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Four-fragment exit channel in the interaction of 1050 MeV ^{84}Kr with U studied with mica detectors

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The interaction of 1050 MeV, ^{84}Kr ions with natural uranium has been studied with the help of mica track detectors in the 2π configuration. Three "direct" and seven "indirect" events have been observed with four heavy fragments in the exit channel. These events represent a cross section of (16±6) mb for this channel. The correlated tracks of two of the direct events have been used for kinematical analysis. The results indicate a two-step reaction mechanism. In the first step a "quasifission" process takes place which is followed by the sequential fission of at least one of the first step masses.

In the study of heavy-ion reactions, considerable attention has been paid to specifying the characteristics of different reaction modes and investigating the conditions under which a particular mode is dominant (see Refs. 1–3 and references therein). It is generally recognized that the boundaries between different reaction types are not sharp and there could be competition between two or more qualitatively different mechanisms under the given entrance channel conditions (see, e.g., Refs. 4 and 5). Sometimes an intermediate reaction type evolves which explains the transition region in a better way. Thus "quasifission" has become established as an intermediate stage between compound nucleus and deep-inelastic reactions.[6–12] In the reaction $^{84}\text{Kr}+^{238}\text{U}$ at 12.5 MeV/nucleon, we present data on four heavy fragments ($A>30$) in the exit channel, which is consistent with the picture of a quasifission process followed by the sequential fission of at least one of the first step masses. This is borne out by the indication of a large mass transfer in the first step of the reaction, which is a characteristic feature of the quasifission process. In view of the rarity of the quasifission mode for very heavy reacting partners,[12] it is understandably difficult to discern by counter techniques. The glass and mica detectors are ideally suited to study this kind of reaction, since each individual interaction of a given multiplicity is recorded as an isolated event, thereby allowing the reliable estimation of low cross sections.[13] Such detectors have been effectively used for the study of heavy ion interactions as reported previously.[14–20]

The results of our calculations, described below, indicate that the four final masses which produce the observed four correlated tracks in the detector originate from a two-step process. In the first step a large mass transfer takes place from the target to the projectile, accompanied by a large kinetic energy loss. In this step either two or three primary masses are produced. One of these masses undergoes sequential fission, giving rise to a pair of fragments with relative velocity (2.3±0.5) cm/ns, as expected from fission Q-value systematics.[21] The other pair of masses is either directly produced in the first step or is originated from the fast fission of a primary mass, since the relative velocity of this pair lies outside three standard deviations as compared to the empirical value based on the assumption of an equilibrated first-step fragment. The key point in arriving at these conclusions is our ability to derive masses and velocity vectors of the final fragments using the measured three-dimensional coordinates of the correlated tracks produced as a result of a single projectile target collision.[17]

The experiment was performed with a 1050 MeV ^{84}Kr beam of UNILAC, Gesellschaft für Schwerionenforschung (GSI) having a fluence of 2×10^6 ions/cm^2. The target was in the form of UF_4 which was vacuum deposited on ten Muscovite mica sheets and having a thickness of (0.9–1.6) mg/cm^2 with an area of 12.6 cm^2 each. The exposures were made with the beam axis perpendicular to the detector surface.

The uranium layer was removed after exposure and each detector was treated for 10 min (room temperature) in 48% H_2F_2. This time is expected to be long enough to fully etch the tracks formed by the reaction products.[22] The details of the etching techniques are given elsewhere.[23] With the help of measured track lengths and angles, a complete kinematical picture of the process can be reconstructed by using the computer program PRONGY.[17] The essential ingredients of this procedure are a velocity-range relation for different masses (which is specific for a given detector) and the coupled equations for momentum conservation (with an additional constraint of total mass conservation), i.e.,

$$\sum_{i=1}^{N} m_i \mathbf{v}_i(m_i,l_i)=\mathbf{p}_{\text{in}} ,$$

$$\sum_{i=1}^{N} m_i = m_P + m_T , \qquad (1)$$

$$v(m,l)=\sum_{\mu=0}^{2}\sum_{\nu=0}^{4} c_{\mu\nu} m^{\mu} l^{\nu} .$$

In the above equations m_i, v_i, and l_i are the masses, velocities, and observed track lengths of N final fragments, m_P and m_T are the projectile and target mass, respectively, and $\mathbf{p}_{in}$ is the incident momentum. The coefficients $c_{\mu\nu}$ are determined by a calibration procedure which has been discussed in detail in Ref. 17. For the present reaction, the 15 fitted coefficients when used in Eq. (1) reproduce the mean values of seven independent quantities. We analyzed 600 binary events of the reaction under study which yielded the average mass of the projectile and target to be 84.2 u and 238.8 u with a total kinetic energy loss of −2.3 MeV. There were in the same reaction 80 ternary events which were analyzed without the mass conservation constraint, and the average value of total mass was found to be 324 u. Furthermore, 207 binary events produced in the reaction $^{nat}U(n_{th},f)$ were subjected to similar analysis, and the mean values of fission fragment masses and Q value were found to be 103 u, 133 u, and 185 MeV, respectively. A comparison of the resulting mass-dependent velocity range curve was made with the calculation of Benton and Henke,[24] which showed a close agreement between the calibrated and theoretical curves. A number of reasonable variations in this curve were tried. In each case one of the fitted quantities could be improved while the value of some other quantity was seen to disagree somewhat with respect to the expected value. In no case were the four-prong results found to change qualitatively. In this way the possibility of obtaining results which could be artifacts related to the behavior of the velocity-range curve was satisfactorily excluded. Some of the preliminary results for the present reaction obtained with a different set of coefficients were partially reported earlier.[25] A detailed description of the analysis of two-, three-, and four-prong events along with further details of calibration shall be published elsewhere.[26]

By optically scanning the etched detectors, it was found that there are three four-prong events which are apparently consistent with the requirement of momentum conservation (i.e., the angle between any pair of adjacent track projections in the plane of observation is less than 180°). These have been termed "direct" events. Seven events with three correlated tracks were observed in which the momentum conservation could not have been possible unless one fragment had a mass less than 30 u (detector threshold) or it was emitted backwards in the laboratory system (2π-geometry detector). These kind of events have been designated "indirect" four-prong events. They have been included in the calculation of the reaction cross section but are obviously not used for kinematical analysis. It may be mentioned that some of the genuine four-prong events with only two or three registered tracks could remain hidden in the large number of binary and ternary events. Therefore, the cross section calculated as above should be viewed as a lower limit. Using a 10% uncertainty for the measurement of target thickness and target area and a 10% uncertainty for heavy ion dose, we calculate the cross section of the four-particle exit channel to be (16±6) mb. This is to be compared with the classical total reaction cross section of 3929 mb, estimated by using the interaction radius systematics of Wilczynski.[27]

The three-dimensional track parameters of the three direct events were used to extract kinematical quantities with the help of Eqs. (1) using the computer program PRONGY.[17] In the case of one of these events, however, unphysical masses were returned. This result could be attributed to the measurement difficulties, since in the case of this event, one fragment had a very deep track making a very small angle with the direction of the incident beam. This event was rejected for further analysis. In order to ascertain the uncertainties of computed quantities corresponding to the maximum experimental errors in the measurements of lengths and angles (related to the projected length and depth uncertainty of ±1.5 μm and azimutal angle uncertainty of ±3°) the Monte Carlo simulation of each event was performed as follows. The track lengths and angles of a particular event (11 independent quantities) were randomly varied according to the Gaussian distributions centered at the measured values and having standard deviations of $\frac{1}{3}$ of the corresponding maximum experimental errors. Then 600 sets of parameter combinations were chosen arbitrarily from these distributions. The kinematical quantities computed from these 600 sets were represented by Gaussian distributions. The mean values and standard

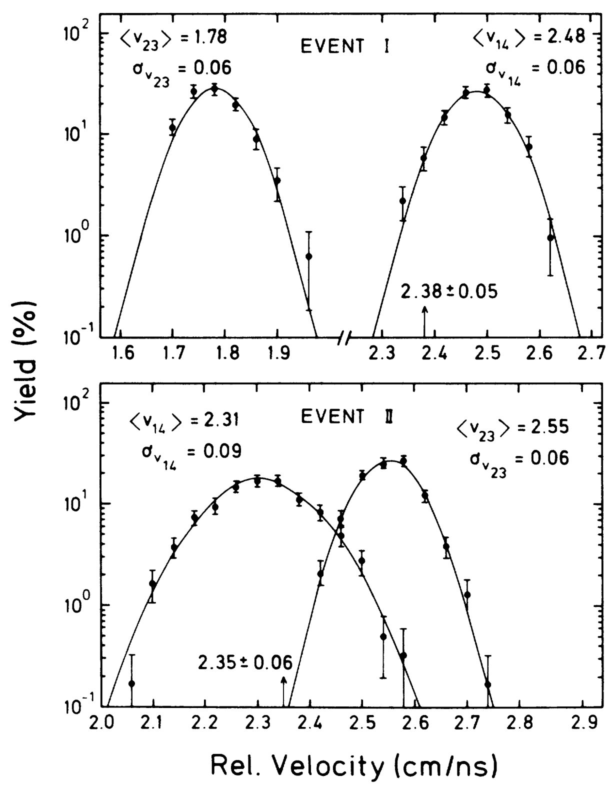

FIG. 1. The Gaussian distributions of relative velocities $v_{23}=|\mathbf{v}_2-\mathbf{v}_3|$ and $v_{14}=|\mathbf{v}_1-\mathbf{v}_4|$ of the complementary pairs of final masses produced in the reaction (1050 MeV) $^{84}Kr+{}^{nat}U \to m_1m_2m_3m_4$. The standard deviations $\sigma_{v_{14}}$ and $\sigma_{v_{23}}$ correspond to the experimental errors alone. Arrows indicate mean values of empirical relative velocities, in the case of pairs arising from sequential fission.

TABLE I. Kinematical quantities derived from the analysis of three-dimensional track parameters in the case of two four-prong events observed in the reaction (1050 MeV) ^{84}Kr+ ^{nat}U.

	Event I			Event II		
First-step masses (u)	(196±5)		(126±5)[a]	(143±7)		(179±7)[a]
First-step kinetic energy Loss (MeV)		(408±20)			(654±10)	
Laboratory scattering angles (deg)	43.9		54.0[a]	44.8		24.5[a]
Final masses (u)	(92±5)+(104±3)		(37±10),(89±6)	(59±8)+(84±4)		(76±4),(103±6)
Fission Q values (MeV)	154.5		40.4[a]	96.1		139.5[a]
Relative velocities (cm/ns)	(2.48±0.06)		(1.78±0.06)	(2.31±0.09)		(2.55±0.06)
Empirical relative velocities[b] (cm/ns)	(2.38±0.05)		(2.5±0.1)	(2.35±0.09)		(2.37±0.06)

[a]These quantities are valid if the second pair also results from a fission process in which the kinematics is distorted by final state interaction.
[b]According to Viola's systematics (Ref. 21).

deviations thus obtained were regarded as the resultant quantities and their experimental uncertainties, respectively. This procedure was performed for both events in order to derive uncertainties of masses, velocities, and kinetic energies of final fragments. The velocity vectors of four final fragments constitute three complementary relative-velocity pairs. For each event, only one relative-velocity pair was chosen as follows. Out of all possible combinations in which the final four masses can be paired, we select those pairs whose relative velocities lie within three standard deviations of the corresponding empirical value (assuming equilibrated fission). Thus the selected pairs are the most probable candidates for being fission fragments. The relative velocities obtained in the case of alternative pairing all lie outside three standard deviations of the respective empirical values. The complementary relative-velocity pairs selected in this way are shown in Fig. 1. It should be noted that the Gaussian distributions of the computed quantities arise because of the Monte Carlo simulation of a single measurement. The standard deviations of these distributions therefore represent pure experimental uncertainties. Also indicated by arrows on these figures are the empirical relative velocities corresponding to the fission of equilibrated first-step masses. The final masses are shown in Fig. 2. In these figures, the pair of masses whose relative velocity agrees within three standard deviations with respect to the mean of empirical relative velocity are marked and the corresponding prefission mass is quoted. The detailed kinematical quantities are given in Table I. The uncertainties in empirical relative velocities correspond to the uncertainties in the mass split. In these results we notice that the first step is characterized by large mass transfer from the heavier to lighter reaction partner (the mass asymmetry is reduced from 0.48 to less than 0.2), along with a kinetic energy loss (KEL) which is 50–80% of the entrance channel center-of-mass energy. This is a very interesting situation and can only be categorized as a mechanism intermediate between a deep inelastic and a fusion process, i.e., a quasifission reaction. It is also evident that one pair of final masses has been produced by sequential fission. However, the origin of the other complementary pair is ambiguous. It is not unlikely that this pair was produced by fission from an unequilibrated first-step mass or else the fission fragments were strongly deviated by the Coulomb field of the other first-step mass.[28] This observation is in contrast to the double-sequential fission noted in the reactions ^{208}Pb+ ^{208}Pb and ^{238}U+^{238}U.[16,20] In view of the small number of events, it is beyond the

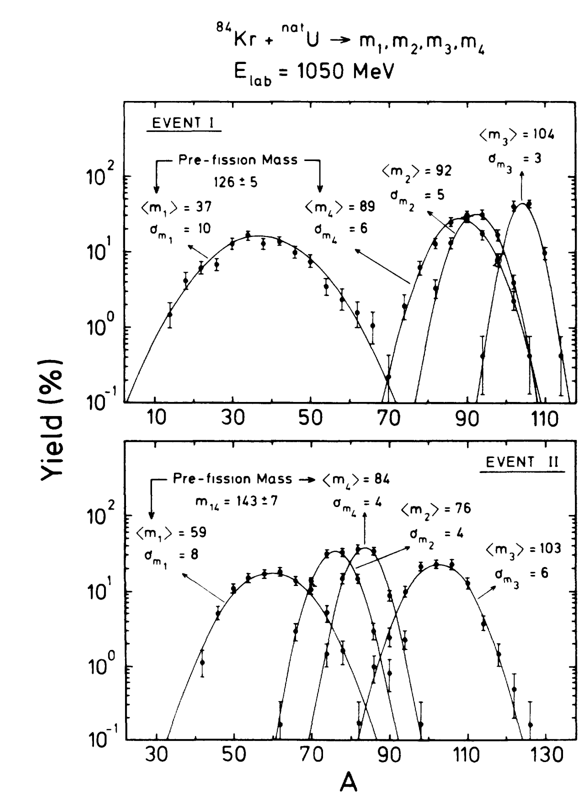

FIG. 2. The Gaussian distributions of final masses observed in two direct events of the reaction (1050 MeV) ^{84}Kr+ ^{nat}U. The pairs of masses originating from sequential fission are marked.

scope of this communication to assess the final state interactions quantitatively from angular distributions of final fragments.

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[1]R. Bass, *Nuclear Reactions with Heavy Ions* (Springer, Berlin, 1980).
[2]*Heavy Ion Collisions*, edited by R. Bock (North-Holland, Amsterdam, 1980).
[3]*Treatise on Heavy-Ion Science*, edited by D. A. Bromley (Plenum, New York, 1985).
[4]J. M. Alexander, E. Duek, and L. Kowalski, Z. Phys. A **323**, 83 (1986).
[5]Y. Blumenfeld *et al.*, Nucl. Phys. **A455**, 357 (1986).
[6]J. Galin, D. Guerreau, M. Lefort, and X. Tarrago, J. Phys. (Paris) **32**, 7 (1971).
[7]B. Heusch *et al.*, Nucl. Phys. **A288**, 391 (1978).
[8]C. Lebrun *et al.*, Nucl. Phys. **A321**, 207 (1979).
[9]B. Borderie *et al.*, Z. Phys. A **299**, 263 (1981).
[10]C. Gregoire, C. Ngô, and B. Remud, Phys. Lett. **99B**, 17 (1981).
[11]Z. Zheng *et al.*, Nucl. Phys. **A422**, 447 (1984).
[12]J. Töke *et al.*, Nucl. Phys. **A440**, 327 (1985).
[13]R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids: Principles and Applications* (University of California Press, Berkeley, 1975).
[14]P. Vater *et al.*, Phys. Rev. Lett. **39**, 594 (1977).
[15]P. A. Gottschalk *et al.*, Phys. Rev. Lett. **42**, 359 (1979).
[16]H. A. Khan *et al.*, Nucl. Instrum. Methods **173**, 155 (1980).
[17]P. A. Gottschalk *et al.*, Phys. Rev. C **27**, 2703 (1983).
[18]R. Haag *et al.*, Z. Phys. A **316**, 183 (1984).
[19]H. A. Khan *et al.*, Phys. Rev. C **32**, 1551 (1985).
[20]P. Vater *et al.*, Nucl. Tracks Radiat. Meas. **11**, 5 (1986).
[21]E. V. Viola, Jr., Nucl. Data Sheets **A1**, 391 (1966).
[22]H. A. Khan *et al.*, Nucl. Tracks **4**, 109 (1980).
[23]P. Vater *et al.*, Nucl. Instrum. Methods **147**, 271 (1977).
[24]E. V. Benton and R. P. Henke, Nucl. Instrum. Methods **67**, 87 (1969).
[25]H. A. Khan *et al.*, in *Proceedings of the 11th International Conference on Solid State Nuclear Track Detectors, Bristol, 1981*, edited by P. H. Fowler and V. M. Clapham (Pergamon, Oxford, 1982).
[26]I. E. Qureshi *et al.*, submitted to Nucl. Phys.
[27]J. Wilczynski, Nucl. Phys. **A216**, 386 (1973).
[28]P. Glässel *et al.*, Z. Phys. A **310**, 189 (1983).