CONF-880896--6

DE89 004272

Concluding Remarks

presented

at the

Symposium on Heavy Ion Reaction

Dynamics on the Tandem Energy Region

Hitachi, Japan

August 1-3, 1988

R. R. Betts

Physics Division

Argonne National Laboratory

Argonne, Illinois 60439, U.S.A.

Concluding Remarks

R. R. Betts
Physics Division
Argonne National Laboratory
Argonne, Illinois 60439, U.S.A.

The title of this conference "Heavy Ion Reaction Dynamics in the Tandem Energy Region" implies the study of reactions in an energy region in which reaction mechanism and nuclear structure are intimately connected. This lesson, although advertised from the earliest days of heavy ion reaction studies, is only now beginning to be understood in detail. Not too long ago, it was common to see figures such as that shown in the upper portion of Fig. 1, in which the aim was to place the different aspects of heavy ion

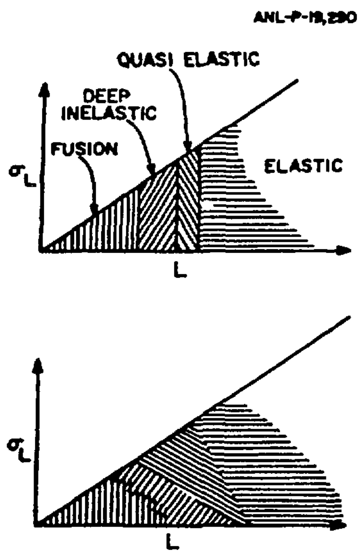

Fig. 1. Schematic illustration of the divisions between various reaction processes. The upper portion shows the old sharp divisions, the lower the more recent view.

reactions into distinct categories each of which corresponded to a specific range of impact parameters and thus angular momenta. We have learned in the transition from the MACROSCOPIC to MICROSCOPIC understanding of these reactions that such divisions are in many ways artificial. The experimental and theoretical boundaries between these categories are diffuse rather than sharp, and it is the structure of the system which in many ways moderates these divisions.

The detailed and microscopic studies presented and discussed at this conference are the result of experiments carried out with many of the new generation of large tandems and linacs which, with their near ideal beam quality, allow precise and detailed studies of heavy ion reactions. Equally important in this are the new and sophisticated pieces of apparatus such as magnetic spectrometers, recoil separators, gamma ray and charged particle arrays.

At the lowest energies and at the largest distances of closest approach, we expect heavy-ion interactions to be at their simplest, with only Coulomb excitation and transfer reactions being important. In such cases, by careful variation of scattering angle and beam energy it is possible to envisage the situation of two nuclei at their distance of closest approach being analogous to that of a junction between two solids. The parallel has been drawn[1] in which the reaction Q-value plays the role of the voltage across the junction and an effect such as the shift in the effective Q-value of a transition is analogous to the contact potential between two solids. It is therefore appealing to search for effects such as Josephson tunneling in nuclear collisions. It is important to realize, however, that there are fundamental differences between the nuclear and solid-state cases as illustrated in Fig. 2. This figure shows the effect of the finite size of the nucleus on the spectrum of a

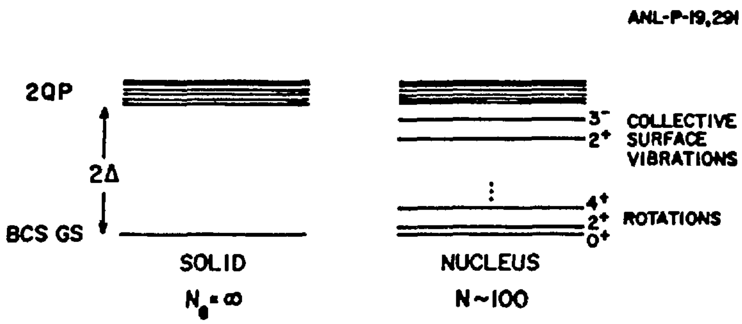

Fig. 2. Spectrum of an infinite superconductor (left) contrasted with the spectrum of a finite system showing the collective surface excitations in the gap.

superconductor. This finite size implies a surface, which then allows for rotations and surface vibrations of the system, which are likely to give the nuclear case a richness and complexity far beyond the solid-state case. Already we see that our understanding of the transfer of nucleons in this large distance regime is rather deficient. The dependence of the transfer probability on the distance of closest approach is seen[2,3] in many cases to be very different from the behavior expected from the fall off of the wavefunction of the transferred particle(s) as is shown schematically in Fig. 3. The variety of

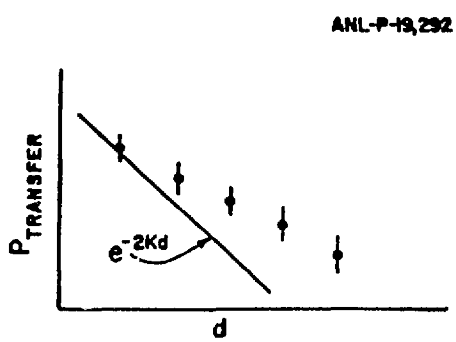

Fig. 3. Transfer probability of neutrons shown plotted as a function of distance of closest approach. The curve is the expectation based on a semi-classical model. K is the wave number of the transferred particle. The deviation of the data from this curve is the so-called "slope anomaly".

the occurrence of this phenomenon and the lack of any explanation already tells us our understanding of reactions at large distances leaves much to be desired.

In the vicinity of the barrier we see the full complexity brought about by the coupling between the elastic, inelastic, transfer and fusion channels which is most dramatically manifest in the enhancement of the sub-barrier fusion of heavy ions over the predictions of models based on penetration of the one-dimensional potential, shown in Fig. 4. The full force of

ANL-P-19,293

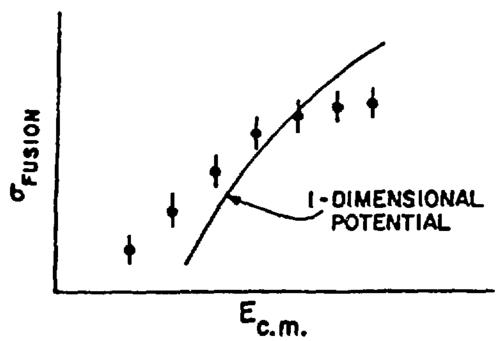

Fig. 4. Cross-section for heavy-ion fusion near the interaction barrier. The curve is typical of the calculated fusion using a one-dimensional potential. The low energy data are enhanced over this prediction.

coupled channels theory has been brought to bear on this problem, which is a quite general one appearing in many other areas of physics in which quantum tunneling is important. The classic case study presented[4,5] at this meeting is that of $^{16}O+^{208}Pb$ in which we saw the most complete set of data and calculations which are generally in excellent agreement with one another. An important result emerges from this work. Namely, the connection between the real and imaginary parts of the scattering potential through a dispersion relation, and the consequent appearance of a polarization potential which must be added to the real potential whenever new reaction channels are opening.

Despite this good understanding of many features of the data there are outstanding discrepancies. The most notable of these is the disagreement[6] between measured and calculated compound nucleus spin distributions as shown in Fig. 5. The best coupled channels calculations consistently underpredict

ANL-P-19,294

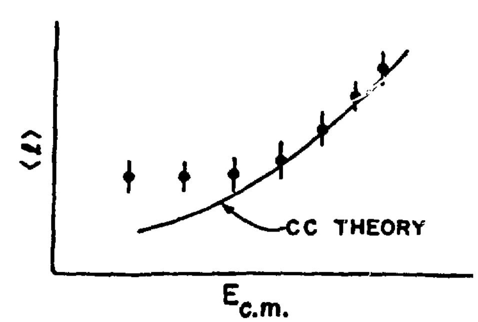

Fig. 5. Measured mean spin in the compound nucleus shown as a function of energy. The curve shows the underprediction at low energies typical of the results of coupled-channels calculations.

the measured values of the average compound nucleus spin. This discrepancy needs to be resolved and comparison needs to be made between experiment and theory for other moments of the spin distribution if these can be experimentally determined.

A question which arises from this discussion, is exactly how far it is possible to go with these coupled channel and related treatments. The couplings are not particularly strong for systems such as $^{16}O+^{208}Pb$ - what happens in the case of well-deformed collective nuclei ? Experimentally, we can envisage data as good as that for the lighter projectiles for much more massive projectiles[7,8] but, given the tremendous theoretical effort needed to treat these systems as well as the experimental effort, perhaps it is possible to agree on a few systems for study on which our efforts can be concentrated.

One problem is already clear in the case of strongly coupled systems. Many of the coupling matrix elements are unknown and are unlikely ever to be experimentally determined. In this case we must resort to nuclear structure models to give us the required information. What then happens when theory and experiment disagree - which of the many tens of parameters in the calculation is at fault ? Perhaps, when the number of couplings is very large it is possible to treat them statistically. What are the expected results from such an approach ? In this vein, another question is to what extent does it make sense to use a basis consisting of the excited states of the colliding and product nuclei and their relative motion in these very complex situations. Approaches in terms of features of the composite system such as Molecular Orbitals[9] or shell effects[10] in the potential energy surface of the colliding ions offer possibilities.

Despite this complexity, simple approaches can work[3,11]. We have seen, as shown in Fig. 6, how a simple parametrization[3] of the cross-sections for quasi-elastic neutron transfer can bring a vast range of data onto the same footing. These careful evaluations of systematic results are extremely important in that it is then the deviations from the overall behavior that show the effects of nuclear structure on the reaction mechanism.

One area of work which has consistently pushed the connection between dynamics and structure to the current state of the art, is that of resonances in heavy ion collisions. As we have heard[12,13], a detailed and consistent picture of experimental energies, spins and in some cases parentage has emerged. The interpretation of these results in terms of the different minima

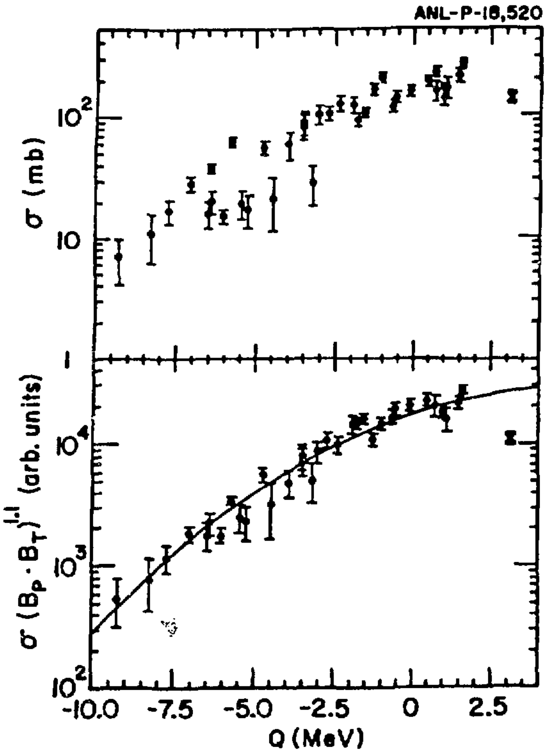

Fig. 6. Systematic behavior of one neutron transfer systematized by plotting versus ground state Q-value and multiplying the measured cross-sections by the factor $(B_P \bullet B_T)^{1.1}$.

of the deformed potential energy surface[14] of the composite nucleus ^{24}Mg as shown in Fig. 7, and the identification[15] of these minima with different

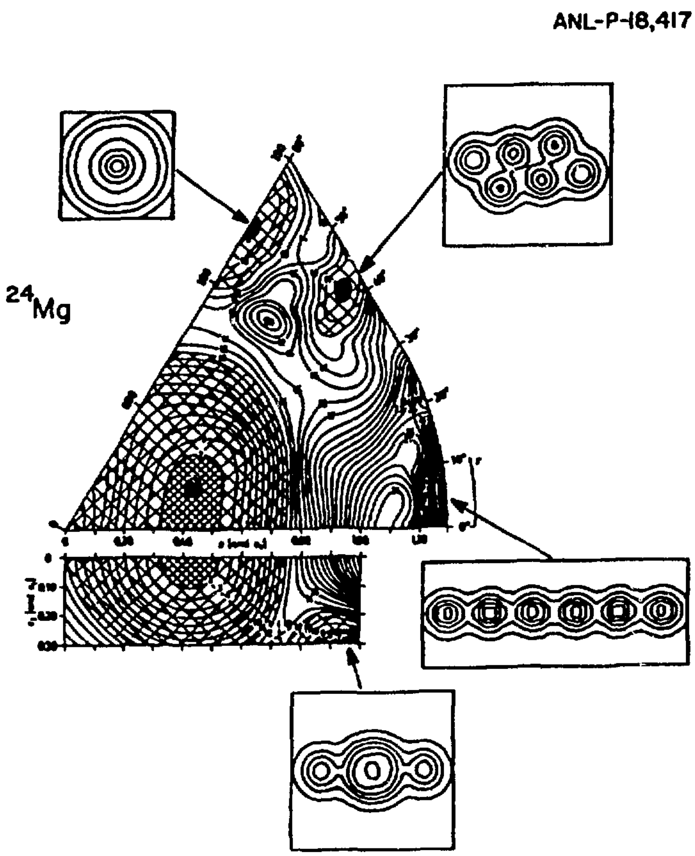

Fig. 7. Potential energy surface for ^{24}Mg calculated using the deformed shell model together with density contours for stable configurations calculated using the cranked cluster model. The correspondences are indicated.

cluster configurations is both appealing and in many ways consistent with the data. The correct inclusion of these structural features with the reaction dynamics is likely to provide, at last, the understanding of this and similar phenomena.

Resonance phenomena in light heavy ion systems indicate that a significant fraction of the total reaction cross-section for these systems is proceeding through a set of states with lifetimes somewhere between that of the equilibrated compound nucleus and the collision time. In much heavier systems, as was discussed[16-18] in the case of quasi-fission reactions, a similar situation holds. Namely, an important reaction process which in many ways looks like the decay of an equilibrated system, but which is not the decay of the idealized compound nucleus. Even in reactions which might be thought to be pure "compound" such as fusion-evaporation reactions, evidence[9,10] has been found in the spectra of neutrons, protons and alpha particles that there is an entrance channel dependence, not expected on the basis of the classical compound nucleus hypothesis. Many features of these sets of data can be interpreted in terms of the decay of systems which are not fully equilibrated - most likely the shape degree of freedom not being completely relaxed. This area opens up many exciting new possibilities for study and will surely see a focus of effort in the future.

Finally, there was discussion of reactions in the higher energy region from 10 to 100 MeV/u. In this energy range, as illustrated in Fig. 8, we

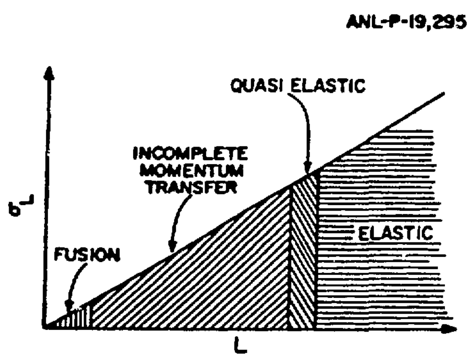

Fig. 8. Division between reaction processes at energies between 10 and 100 MeV/u.

are still trying to categorize the different classes of reaction. It is already clear that reactions under the generic title of "Incomplete Momentum Transfer" dominate the total reaction cross-section. Such processes have appeared under the labels of incomplete fusion, massive transfer, fragmentation, shattering etc. It is not clear to what extent many of these are distinct. Our experience at lower energies tells us that the boundaries between these classes will be diffuse and that it is nuclear structure which will mediate these divisions. At these higher energies, these modes will be different from those at lower energies. The shorter collision times at the higher energies suggest the importance of higher frequency excitations such as giant resonances etc. and this opens up the possibility of studying new and exciting aspects of nuclear structure.

As the last speaker, I have the opportunity of adding a few words of thanks which, although personal, I am sure come from all the participants. I thank Drs. Sugiyama, Iwamoto and Ikezoe for all their efforts which have made this a lively, stimulating and pleasant conference. It is clear there are exciting times ahead at the interface of structure and dynamics which occurs in this energy regime. This research was supported by the U.S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

References

1. W. von Oertzen, these proceedings.
2. R.R. Betts, these proceedings.
3. K.E. Rehm, these proceedings.
4. B.R. Fulton, these proceedings.
5. M.A. Nagarajan, these proceedings.
6. M.L. Halbert, these proceedings.
7. G. Montagnoli, these proceedings.
8. Y. Sugiyama, these proceedings.
9. B. Imanishi, these proceedings.
10. A. Iwamoto, these proceedings.
11. P.R.S. Gomes, these proceedings.
12. A.E. Smith, these proceedings.
13. R.W. Zurmühle, these proceedings.
14. G. Leander and S.G. Larsson, Nucl. Phys. A239, 93 (1975).
15. S. Marsh and W.D.M. Rae, Phys. Lett. B180, 185 (1986).
16. B.B. Back, these proceedings.
17. M. Ogihara, these proceedings.
18. U. Nagame, these proceedings.
19. W. Kühn et al., Phys. Rev. Letters 51, 1858 (1983).
20. R.R. Betts et al., to be published.