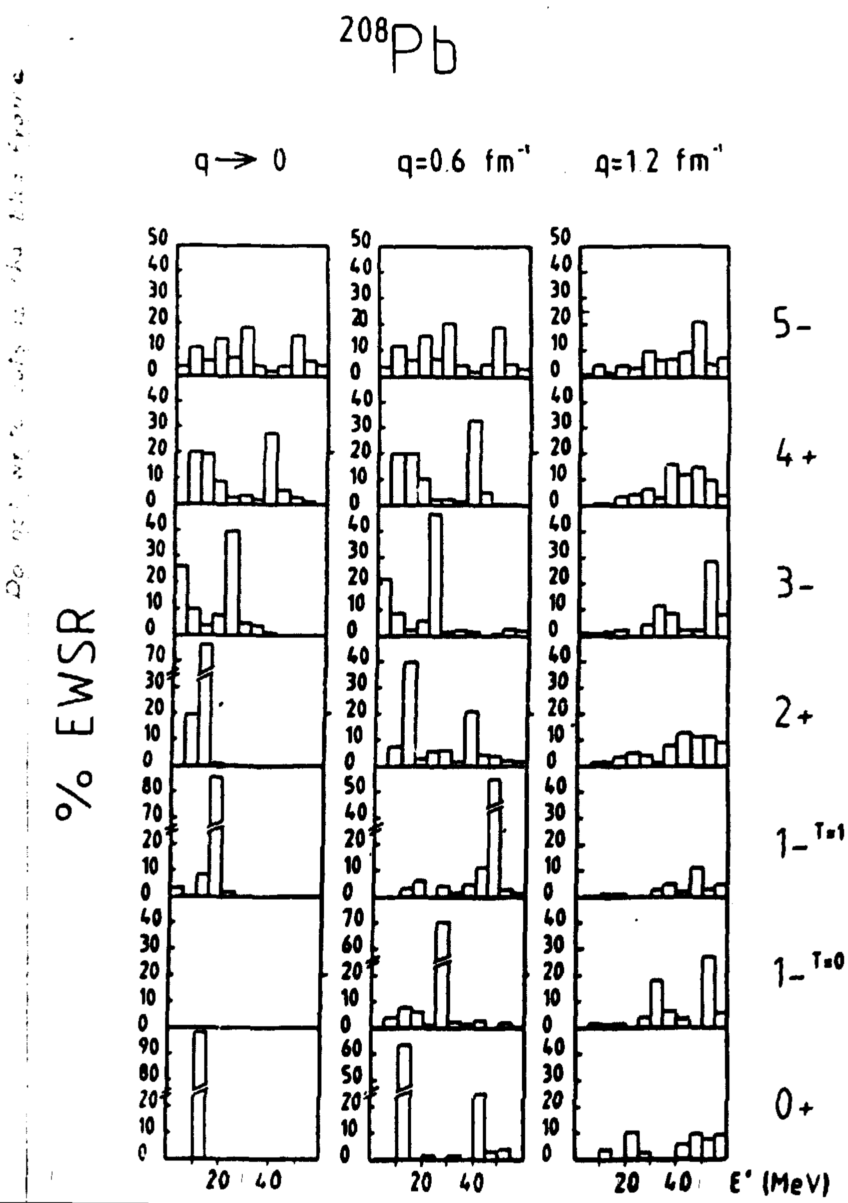


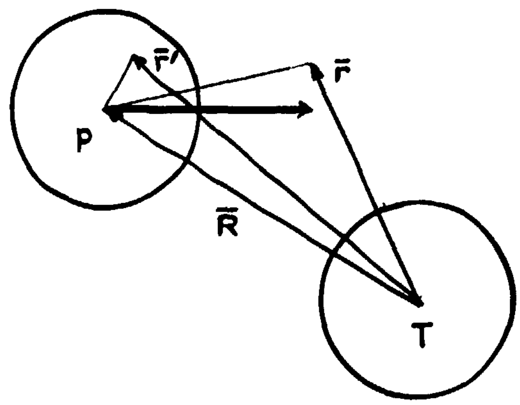
Fig. 4. - RPA response to $j_J(qr)$ operator for q = 0, 0.6, and 1.2 fm^{-1} is grouped in energy bins of 5 MeV. The height of columns represents percent of $m_1(q)$. $J^\pi = 0^+$, 2^+, and 4^+ are shown.

II - SOME THOUGHTS ON THE HIGH ENERGY STRUCTURES OBSERVED IN HEAVY ION COLLISIONS

The strength distributions previously discussed reveal that the structures above 50 MeV can hardly be associated with free or coherent particle-hole transitions. Even for those structures located between 40 and 50 MeV, it is not obvious that the effective field arising in the collision would not differ appreciably from those considered here. Consequently, to pursue the investigation one has to study in more detail the processus during the collision, taking into account the experimental conditions.

In Frascaria's experiment, one can first assume that the two colliding nuclei keep their identity throughout the collision. Evidently, this is possible only if the overlap of the two densities is small or, equivalently, if the impact parameter is large enough. This excludes, in particular, central collisions. Such an assumption allows one to treat the relative coordinate between the two fragments as a well defined dynamical variable. On the other hand, according to the experimental evidence already mentioned in the introduction, the projectile remains in its ground state so that the only other degrees of freedom to be considered are those associated with the excitations of the target. After having singled out a small number of variables one has to define explicitly the interaction between the two colliding nuclei. For each separation distance " R " between the fragments, this can be achieved by calculating the interaction energy of the fields produced by the corresponding densities $\rho^{P}(r)$ and $\rho^{T}(r',t)$

$$\mathcal{V}(R) = \int \rho_0^{P}(r)\ \mathcal{V}(r-r'-R)\,\rho^{T}(r',t)\,dr\,dr'$$



Here $\rho_0^{P}(r)$ and $\rho^{T}(r',t)$ denote the density of the projectile in its ground state and the target density, respectively. Now, since ^{40}Ca and ^{208}Pb are known to be rigid nuclei against deformations, it is reasonable to admit that the excitations of the target are induced by density fluctuations of small amplitude around the equilibrium density $\rho_0^{T}(r)$. This assumption leads to the following decomposition of $\mathcal{V}(R)$

$$\mathcal{V}(R) = \mathcal{V}_0(R) + \sum_N F_N(R)\,\theta_N^{+} + F_N^{*}(R)\,\theta_N$$

where the second term describes the coupling of the relative motion to the phonon excitations of the target. If the operators θ_N^{+} are identified with the creation operators corresponding to the R.P.A. states, the quantity $F_N(R)$ can be written in the form :

$$F_N(R) = \int \rho^{0}(r)\,\mathcal{V}(r-r'-R)\,\rho^{N}(r')\,dr'\,dr$$

where $\rho^N(r')$ is the R.P.A. transition density. In other more phenomenological approaches, this coupling term is replaced by the derivative of the self consistent field with respect to some collective variable characterizing the density oscillations.

With all these simplifying assumptions, the description of the collision is relatively simple, since one has only to study the response of the target to the external field produced by the projectile considered here as an inert composite particle. However, one should keep in mind that this model is unreliable for central collisions and more generally for all situations corresponding to an impact parameter less than the grazing one. As a consequence a quantum mechanical estimate of the response function as provided by the plane wave Born approximation is no longer possible in the present context.

In order to extract simply information on the response function, one may treat classically the relative motion of the ions. If the energy lost by the incident fragment is not exceedingly large, this approximation should be reasonable. In fact, the De Broglie wave length corresponding to the motion of the incident ion is relatively small ($\simeq$. 2 fm^{-1}) for all experiments in question. In the classical approach, the quantities $F_N(R(t))$ become functions of the classical trajectory, which allows one to find an exact solution of the time dependent Schrödinger equation. With the model Hamiltonian adopted here, the Schrödinger equation takes the simple form

$$i\hbar \frac{\partial \Psi(t)}{\partial t} = \sum \hbar\omega_N \theta_N^+ \theta_N + \sum F_N(R(t))\,\theta_N^+ + h.c. \qquad (1)$$

where $F_N(R(t))$ is evaluated for the trajectory given by the classical equation of motion

$$M\ddot{R} = -\bar{\nabla} V_0(R) + \sum \bar{\nabla} F_N(R) \langle \Psi | \theta^+ | \Psi \rangle + h.c. \qquad (2)$$

The solution of equation (1) is straightforward if one recalls a well known property of the coherent states

$$\Psi(t) = e^{-\sum_N \alpha_N(t)\theta_N^+ - \alpha_N^*(t)\,\theta_N} |0\rangle \qquad (\theta|0\rangle = 0)$$

which are frequently used in field theory. Such a state is the vacuum of the boson operators $\xi_N = \theta_N + \alpha_N$. Using this property, it is found that a coherent state is a solution of the time-dependent Schrödinger equation provided that the coefficients $\alpha_N(t)$ satisfy a simple first-order differential equation. We give here only the result :

$$\alpha_N(t) = -i e^{-i\omega_N t} \int_{-\infty}^{t} e^{+i\omega_N \tau} F_N(R(\tau))\, d\tau$$

Note that the right-hand side of equation (2) can be explicitly written using the relation : $\langle \Psi | \theta_N | \Psi \rangle = -\alpha_N$. Thus, once we know the classical trajectory, the complete wave function characterizing the time evolution of the target is well defined. In particular, the probability of finding, after the collision, the target with a given number of phonons excited is a Poisson distribution. This model is a simple version of the more complete approach defined by R.A. Broglia and collaborators /12/. H. Tricoire et al. /13/ have developped, in the same spirit, a model which can deal with large-amplitude collective vibrations of the fragments.

Such a simple picture of the reaction should allow one to find out whether the regularly spaced structures can be attributed to multiphonon excitations of the type 2^+, 3^-, 4^+ observed in ^{40}Ca or ^{208}Pb at energies near 20 MeV. P. Chomaz and D. Vautherin are using such a picture to study the distributions in final energy of relative motion in the reaction ^{36}Au + ^{208}Pb. One may refer to the contribution of N. Frascaria et al. at this conference which is entitled "Evidence for structures in the ^{36}Au + ^{208}Pb inelastic scattering and few nucleon transfer reactions at 11 MeV/n" for further details. Indeed, it is a great temptation to identify the energy spectrum of the Ar with a Poisson distribution. The question remains whether the simple multiphonon approach presented above would be able to reproduce the trend of this distribution.

III - CONCLUSION

In conclusion, several studies on the response of the nucleus, using external fields of different nature tell us that some structures still persist at high energy (40-50 MeV) for all multipolarities up to L = 6. As the multipolarities increase beyond L = 6, the strength distributions become structureless. They also reveal that the trend of the response depends crucially on the momentum transfer and, consequently, on the radial dependence of the external fields. Furthermore, since the strength spreads widely with increasing momentum transfer, one cannot attribute to these high energy structures a collective character. Finally, for the structures at higher energy one has to invoke many particles - many holes transitions. The simple multiphonon model could be a good starting approach to study these more complex excitations.

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