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Presented at the Symposium on "The many Facets of Heavy-Ion Fusion Reactions", Argonne, IL, March 24-26, 1986

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March 1986

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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LBL-21336

Heavy Ion Fusion Reactions in Perspective

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Summary talk for the Symposium on "The Many Facets of Heavy-Ion Fusion Reactions,"

Argonne National Laboratory, 24-26 March 1986

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

HEAVY-ION FUSION REACTIONS IN PERSPECTIVE

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When preparing this summary talk, the most pressing question on my mind was: Why do we need summary talks? Certainly not merely for someone to summarize what has been said in the course of the meeting. Anyone who wants to know that can simply read the proceedings and that will be more accurate and complete. Rather, the summary session is a special period set aside at the end of a meeting for everyone to reflect upon what has happened. If this were a winter meeting, one might call it the aprés ski; perhaps we should call it the Nachspiel. Accordingly, I shall not attempt to summarize, in the narrow sense of the word, with a few kind phrases about every single contribution. Rather, I shall highlight some of the themes that I found particularly stimulating and, where possible, I shall indicate some future directions that seem promising.

This Symposium is devoted to nuclear fusion, so perhaps it is appropriate to start by clarifying what is meant by fusion. For our present purposes, fusion is the process by which a given system changes from a dinuclear configuration to a mononuclear one. In this sense, fusion is the opposite of fission. Accordingly, one can hardly expect to understand one without the other. Fusion and fission are like two sides of the same coin.

One of the fascinating features of fusion, as well as fission, is that the very number and character of the active degrees of freedom change dynamically. In this aspect, fusion is fundamentally different from pure mononuclear dynamics (vibrations) or pure dinuclear dynamics (direct reactions).

The Symposium was organized into five main sessions, plus the current summary session, each concentrating on a particular facet of heavy-ion fusion reactions. Those categories correspond roughly to different intervals of bombarding energy. This appears eminently sensible and I shall adopt the same principle in organizing my remarks.

The evolution of the fusion process was illustrated by the first figure shown by Vick Viola. At low energies fusion is not a typical process, but appears as a mere quantal fluctuation out of an otherwise newly elastic collision process. As the bombarding speed is raised, the interaction barrier can readily be overcome and the nuclei establish close contact. This may lead to a variety of dissipative reactions, including fusion, depending on the specific kinematic conditions. As the bombarding speed is raised still higher, approaching now the nucleonic Fermi speed, the process of "more or less complete fusion" (in the words of Galin) develops into "less complete fusion and more and more incomplete fusion," where an ever smaller part of the lighter nucleus gets caught by its heavier reaction partner. Ultimately, when the available energy becomes comparable to the total binding energy, the system may disassemble into a large number of simple and complex fragments, terminating the evolution from complete fusion through incomplete fusion to "more or less complete confusion."

Sub- and Near-Barrier Fusion

-- of relatively light systems, for which the saddle point lies outside the contact configuration. This is an essentially one-dimensional problem, as long as the system remains outside contact throughout, i.e. the inner turning point must be outside the contact configuration.

Even so, the nuclei are far from structureless, and, in general, the more subthreshold the energy, the more channels must be incorporated. That transfer channels are especially important is suggested by the empirical fact that the observed energy shifts (of the fusion cross section in its dependence on energy) track the Q-values for the nucleon transfer [Beckermann].

However, detailed calculations incorporating the transfer channels explicitly show that transfer is important at generally higher angular momentum than fusion [Rhodes-Brown]. Thus, while the quantitative importance of the transfer channels has been well established, no simple qualitative evidence has yet been found.

If other channels are important in modifying the effective one-dimensional potential barrier, they should also be expected to significantly affect the associated effective inertial mass, which is ordinarily taken simply as the reduced dinuclear mass. No work was reported on this topic, but it would seem an interesting one.

Subbarrier fission is an example of multidimensional barrier penetration. The treatments discussed at this meeting all reduced the problem to a set of coupled one-dimensional problems, one for each specific channel considered. When the number of channels required grows large it suggests that an uneconomical approach is being taken. All good physics is perturbative. The trick is to find the best degrees of freedom for the zero'th order approximation. For heavier systems it would seem natural to introduce an additional macroscopic degree of freedom (in addition to the separation), namely the neck opening between the two fusing nuclides. Perhaps others would be required as well. To what extent a suitable additional degree of freedom can be found for lighter fusing systems has not been well explored yet. But it might be a worthwhile undertaking, in view of the growing complexity of the coupled-channels calculations. In fact, the apparent success of the adiabatic model [Rhodes-Brown] might suggest that a simple collective parametrization might be useful.

With all due respect for the heroic efforts by many, I dare to claim that subbarrier fusion is not yet well understood. For a satisfactory understanding, we must be able, within one and the same model, to account for not only fusion but also quasi-elastic reactions as well. This is a sizeable task and probably one is better off starting small. (An additional motivation for concentrating on light systems is that they are the ones of primary interest in astrophysics.) This is the spirit of the coupled-channels studies by Pönisch, reported by Steve Koonin. Here a number of oxygen-oxygen reactions were considered with the same model, and, so it was claimed, a good agreement with data was obtained. I have meanwhile, bit by bit, obtained possession of the results and am now able to show them so that you need not rely on Steve's word alone. Indeed, the calculation gives a simultaneous reproduction of the quasi-elastic reaction $^{17}O + ^{16}O \rightarrow ^{17}O^{*} + ^{16}O$ and the fusion reactions $^{16,17}O + ^{16}O$. (The figures appear in the published manuscript of Koonin's talk.)

Probing the Spin Distribution of Fusion Products

To advance our understanding of the fusion process, it is necessary to consider not merely the total fusion cross section, but also its dependence of the angular momentum. While the mean spin value is pretty well determined by the γ multiplicity, the fluctuations are better probed by other observables. Particularly sensitive to the spin fluctuations is the fission

fragment angular distribution, and Bob Vandenbosch discussed attempts to employ this tool for measuring the spin distribution of the fusion process. As it turned out, the data indicate that the subbarrier spin distribution is significantly broader than expected. This evidence ought to provide stimulation for intensified theoretical efforts to understand this process.

Limitations to Fusion

Fusion is the most important class of nuclear reactions. If it were not for fusion, we wouldn't be here. But fusion does occur, and composite elements are formed in the stress and the world is saved from being immensely boring. Furthermore, it is by fusion that we may artificially extend the nuclear chart beyond its natural boundaries, towards the very limits of stability near the neutron and proton drip lines and in the transuranium region. The synthesis of new elements has always held a special fascination to scientist and layman alike and Peter Armbruster gave us a view of the present status on the limitations of heavy-element production. We have now reached the point where the main limitation on their detection is the lifetime. Not the lifetime of the new species produced (that can be measured quite adequately) but the lifetime of the physicist performing the experiment: The event rate is so low that months of running time is required for a single event. Fortunately, a single event will often suffice to identify unambiguously a new specie, the ultimate feat in experimental accuracy.

The production of superheavy elements remains an outstanding goal in this field. It has become increasingly clear that the main limitation for their production is of dynamical origin. Traditionally, superheavy elements were thought of as species with $Z \approx 114$ (originally it was actually $Z \approx 126$). The special attraction of superheavy elements is two-fold. One is the practical prospects of having long-lived species considerably heavier than presently known nuclei. This aspect has faded, as improved calculations have steadily reduced the predicted stability of these nuclei. The second aspect is the more intellectual excitement about having nuclei whose stability derives entirely from shell effects, their macroscopic fission barrier being zero. This aspect has gained increased actuality as recent calculations have predicted the existence of shell-stabilized <u>deformed</u> nuclei with $Z \approx 108$. Because of their deformation they may be much easier to produce. One

might say that the island of superheavy species has moved much closer to our shores.

Quasi-Fission Reactions

In reactions between heavy nuclei, it is possible, under suitable kinematic conditions, to form a reaction complex somewhat intermediate between a dinucleus and a mononucleus. This distinct class of reactions, named quasi-fission reactions, is characterized by a complete damping of the relative motion and a substantial, yet incomplete, relaxation of the mass asymmetry. Adriano Gobbi showed us an impressive body of data, including complete angular distributions of the fragments as a function of the mass asymmetry. These data have made it possible to determine a fairly universal relaxation time for the mass asymmetry, $t_A = 5.3 \cdot 10^{-21}$ sec. The fact that this quantity appears to be indifferent to the nuclear temperature is an independent indication that nuclear dynamics is dominated by one-body dissipation.

Most models for dissipative nuclear dynamics have been developed for either mononuclei or dinuclei. The existence of quasi-fission reactions therefore present a special challenge to theory which must now address situations intermediate between those two simple extremes. This undertaking will surely be rewarding in shedding new light on the nuclear dissipative mechanism and the associated relaxation phenomena.

Complex-fragment emission

In the course of the last few years, great developments have occurred in the area of nuclear decay modes. Perhaps the most prominent development is the observation of heavy-fragment emission from both cold and hot nuclei. At zero temperature, spontaneous emission of complex fragments, such as ^{12}C or ^{16}O, has been observed for a number of heavy nuclei. These processes provide a continuous link between elementary radioactivity and spontaneous fission and, indeed, a general model for their description has been developed recently.

At this Symposium, Luciano Moretto reported on a comprehensive study of complex-fragment emission from hot nuclei. These processes are intermediate between ordinary evaporation of simple fragments and compound-nucleus fission. By generalizing ordinary symmetric-fission theory to include the mass-asymmetry degree of freedom, it is possible to account quantitatively

for the observed yields, the determining quantity being the barrier height for a specified mass asymmetry.

The experimental studies of complex-fragment emission has so far been carried out up to temperatures of around 6 MeV. It is of great interest to push the studies towards even higher temperatures, since the liquid-gas phase transition is expected to occur at temperatures of 8-10 MeV and be manifested in multifragmentation. As was noted by Moretto, at such high temperatures uninteresting "spurious" multifragment final states are expected as resulting from sequential complex-fragment emission processes. This background will greatly obscure the possible "genuine" multifragmentation processes and therefore their study is essential for our ability to detect the nuclear liquid-gas phase transition.

Incomplete momentum transfer

An important limitation on the fusion of two nuclei is the relative velocity with which they collide. This facet of heavy-ion fission reactions is reflected in the incomplete momentum transfer to a target nucleus. This class of reactions may be used to study the energy dependence of the dynamics and energy dissipation in nuclear collisions, especially to probe the spectral transition from mean-field dynamics at low energies to dynamics dominated by direct nucleon-nucleon collisions at energies above the Fermi energy.

This topic is in rapid development and we heard a number of contributions about recent progress. As Vick Viola pointed out, the interpretation of the data would be greatly aided if some information could be obtained about the impact parameter. This may be possible through the simultaneous measurement of the light-fragment multiplicity.

On the theoretical side, calculations with precompound models have been quite successful in reproducing the data. However, in order to gain deeper insight into the nuclear dynamics, more microscopic models are needed. The VUU model appears particularly promising.

Models for preequilibrium phenomena

Our ability to model the dynamics of a nuclear reaction at intermediate energies is still in its infancy. A significant step forward has been made by the development of the Vlasov-Ühling-Uhlenbeck model which follows the motion of all the individual nucleons as they interact with the mean field

and each other. Marshall Blann called this the "Cadillac of Models" and the term may be especially appropriate in view of its gas-guzzler appetite for computer time. Betty Tsang showed an example of how this model may be used to improve our understanding of the reaction dynamics.

Rather than riding the Cadillac, Marshall preferred the BMW of models, namely the Boltzmann Master Equation, the "ultimate relaxation machine." In its basic form, it describes the excited nucleus in terms of single-particle excitations which are grouped according to their energy. Such an approach appears well founded if the relaxation time among excitations with similar energy is short in comparison with the relaxation of the energy distribution of the excitations. This situation is expected to be realized, for example, in a moderately excited nucleus where the nucleonic states may be randomized through their energy-conserving interactions with the mean field, before the onset of the energy relaxation effected by direct two-body collisions. More generally, one might expect the assumption to be valid if close-lying nucleonic states couple stronger than states lying far apart in energy. Within the limitations of this basic condition, the BME model is a powerful and flexible tool. As we heard from Marshall, it may be used to calculate, for example, subthreshold pion production (with some success) and high-energy γ rays. On the other hand, phenomena occurring on a time scale shorter than the randomization time can not be addressed with the basic form of the model. However, refinements can be, and have been, added so that more detailed aspects, such as directional effects, can be addressed.

Molecular dynamics

Very instructive results were discussed by Vijay Pandharipande. They were calculated in a microscopic classical model whose parameters were chosen to represent ordinary argon. Central collision were studied for a range of energies, and a spectrum of reaction types were seen, in qualitative correspondence with nuclear reaction data.

This type of approach is very powerful for gaining insight into the reaction dynamics. As was pointed out, however, such calculations do not really simulate nuclei, at least not at this stage.

Explicit dynamical calculations in a microscopic model may be of particular value for the key problem of how to probe the matter properties in experiments on collisions of finite nuclei. This is a central problem which

must be clarified before we can hope to determine the phase structure of nuclear matter.

Closing remarks

As nuclear physicists, we live in a time of peril, as budgetary problems abound, so it is vital to explicitly recognize why our nuclear physics studies are relevant in a wider context. It is important to show, to ourselves and, in particular, to the rest of the world, that our problems are of interest outside the confines of our own field. This point was alluded to by Steve Koonin, who emphasized that subbarrier fusion is not only of interest in itself but also to astrophysicists, who are trying to understand nucleosynthesis in stellar environments. There are a number of other aspects of fusion reactions that are of general importance. They encompass: tunneling of complex systems, or multidimensional barrier penetration; the origin and character of dissipative phenomena in small quantal systems, including the transition from ordered to chaotic nucleonic motion; the occurrence of collective phenomena and the interplay between collective and single-particle degrees of freedom; and the transition from a cohesive liquid-like phase to a gas of nuclear fragments. This list is not complete, and I urge you, as a homework exercise, to expand the list with additional topics.

This Symposium has demonstrated both the variety and the diversity of the field of heavy-ion fusion reactions; it has delineated the present frontiers; and it has provided stimulation for tackling the many exciting new problems that our past progress have revealed.

Acknowledgement

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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