Science and Art in Heavy Ion Collisions

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One of the more intriguing phenomena discovered in heavy-ion physics is the seeming appearance of high energy structure in the excitation spectra of inelastically scattered heavy ions. For reasons to be illustrated below, these may well be a phenomena unique to heavy ions and their explanation perhaps unique to TDHF.

The calculations which I will subsequently describe were motivated by the experiments of Nimet Frascaria(1) and her group at Orsay. Figure 1 shows the energy spectra of specific fragments from the collision of 400 MeV laboratory energy ^{40}Ca incident upon ^{40}Ca. Figure 1a displays the spectra for ^{36}Ar. The apparent independence of the excitation spectra over a range of scattering angles lend credence to the observed structure being "giant resonance like" in their origin. This interpretation is supported in Fig. 1b where the spectra of

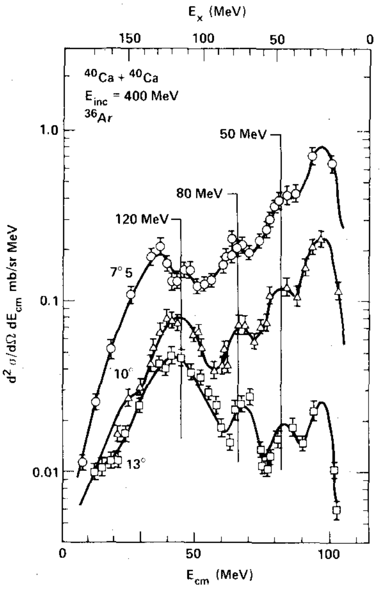

Fig. 1a

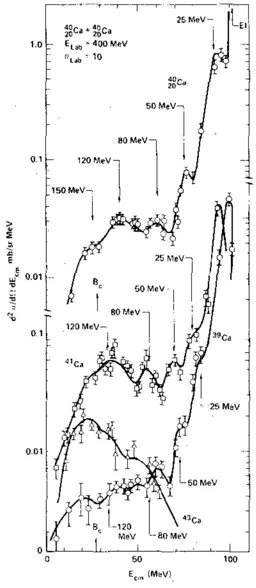

Fig. 1b

several species at fixed angle are displayed. A laboratory scattering angle of 10° corresponds (for this system) to a peripheral collision. The experiment was also performed for a more central scattering angle (and correspondingly more inelastic collision) and the excitation spectra remained unaltered in energy but the "peaks" were reduced in size by an order of magnitude.

Besides being beaten on by the experimenters, Flocard and I were motivated to explore this phenomena by the work of Van Gai$^{(2)}$ who argued that there could not be giant resonances above 40 MeV. His position was based upon the finiteness of the shell model potential with the consequence that there could not be any <u>collective</u> strength at high energy. His argument is very convincing because it is so simple.

Our approach was to model the experimental situation in TDHF.$^{(3)}$ After choosing the initial conditions to duplicate the experimental incident energy and final scattering angle, the calculation was terminated with the fragments well separated and therefore interacting only through a central Coulomb potential. The calculation was then re-started in a frame fixed on the center of mass of one of the fragments which was then allowed to evolve in time while the cartesian moments of the (ordinary) density were computed and stored. The buzz words to describe this calculation are symmetric fully three dimensional TDHF with BKN Force in coordinate space with 4N symmetry and the details and references are available.$^{(4)}$ The calculation was repeated for a more central collision and Table 1 shows the results for both collisions. Figure 2 displays the density

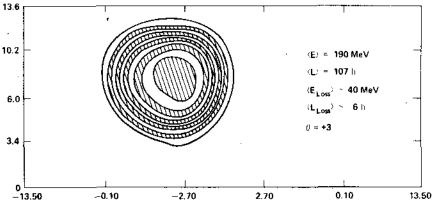

Fig. 2

contours projected onto the reaction plane for an isolated fragment. Table 1 shows the initial angular momentum transfer and energy loss for both fragments, and the centre of mass scattering angle for the two cases run. $L_{\text{initial}} = 107h$ is the more peripheral collision and corresponds to the experiment.

Our procedure was to Fourier transform the Cartesian moments of the density and look at the spectrum. Figure 3 displays the rms radius of the system for the $2 \cdot 10^{-21}$ sec it was followed. That such a system might have a rich Fourier spectrum is confirmed in Fig. 4 which displays the Fourier transform of $\int d^3r\, y^2 \rho(r,t)$. Note the change in scale by a factor of 10 at 20 MeV and again at 40 MeV. While the observed spectra are too broad to isolate which are harmonics and which are primitive vibrations, the fact is there are excitations at high energy. Figure 5 shows spectra for a variety of moments which again exhibit high

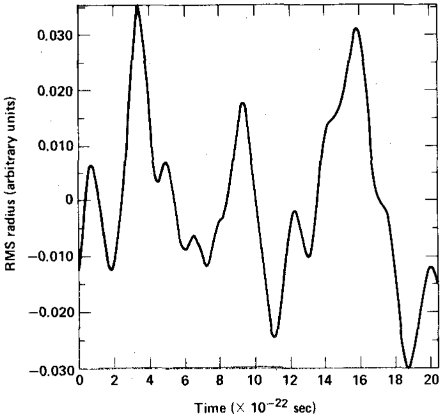

Figure 3

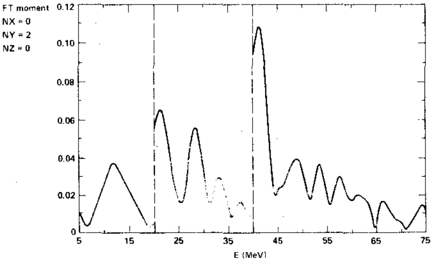

Figure 4

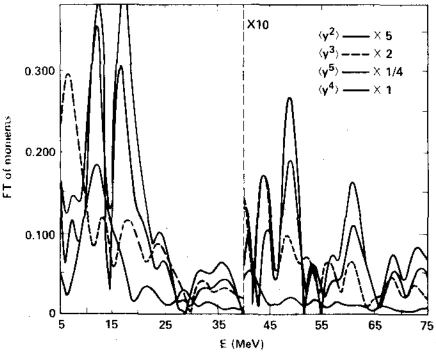

Figure 5

energy (more properly, high frequency) motion. While we have not shown that the observed structure is the one seen in our calculation, it is supportive that the TDHF calculation exhibits high energy peaks and when the calculation is repeated at a more central collision ($L = 97\hbar$), the Fourier spectrum remains but the amplitude of the high energy peaks goes down on order of magnitude, mimiking experiment.

Before proceeding I would like to remind you of the viewpoint of an American sage:

"There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.

Mark Twain in "Old Times on the Mississippi"

Because up till now I have retold what I know and I will now spend a few minutes on plans and speculations.

Either Frascaria is wrong or we are dealing with a very interesting and new phenomena. Narrow resonances (if that is not a tautology) at 50 MeV and above would be intensely interesting even if they were "simple" giant resonances. If one accepts Van Gai's argument that they are not, one must conclude they must be a different and perhaps new type of state. Let us attempt to delineate the possibilities:

(a) They represent the appearance of some new symmetry (but I can't produce a candidate).

(b) They represent giant resonance built upon giant resonances. That is, the heavy ion collision having excited the target or projectile, to say, the dipole state

$$|\Psi_D\rangle = D|0\rangle$$

Then proceeds to build, say, a quadrupole state upon it

$$|\Psi_{Qd}\rangle = Q|\Psi_D\rangle$$

etc. These are not "true" multi-boson states because of blocking and changes in the size of the mean field, but approximately, the energy of the observed state would be the sum of its constitutents

$$E_{OBS} = \sum_{i=1}^{N} E_{GRi}$$

and the probability of formation

$$P_{OBS} = \sum_{i=1}^{N} P_{GRi} \text{ ,}$$

the product of probabilities for excitation of the individual resonances. This picture and the data are sufficiently imprecise that the measurements are not inconsistent with this idea. In this model, these states would be improbably seen in other than heavy ion reactions because it necessitates the sequential application of one body operators.

(c) The observed states are "true" multiple particle-hole states,

$$|\Psi_{obs}\rangle = \sum_{ijk\ell} \alpha_{ijk\ell}\, a_i^{+} a_j^{+} a_k\, a_\ell |0\rangle + \sum_{ijk\ell mn} \beta_{ijk\ell mn}\, a_i^{+} \cdots\cdots$$

which can be excited only by "true" many body operators, not products of single particle operators. These would truly be unique to heavy ion physics because only a heavy ion will behave as a many body operator.

(d) Lastly, the states are large amplitude semi-classical motion.

Clearly spectulations (b), (c) and (d) are not independent in the sense that linear combinations of the (a) can make the (c) and (d), etc. but in the sense of which is the leading of principal term the descriptions are quite disparate.

Within the context of Mark Twain's admonition, there is one preliminary datum[5] which can be used either to support hypothesis (b) and (c) or discredit the entire picture. Figure 6 shows the proton spectrum in coincidence with the

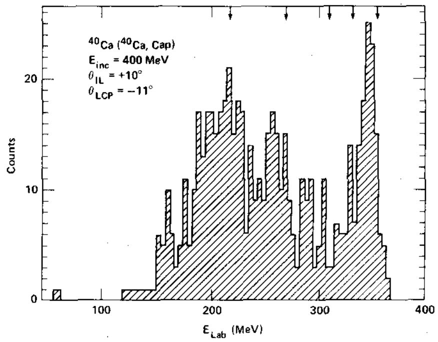

Figure 6

peaks in the spectra of the heavy ion excitation. The detected protons have an energy of approximately 10 MeV corresponding to prompt emmision from a low-lying particle-hole pair. This would support the idea of a giant resonance decay. However, the observed energy <u>also</u> corresponds to the beam velocity which is not obviously in any of the pictures we have described. Clearly one must await the results at other incident energies.

TDHF provides us with a unique tool to attempt to discriminate among these choices or perhaps even rule them out.

By repeating the previous calculation in which the density was evolved and its Cartesian moments calculated, we could instead calculate

$$I(r,L,M,z) = \int_{|\vec{r}|=r} d\Omega\, Y_{LM}(\hat{\Omega})\, \rho(\vec{r})$$

and Fourier analyze I. This will tell us where in r and what in (L,M) the Fourier spectra observed in our previous (Cartesian) calculation originated. An alternative is to project the TDHF wave function over a giant resonance and Fourier analyze the resultant form factor.

A somewhat more ambitious program that will delineate among some of the options would involve replacing the TDHF <u>collision</u> calculation by the same trajectory for the Hartree-Fock potential of the projectile.

This would approximate the collisions by an external potential acting on the target (see Fig. 7). Gogny[6] and collaborators has examined the RPA spectra as a function of momentum transfer for a calculation in which the usual radial moments of the electric multipole operators are replaced by $j_L(qr)$. While his procedures are controversial, he does find high energy spectra for $q \sim 1$ fm. While his choice of $j_L(qr)$ as the heavy ion operator is probably idiosyncratic, the conclusion is that a sufficiently complicated radial operator will produce a high energy spectra. Van Gai's[2] calculation is only for normal electric multipoles. Hence calculating the "correct" potential form factors in this way would test hypothesis (6) and extract the appropriate input for a more realistic RPA calculation. The fixed external potential of the projectile would act as a sequential single body operator. The comparison between the results of this external potential and the full TDHF response of the two interacting heavy ions would delineate the many body operator component, testing hypothesis (c). One can expect a variety of these ideas to be explored by various linear combinations of people at Orsay and Livermore certainly in time for the next TDHF meeting.

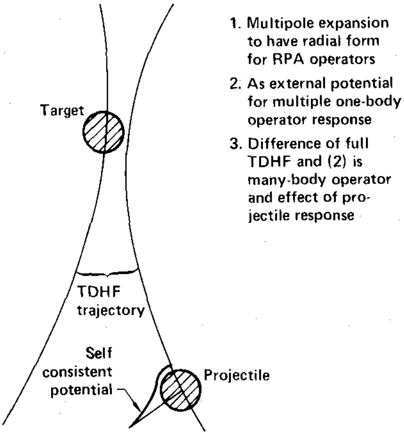

Figure 7

Now switching topics to a more artistic application of TDHF I would like to show you a color movie of the scattering of ^{86}Kr + ^{139}La at E_{lab} = 505 MeV. The calculation used the Skyrme III force in the frozen[7] and filling[8] approximation in three dimensions by an amalgam of workers.[9] Table II summarizes the results for the 13 impact parameters studied and Fig. 8 shows the requisite

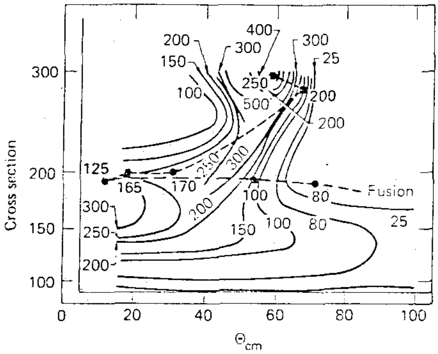

Figure 8

juxtaposition of calculation and experimental[10] Wilshinski plot. The calculated fusion cross section and deeply inelastic cross section agree with experiment.[10] The movie was prepared by the LLNL Computer Graphics Group's Nelson Max.

Acknowledgment

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TABLE I

L/h	$\frac{\Delta L}{h}$	ΔE MeV	θ_{cM} deg
97	10	60	-6
107	6	40	+3

TABLE II

L	E_{final}	θ_f	t interacting 10^{-22}sec.	Z_{LF}
0	198	180	44.8	34.3
5	fused		>44.5	
10			>44.5	
25			>44.5	
50			>54.5	
60			>44.5	
80	199	70	34.2	34.3
100	200	52	32.0	33.9
125	201	-7	38.7	34.4
165	207	14	21.6	34.6
170	210	28	18.4	34.6
200	284	66	3.2	36.0
250	294	57	0	36.0
∞	311			

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