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Complete Fusion Nuclear Reactions Induced by Krypton Ions. Effective Threshold and Minimum Distance of Approach for the Reactions $Cd^{116} + Kr^{84}$ and $Ge^{72} + Kr^{84}$

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Effective energy thresholds have been measured for the cross sections of complete fusion reactions induced by krypton ions on Cd^{116} and Ge^{72}. They show that the minimum distance of approach for the reaction is shorter than with lighter projectiles and corresponds to a Coulomb repulsion at a distance of $r_0(A_1^{1/3}+A_2^{1/3})$ fm with $r_0=1.32$ fm instead of 1.45 fm.

Several questions have arisen on the problem of making a complete fusion nucleus by very heavy-ion-induced reactions, particularly with the purpose of synthesis of new heavy and superheavy nuclides. One of them is related to the height of the Coulomb barrier which might be enhanced because of a deformation of the target nucleus at the approach of the highly charged projectile.[1] Also some doubts were expressed as to the possibility of formation of a fusion nucleus.[2]

We have undertaken a study of these two points with Ar^{40} and Kr^{84} beams which are now available at Orsay from the accelerator ALICE.[3] A first set of results on the reaction Ar + Dy has shown[4] that the experimental threshold is in good agreement with a minimum distance of approach necessary for fusion calculated with $r_0 = 1.45\times10^{-13}$ cm, i.e., at the same value of r_0 as for lighter ions like C^{12}, O^{16}, or Ne^{20}. The calculation is made on the assumption of pure Coulomb repulsion between two centers placed at a distance of approach $r_0(A_1^{1/3}+A_2^{1/3})$. Such a behavior does not hold for krypton projectiles, as is shown for two sets of experiments on Cd^{116} and Ge^{72}. We have measured the yields of reaction products resulting from the compound nucleus Po^{200} in the case of Cd^{116}, and from Er^{156} in the case of Ge^{72}, after de-excitation by emission of a number of neutrons. The apparent threshold has been determined with fairly good precision. It was 147 MeV (c.m.) for the reaction Kr^{84} + Ge and 204 MeV for Kr^{84} + Cd. Both values correspond to a minimum distance of approach calculated with $r_0 = 132$ fm, corresponding to a classical Coulomb barrier 10% higher than for lighter ions including Ar^{40}.

Energy determinations were done in another set of experiments[5] with a magnetic analyzer by measuring magnetic-rigidity values for direct beams of Kr^{24+} (505 ± 5 MeV) and Kr^{23+} and Kr^{22+} (360 ± 4 MeV). Also krypton ions were scattered at small angles by thin gold or carbon foils and magnetic-rigidity measurements were made on various charges around Kr^{31+}. More details on the charge distribution after stripping by the target are given by Baron.[5] Nickel foils were used in some experiments for degrading the energy down to 350 MeV in the laboratory system. The energy loss was calculated according to Northcliffe and Schilling's data.[6] However, the stopping power of heavy ions in such an energy range is not very well known. But we have shown in preliminary experiments that the same cross sections were found for Er^{153} produced either with Kr^{22+} without degrader or by Kr^{24+} with a degrader on the beam.

The krypton beam energy was varied between 350 and 494 MeV at an intensity in the range of 10^8–10^9 ions per sec. The beam passed through a nickel foil in which the energy loss had been calculated, and bombarded targets placed in a reaction chamber filled with helium. The recoiling nuclei were collected away from the beam with a helium-jet apparatus. α emitters were counted with an annular surface-barrier detector and an overall efficiency of the order of 10% was measured when half-lives were longer than 1 sec. More details are given elsewhere on the "helium-jet" collection apparatus.[7] Targets were

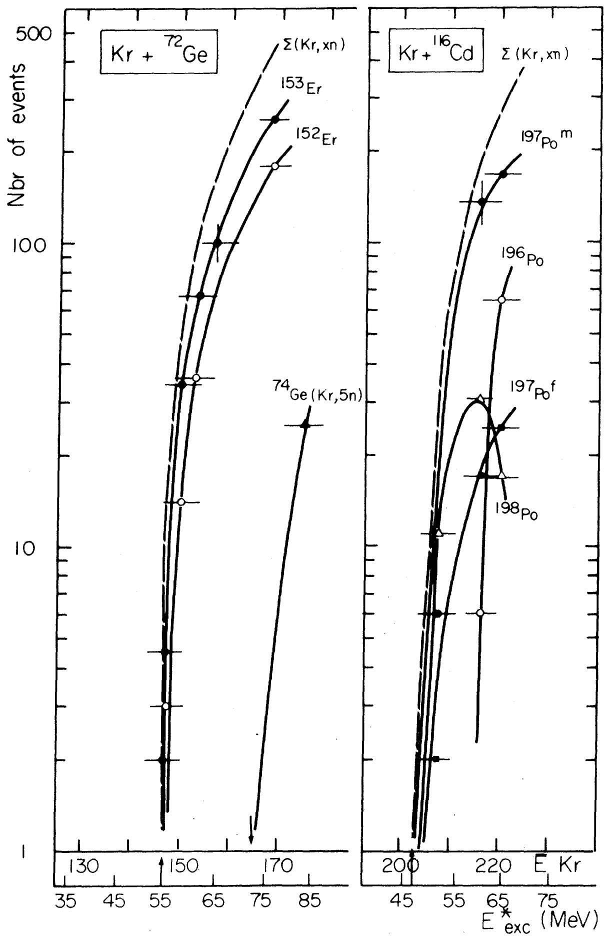

FIG. 1. Excitation functions for reactions $Kr^{84}+Ge^{72}$ and $Kr^{84}+Cd^{116}$. The double scale on the abscissa represents bombarding energies in the center of mass system, $\bar{E}$, and excitation energies; horizontal bars express the width in energy spread because of the target thickness. Kr + Ge, one event = 200 μb; Kr + Cd, one event = 7 μb. The arrow on the left side shows the threshold for the reaction (Kr, 5*n*).

1 mg cm^{-2} thick: Cd^{116}, Ge^{74}, and natural Ge. During the bombardment of Cd^{116}, polonium isotopes were collected and identified by characteristic α decay. Po^{196}, Po^{197m}, Po^{197f}, and Po^{198} were counted; Fig. 1 shows the excitation functions. Both excitation energies and projectile energies in the center of mass system are given as abscissas. From the number of events shown on the ordinate, one may deduce the cross section, one event corresponding to 7 μb.

The effective threshold, clearly determined as 204 MeV, is certainly due to the Coulomb barrier and not to a negative *Q* value since it corresponds to a high excitation energy (around 50 MeV). It may be also noticed that the reaction (Kr, 2*n*) yielding Po^{198} has low yield, probably because its maximum should occur at an excitation energy much lower than 50 MeV, and therefore below the Coulomb barrier. The highest cross section was observed for Po^{197m}, (Kr, 3*n*), but it does not exceed 1 mb. This is probably due to a strong effect of fission competition in the de-excitation process.

The cross sections are much higher for germanium than for cadmium. This is shown in the figure, in which each event for the production of Er^{153} or Er^{152} corresponds to 0.2 mb. The reason is certainly the much lower effect of fission on the rather light compound nucleus Er^{156}.

Actually the results were obtained on a natural germanium target, but it is easy to show that Er^{152} and Er^{153} are completely formed by the (Kr, 4*n*) and (Kr, 3*n*) reactions, respectively, on the isotope Ge^{72} (abundance 27.43%).

First of all, we performed an experiment on a separated target of Ge^{74}. The threshold for the reaction $Ge^{74}(Kr^{84}, 5n)Er^{153}$ was observed at 165 MeV, i.e., 20 MeV higher than the threshold found for Er^{153} with natural germanium. The excitation function peaked at 180 MeV, corresponding to 85 MeV of excitation. If one takes account of the separation energy for five neutrons, which is approximately 45 MeV, there is 40 MeV left available for the kinetic energy of neutrons and for γ rays. Such a mean value (8 MeV per neutron) is very large, as compared with all other data obtained with lighter ions.[8]

Another possibility for producing Er^{153} and Er^{152} with nautral germanium could be the reactions $Ge^{70}(Kr, n)$ and $Ge^{70}(Kr, 2n)$, since the abundance of Ge^{70} is 20.52%. However, at an excitation energy of 50 MeV, the probability of evaporation of three or four neutrons is certainly larger than for one or two neutrons, as was already observed in the case of Kr + Cd. Moreover, if there were a contribution in the synthesis of Er^{153} from $Ge^{70}(Kr, n)$, the conclusion on the position of the reaction threshold would be even stronger.

For several years, there has been the feeling that many new nuclides, and particularly superheavy elements, could be produced in complete fusion reactions induced by very heavy ions.[9,10] The present results seem to us of interest since they give for the first time experimental data on the fusion cross section between a very heavy projectile and two sets of targets in an energy range between the Coulomb barrier and 50 MeV above. They show a larger apparent threshold energy for the fusion cross section than expected from results for lighter ions, an effect that might be due to a Coulomb deformation. Therefore, the energy range for which a fusion reaction may be induced at low excitation energy is reduced. This is clearly shown by the example of Po^{198} for which the cross section is significant only in the narrow energy region between 205 and 220 MeV. The production of superheavy nuclei would be similar to that of Po^{198} in that the former should also be produced after the emission of a small number of neutrons, in order to limit the fission competition. The increase of the effective reaction threshold for the reaction Kr^{84} + Th^{232} makes it necessary to use krypton ions of a higher energy than expected, and therefore the excitation energy of the fusion nucleus might always be sufficiently high to permit fission competition to very much reduce the possibility of formation of superheavy isotopes. Such a result is not in accord with several theoretical calculations which predict deformation effects much smaller.[1,11,12]

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Alternate Models of Particle-Core Coupling in ^{209}Bi†

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Energy levels in ^{209}Bi excited by nonresonant scattering of 16.10-MeV protons are compared with levels reached by scattering from a group of isobaric analog resonances at $E_p = 14.95$ MeV. The nonresonant results are sensitive to the parentage of ^{208}Pb core excitations in the levels of ^{209}Bi, while the resonant data provide information about the ^{210}Bi parentage.

The concept of particle-core coupling has become increasingly important for the understanding of the level structure of heavy odd-mass nuclei, particularly near closed shells.[1] An outstanding example of this phenomenon is found in the ^{209}Bi spectrum[2] where a septuplet of levels is formed by coupling the $h_{9/2}$ proton to the 3^- collective vibration of ^{208}Pb. Recently, another group of levels in ^{209}Bi has been identified as a decuplet[3,4] based on the 5^- second excited state of ^{208}Pb, which contains only one dominant particle-hole configuration[5] and is considerably less collective than the 3^- state. The assignment of a second multiplet, based on a core state that is only moderately collective, raises the question of coupling to the 4^- third excited state[6,7] of ^{208}Pb, which is an excellent example of a noncollective one-particle, one-hole state.[5] According to the usual particle-vibration concept, the 4^- state would not be expected to form the basis of a particle-plus-core multiplet analogous to the 3^- and 5^- cases already reported.

In this Letter we report new results on the particle-core structure in ^{209}Bi, and in addition, we describe a method of resonant and nonresonant scattering, which may prove useful for sim-