Correlations Between Fission Fragments for 172 MeV $^{20}$Ne + $^{197}$Au:
A Case Study for Incomplete Fusion

E. Duek
Department of Chemistry, State University of New York at Stony Brook,
Stony Brook, New York, USA

L. Kowalski
Department of Physics and Geoscience, Montclair State College,
Upper Montclair, New Jersey, USA

M. Rajagopalan and John M. Alexander
Department of Chemistry, State University of New York at Stony Brook,
Stony Brook, New York, USA

D. Logan
Department of Chemistry, Carnegie-Mellon University,
Pittsburgh, Pennsylvania, USA

M.S. Zisman
Lawrence Berkeley Laboratory, Berkeley, California, USA

Morton Kaplan
Department of Chemistry, Carnegie-Mellon University,
Pittsburgh, Pennsylvania, USA

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Angular and energy correlations have been measured for coincident fission-fragment pairs from the reaction of $^{197}$Au with 8.6 MeV/u $^{20}$Ne. These data have been analyzed to test for fission after incomplete fusion and its admixture with fission generally attributed to the relatively pure compound-nucleus mechanism. A Monte Carlo kinematic simulation program has been written to provide a basis for detailed comparisons of the experimental data to the calculations that employ various mechanistic assumptions. We conclude that incomplete fusion is indeed a prominent precursor to fission even for incident energies of less than 10 MeV/u. Similar data from earlier studies have been reanalyzed and shown to be consistent with this conclusion.

*Nuclear Reactions:* $^{197}$Au ($^{20}$Ne, fission), $E=172$ MeV, measured energy and angular correlations for fission-fragment pairs. Analysis made of these and other similar studies by a Monte Carlo reaction-simulation program.
I. Introduction

One of the earliest debates in the study of heavy-ion reactions concerned the possible existence of a “buckshot mechanism” in which the complex nuclear projectile shatters into smaller particles some of which might be observed in a forward-peaked spray [1]. Zucker's review article in 1960 [2] showed that the bulk of the experimental results available at that time fell into only two categories: (a) few nucleon transfer reactions and (b) complete fusion, and that the proposed buckshot mechanism was not needed as a major reaction class. Shortly thereafter, in the early 1960's two important additional observations were made: (1) Copious numbers of forward-peaked H and He particles were found in reactions such as 10 MeV/u \(^{16}\)O + \(^{209}\)Bi [3]. They were attributed to the breakup of a projectile-like nucleus moving away from the reaction center, often along a quasi elastic trajectory [3]. (2) A new class of multinucleon transfer reactions was observed with large translational energy loss and angular distribution very different from that characteristic of few nucleon transfers [4]. The concept of frictional energy loss was introduced to describe these strongly damped reactions [4].

The great richness of these deeply inelastic reactions (DIR) was brought out much more clearly in the early 1970's [5], and the competition between fusion and DIR became an active field of study. Great attention was placed on systematization of the so-called critical \(l\) value, identified with the mean value of the entrance channel angular momentum that divides fusion reactions with low \(l\) from DIR of larger \(l\) [6]. Just as the systematic pattern of \(l_{\text{crit}}\) values began to fill impressively large graphs and tables [7], the phenomenon of incomplete fusion (or massive transfer) was observed to be important and a potentially serious complication for the interpretation of the apparent values of \(l_{\text{crit}}\) [8]. It is clear that we must re-examine our evidence for complete fusion. If incomplete fusion (or massive transfer) reactions have been heavily mixed with complete fusion reactions, then our inferences of energy and angular momentum deposition in fusion must be correspondingly altered. The discordant overtones of buckshot have been fired back into the front rows of the orchestra [1].

One extensively used test for momentum transfer in nuclear reactions is the angular correlation of fission fragment pairs. The method was first introduced for light-ion reactions [9, 10] and then extensively used by Sikkeland, Viola and others for heavy-ion reactions [11-18]. Measured angular correlation functions for reactions of \(^{12}\)C, \(^{16}\)O, \(^{20}\)Ne etc. with \(^{197}\)Au, \(^{238}\)U, etc. were resolved into two broad groups and generally termed: (a) complete fusion and (b) fission after few nucleon transfer. For the target \(^{238}\)U a large amount of fission after transfer was observed, but for \(^{197}\)Au or \(^{208}\)Bi mostly fusion-fission was reported. Only for incident energies of \(\geq 10\) MeV/u was evidence presented for fission after incomplete fusion [14, 16-18]. The recent observations of incomplete fusion in a number of non-fission reactions, even at lower incident energies, provides an incentive to re-examine the evidence for fission after complete fusion in heavy-ion reactions at \(< 10\) MeV/u [8].

In recent years extensive forward-peaked light charged particle emission has been observed [19-22] in coincidence with fission for reactions induced by 20 MeV/u \(^{16}\)O. Also fission after incomplete momentum transfer has been clearly identified for beams of \(\geq 15\) MeV/u \(^{4}\)He, and strongly suggested for 12 MeV/u \(^{20}\)Ne [16-18]. Reactions induced by 6.5 - 12 MeV/u \(^{32}\)S and \(^{40}\)Ar have been extensively studied by various methods as discussed in the following paper [23].

We chose for this study the reaction 172 MeV \(^{20}\)Ne + \(^{197}\)Au. From the work of [11-13] and [17] we can expect very little fission after few-nucleon transfer, and therefore the details of the “fusion fission” process stand out clearly and can be re-examined. We have magnified the view provided by an angular correlation study in two ways: (a) The measured fission fragment energy correlations have been used along with the angular correlations to provide distributions in linear momentum transfer [19]. (b) Comparisons have been made to a detailed reaction simulation program that employs the Monte Carlo technique. With these added tools we can examine both the mean values and the widths of the angular correlation function and the distribution of linear momentum transfer. Our conclusion is that, contrary to previous views, there is evidence for an extensive admixture of incomplete fusion along with the complete fusion. Many of the experimental data from the literature [11, 12, 17] have also been re-examined and have been shown to be consistent with this conclusion.

II. Experimental Methods and Results

A beam of 172 MeV \(^{20}\)Ne was provided by the Lawrence Berkeley Laboratory Super HILAC. The average beam energy was monitored by a phase probe system (time of flight) which we adopted as our primary standard for energy determination - both for the beam itself and for the calibration of our.