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COMMENTS ON THE CURRENT STATUS AND POSSIBLE FUTURE DIRECTIONS OF RESEARCH ON HEAVY-ION INTERACTIONS NEAR THE COULOMB BARRIER*

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COMMENTS ON THE CURRENT STATUS AND POSSIBLE FUTURE DIRECTIONS OF RESEARCH ON HEAVY-ION INTERACTIONS NEAR THE COULOMB BARRIER*

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The outstanding characteristic of heavy-ion collisions at these energies is the interplay between several (or perhaps many) channels or degrees of freedom. The couplings between these can result in important multistep contributions to specific reaction channels. At first this would seem to be a disadvantage of working at such energies but, on the contrary, the study of these terms and their interferences can be a rich source of information. (A simple and familiar example of the use of interferences occurs when Coulomb excitation and nuclear interactions compete in inelastic scattering.)

Of course, counting the number of "degrees of freedom" involved in a given situation depends upon the representation chosen. The usual approach to a description of the collision of pairs of heavy ions has been to describe the couplings between the various reaction channels explicitly through sets of coupled equations. Thus we invoke the characteristic degrees of freedom or normal modes of excitation (collective or single particle) of the separated ions; this is appealing because these are the actual channels we can observe experimentally. However, the number of relevant channels can become very large, especially in heavier systems, and their couplings probably conspire so that a simpler and more reliable picture is obtained in terms of the degrees of freedom of the combined system. This I call the macroscopic approach and involves language like "neck formation" and "neutron flow" in the fusion process, for example. There tend to be difficulties involved in projecting out particular final states of the separated nuclei from these models, so this approach is most appropriate for more inclusive types of measurements.

Up until now, we have accumulated a large number of experimental results together with some theoretical analyses.[1] Some of these studies have systematically addressed different aspects of the collision (such as fusion, elastic and inelastic scattering, and transfer reactions) for a given system at a number of energies. More typically, we will

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find these various data for similar, but frustratingly different systems, so they cannot all be put together for a consistent analysis. (I realize that the choice of system is usually determined by the availability of suitable targets, idiosyncracies of detection equipment, and similar practical matters, but I would urge that the effort needed to get around these difficulties would be rewarding. One complete study done well is more revealing than many qualitative or fragmentary studies, and indeed may reveal features that would otherwise be overlooked.)

As will no doubt be evident at this workshop, the variation with bombarding energy of the experimental results is also a critical feature in this energy regime. Again, this entails a greater demand on accelerator time, but the potential rewards make it worthwhile. I need hardly add, too, that the desired data should be precise as well as complete. In these situations, one is often looking for small and subtle effects.

In addition, we may call upon other techniques which can yield further understanding. Studies with polarized beams will be discussed at this meeting. Here I just mention angular correlation measurements such as $(x,x'\gamma)$. These give information on the population of individual magnetic substates, providing a more severe test of theoretical models. The existence of $\sim 4\pi$ γ-detector "balls" has made such measurements feasible to an unprecedented degree.[2)]

Having chastened the experimentalists, I hasten to add that the theorists also have a responsibility to make their models as realistic, and their calculations as complete and precise, as possible! Gross approximations and arbitrary parameter adjustments should be avoided, except perhaps to gain some qualitative guidance. On the other hand, good approximation schemes (such as a careful use of the adiabatic -- also called sudden! -- limits for solving coupled channels problems) are very desirable, and a number of advances have been made in this area (see ref. [3)], for example).

Now that I have got those little homilies out of the way, I turn to comments on some specific areas of research. There are two complementary ways of looking at these phenomena. One is to describe them in great detail via coupled-channels calculations. This has the advantage that it can display explicitly the interplay between various couplings, and it allows one to incorporate directly nuclear structure information (e.g. spectroscopic factors, deformation parameters, etc.) which may be available from independent sources. Such calculations may then have predictive power. Some impressive examples of this approach have appeared[4)] and more are envisaged. They are also very computer intensive. Further, the structure information (essentially coupling strengths) that is needed as input is not always known.

An alternate description is via simple models, such as the optical model, which focus attention on one (or a very few) channels and treat the effects of all others in an average way (e.g. by use of an imaginary potential). These models have adjustable parameters (which, in general, depend upon energy, especially in this energy region), although the models should be constructed to incorporate as much of the relevant physics as possible. If we have been successful in this, the behavior of the resulting parameters extracted by comparison with experimental data should reflect the underlying physics in a simple (and sometimes dramatic) way. A good example of this is the so-called threshold anomaly[1)] in the energy dependence of the (complex) strength of the optical potential for energies in the vicinity of the top of the Coulomb barrier. A very general dispersion relation has been used to correlate the behaviors of the real and imaginary parts. Although there are now many, mostly qualitative, examples (most of which seem to be for ^{16}O projectiles!) of this anomaly for elastic scattering which establish its existence and general features, there is still need for more complete and more precise study to establish its detailed characteristics (for example, can we detect evidence that, as we expect, the radial *shape* of the potential changes with energy, as well as its strength). Further, we need to know whether it can be observed in heavier systems (where good energy resolution is important), or does it get obscured by the strong Coulomb excitation that is present. (Perhaps there is scope for partially inclusive measurements of elastic plus inelastic scattering to low excitations in these cases.) Of course, measurements of elastic scattering alone carry less and less information as one drops to the Coulomb barrier and below, so it is important to supplement them by other observations such as reaction cross sections, fusion data, inelastic scattering (where the Coulomb/nuclear interference remains very important), etc., and to treat these in a coherent manner.

One possibility, scarcely touched on so far, concerns polarization measurements and spin-dependent interactions. It is known that the effective spin-orbit coupling in the optical potential for ions such as $^{6,7}Li$ arises predominantly from virtual excitations; i.e., it has a channel-coupling origin. Hence it should also exhibit a "threshold anomaly." There already is some indication that the importance of these coupling effects depends largely on how far the energy is above the Coulomb barrier.[5)]

The effective couplings for inelastic scattering should also be "anomalous" at energies near the Coulomb barrier (the technique of deforming the optical potential, itself anomalous, to generate the transition potentials already leads us to expect this). So far, there is explicit evidence[1)] only for one transition, excitation of the 3^- in ^{208}Pb by ^{16}O. These data even suggest that the inelastic coupling may be more anomalous than the elastic;

this interesting possibility needs further exploration. There are also indications that there are effects on inelastic scattering which reflect more than a change in strength. Currently these effects have been reproduced[6)] by introducing a strong and energy-dependent reorientation coupling for the excited state. Clearly this does not imply a very large quadrupole moment for that excited state, but somehow is representing the effects of other couplings not presently included in our calculations. It is possible that γ-correlation measurements, which reveal magnetic substate populations, will help to elucidate this problem.

Another area in which strong coupling effects ("multistep amplitudes") have been observed is nucleon transfer reactions. Some progress has been made in understanding these in detail in the case of ^{17}O + ^{208}Pb reactions, where excitation of the weakly bound $1/2^+$ state of ^{17}O plays an important role.[7)] An interesting question here is whether an "optical model" approach is feasible or useful; namely, some simple model for an effective transfer interaction which will incorporate these multistep contributions into an effective one-step one. It is clear that such an effective interaction must involve a change in "shape," not just a change in strength, if it is to be used in the DWBA, because explicit coupled-channels calculations show that angular distributions are changed, as well as cross section magnitudes. Perhaps some early attempts in this direction[8)] need to be revived.

The enhancement of near- and sub-barrier fusion is another aspect of the threshold anomaly phenomena, and should be considered together with observations on other ion-ion processes. This is an area in which many, often extensive, coupled-channels calculations have had some success in reproducing the data and throwing some light on the mechanisms involved. However, these applications have been primarily to collisions with fairly light projectiles or between very asymmetric systems. It is possible that we will be forced to employ more macroscopic models for the heavy systems.

This is also an area in which the optical model approach has been extended, formally and in practice, to include fusion together with elastic scattering, so these two kinds of measurements should be fitted simultaneously.[9)] It has been shown that the imaginary optical potential can be decomposed into a part that describes fusion and a part that describes absorption into other channels. Further, the fusion part can be broken into terms that describe fusion occurring directly from the elastic channel and that which occurs after virtual excitation into more direct channels ("multistep fusion"). The latter are the contributions treated explicitly in the coupled-channels calculations.

A notable feature of fusion studies has been the emergence of the spin distribution $\sigma_F(L)$, where

$$\sigma_F = \sum_L \sigma_F(L),$$

as a critical quantity that any theory of fusion must explain, and more measurements on suitable systems would be very welcome! They provide particularly important constraints on optical model studies. In a sense, the spin distribution is to the total fusion cross section as the elastic angular distribution is to the reaction cross section, although the spin distribution does not contain interference between different partial waves.

It seems to me that the basic questions about sub-barrier fusion that are not fully settled concern "how" and "where." The first, "how," means "which are the important physical processes involved (which are the important channels in the channel-coupling language)?" Much apparent success has attended the use of a few inelastic excitations (these generally being the easiest to include) to low-lying states, especially for rotational nuclei. In some cases, the addition of a few one- or two-nucleon transfers has been shown to be important. (Unfortunately, the relation between cross section and number of channels is nonlinear, so one's perception of the relative importance of different channels can depend upon the order in which they are included!)

The "where" question asks at what separations between two nuclei is fusion initiated. An underlying assumption of early treatments (barrier penetration models) was that the two ions had to fully traverse their mutual Coulomb barrier before fusion occurred. (This single-barrier treatment also yields too narrow spin distributions.) However, optical model studies initiated by Tamura and Udagawa[9] showed that fusion data required the absorption into fusion to occur at radii close to or even beyond the top of the barrier. (At the same time, this naturally results in broader spin distributions, in better agreement with the trend of the measured ones.)

Coupled-channels calculations, on the other hand, still assume that the (now multidimensional) barrier has to be completely penetrated. This implies that the large radii found in the optical model studies reflect the more peripheral multistep contributions that coupled-channels treat explicitly. This view is supported by the finding that, nonetheless, the coupled-channels approach does give the broad spin distributions that seem to be required. Further work is needed to see whether the barrier penetration assumption with coupled-channels is adequate to fully explain any new measurements, or whether perhaps it will become necessary even then to allow fusion to be initiated at larger radii.

Relevant to all of this is the "distribution of barriers" method of describing fusion. Under certain approximations (adiabatic = sudden!), the coupled-channels equations can be transformed to give the fusion cross section as a sum of eigenchannel contributions. Each of these may then be represented by some barrier penetration approximation, with the corresponding eigenchannel barrier. One or more of these eigenbarriers will be lower than the original barrier in the elastic channel and hence enhance the fusion. Stelson[10)] has used this concept in a phenomenological approach to extract empirical distributions of eigenbarriers from a very wide variety of near- and sub-barrier fusion data for projectiles ranging from ^{16}O to ^{64}Ni. Many such barrier distributions are found to be quite flat with a fairly sharp cut-off at some lower "threshold" energy. Stelson finds a remarkable correlation between the threshold energy required and the separation energy of the least-bound neutron in the projectile or target. The threshold energy can be translated into the distance of closest approach on a Rutherford trajectory at that energy. This is found to be close to the distance at which the shell model potentials for projectile and target would overlap sufficiently that the least-bound neutron could "flow" freely from one to the other. These distances are large -- a fermi or more beyond the top of the Coulomb barrier.

These findings suggest that fusion is initiated at relatively large radii by neutron transfer. In more macroscopic terms, one may think of this as the first step in the formation of a neck between the two nuclei. This idea is supported by some supplementary measurements (on ^{50}Ti + ^{93}Nb) at energies below the barrier[11)] which indicate multinucleon (≤ 4) transfer occurring at the same large collision distance as the threshold for fusion of that system. According to this view, collective effects due to surface oscillations only play an important role at even lower energies where the fusion cross section $\lesssim 10$ mb.

Clearly we still have much to learn about fusion!

One final remark, somewhat unrelated to the previous ones, but of interest to me. This concerns the kind of real optical potential appropriate for two nuclei: crudely speaking, deep or shallow? Strong absorption usually obscures (or renders irrelevant!) the answer to this question, except for light systems such as ^{12}C + ^{12}C, ^{12}C + ^{16}O, ^{16}O + ^{16}O, etc. In recent years, the observation of residual rainbow phenomena in their elastic scattering at higher energies has required a local optical potential for these systems to be deep. The relevance of this to energies near or below the Coulomb barrier is the finding that these potentials have just the right depths to support cluster bound states or near-barrier "resonances" with the appropriate (large) number of radial nodes that are required to satisfy Pauli when the system is antisymmetrized. Consequently there is considerable interest in further study and analysis of scattering at these energies to fix resonance parameters, as well as to determine how massive a system can be treated this way (e.g., ^{28}Si + ^{28}Si?).

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