

Reactions with ^{40}Ar and ^{84}Kr leading to the same compound nucleus, ^{200}Po

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Excitation functions were measured for the deexcitation by neutron evaporation of the compound nucleus ^{200}Po formed in the interactions of $^{84}\text{Kr} + ^{116}\text{Cd}$ and $^{40}\text{Ar} + ^{160}\text{Dy}$. In general, the results are consistent with the predictions of the statistical model of nuclear reactions, including effects of angular momentum and deexcitation by fission. However, few neutron (2n,3n) evaporation is more favored in ^{84}Kr -induced reactions than in those involving ^{40}Ar , a result that is not predicted by the statistical model.

The comparison of compound-nuclear reactions induced by heavy ions with different masses provides information about angular momentum effects in the entrance and exit channels and the competition between nucleon evaporation and fission.¹ Recent interest² has focused on reactions induced by projectiles with $A > 20$. For example, in our study³ of the formation and decay of ^{158}Er produced in reactions with either ^{40}Ar or ^{84}Kr , we found that the deexcitation of that compound nucleus by neutron evaporation was independent of its production mode. Thus it was not necessary to invoke special entrance-channel effects as had been done to explain earlier data⁴ for the same two systems (however, see Ref. 5).

Herein we extend this comparison of heavy-ion-induced complete fusion to the interactions of $^{40}\text{Ar} + ^{160}\text{Dy}$ and $^{84}\text{Kr} + ^{116}\text{Cd}$ which lead to the compound nucleus, ^{200}Po . Because such a heavy system has a high fission probability, cross sections for surviving evaporation residues will be significantly smaller than those for a medium-weight system.⁶ Nevertheless, observation of systematic differences between the (Ar,xn) and (Kr,xn) excitation functions should be a sensitive indication that the competition between fission and neutron evaporation is affected by the mode of formation of the compound nucleus. We previously published the data for the $^{40}\text{Ar} + ^{160}\text{Dy}$ reaction.⁷ However, the energy scale for these excitation functions has been shifted to lower energies by 4 MeV as a result of additional measurements.^{8,9} The data for the $^{84}\text{Kr} + ^{116}\text{Cd}$ reaction are new and allow us to compare the deexcitation modes of the ^{200}Po compound system formed two different ways: in a roughly symmetric manner, $^{84}\text{Kr} + ^{116}\text{Cd}$, and in an asymmetric way, $^{40}\text{Ar} + ^{160}\text{Dy}$.

The ^{84}Kr experiments were performed with the use of a helium gas-jet system at the Lawrence Berkeley Laboratory SuperHILAC. The experimental procedures have

been discussed previously.^{3,7} The ^{116}Cd (97.2%) targets were prepared by electrodeposition of cadmium oxide onto thin Ni foils; most of the targets used were 0.6 mg/cm² thick. All Po nuclei formed in the irradiations are known α -particle emitters; their α -decay characteristics are given in Ref. 10. Note that at all bombarding energies the relative yields of the different Po products are independent of the gas-jet collection efficiency. These yields were then converted to absolute cross sections by comparison with yields of nuclides with known cross sections measured with the same gas-jet system but produced in other nuclear reactions, such as $^{40}\text{Ar} + ^{164}\text{Dy}$ and $^{84}\text{Kr} + ^{74}\text{Ge}$ (Refs. 3 and 7). Time-of-flight (TOF) techniques determined the energies of the ^{84}Kr ions that were extracted (620 MeV) from the SuperHILAC, and of those that passed through various absorbers placed before the targets (see Ref. 11).

Measured excitation functions for the isotopes ^{198}Po to ^{194}Po , produced by ^{40}Kr , are plotted in Fig. 1. The closed points represent cross sections that were determined at five different energies in conjunction with the TOF measurements; the energy coordinates of the open points were not directly measured, but were obtained from a range-energy table based on the TOF values. The agreement between the open and closed points is seen to be good for all (Kr,xn) excitation functions. Analogous excitation functions for ^{197}Po to ^{194}Po , produced by ^{40}Ar , are shown in Fig. 2.

The similarity between the (Kr,xn) and (Ar,xn) curves, for each value of x, is apparent in terms of the thresholds and peak positions of the corresponding excitation functions. The peaks of the Kr and Ar curves occur at approximately the same excitation energies, 48 MeV for 3n, 55 MeV for 4n, 64 MeV for 5n, and 76 MeV for 6n emission. The most noticeable difference between the Kr and Ar data is the observation of the ^{198}Po product from the (Kr,2n) reaction, but not from the (Ar,2n) reaction.

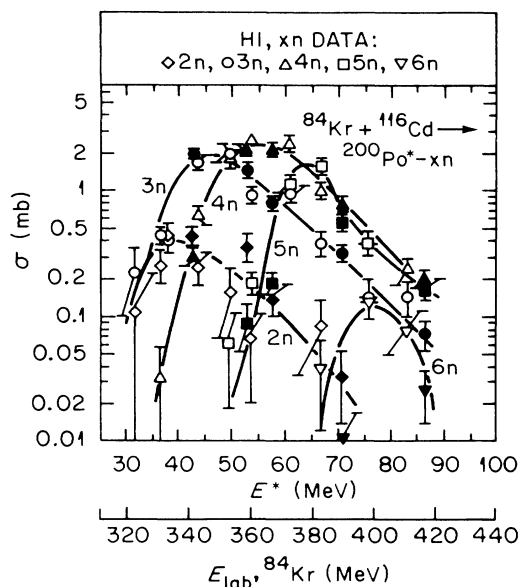


FIG. 1. Excitation functions for $^{200-x}\text{Po}$ products formed in bombardments of ^{116}Cd with ^{84}Kr . Closed points were obtained in conjunction with TOF measurements of the beam energies. Data indicated by the open points have energies derived from range-energy data obtained in our TOF experiments. The points at $E^*=76$ MeV, marked by horizontal bars, were obtained with a ^{116}Cd target of 1.1 mg/cm^2 . Curves are drawn to guide the eye.

A similar result was noted in Ref. 4, which was one of the first reports of a $(\text{HI}, 2n)$ reaction. Follow-up studies¹² have shown that the probability of the emission of only one or two nucleons is generally larger in symmetrical, rather than in asymmetric, systems. Another difference is that the (Ar, xn) cross sections are larger by factors of ~ 2 to 4 than the corresponding (Kr, xn)

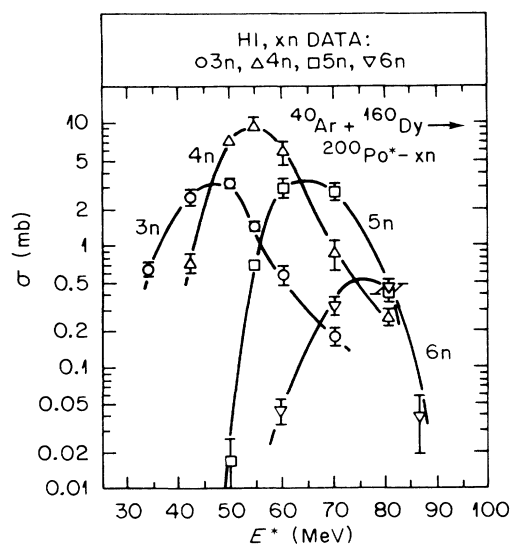


FIG. 2. Excitation functions for $^{200-x}\text{Po}$ products formed in the reaction of ^{40}Ar with ^{160}Dy . Curves are drawn to guide the eye.

values. Thus, the $3n$, $4n$, $5n$, and $6n$ reactions with Ar have peak values of 3.2 , 9.2 , 3.4 , and 0.52 mb, while the respective maxima for the Kr reactions are 1.9 , 2.4 , 1.5 , and 0.13 mb.

These trends can be understood in terms of the statistical model of compound-nuclear reactions. From the independence hypothesis, the cross section for a (HI, xn) reaction, at a particular excitation energy, is given by the product of the compound-nucleus formation cross section $\sigma_C(\text{HI})$, and the probability that it deexcites by the emission of x neutrons, P_{xn} . Then the ratio of xn cross sections produced by Ar and Kr ions at the same excitation energy is

$$\sigma(\text{Ar}, xn)/\sigma(\text{Kr}, xn) = \sigma_C(\text{Ar})/\sigma_C(\text{Kr}). \quad (1)$$

The formation cross section, expressed as a sum of l waves,

$$\sigma_C = \pi \lambda^2 \sum_l (2l+1) T(l), \quad (2)$$

([where λ is the projectile's wavelength in the center-of-mass system and $T(l)$ is its transmission coefficient]) is made up of the evaporation residue cross section, σ_{ER} (which predominates at low l values), and the fission cross section, σ_F (which increases as σ_{ER} decreases and dominates at large l values). At a constant excitation energy, E^* , the model predicts that the l value at which σ_{ER} goes to zero is the same for Ar+Dy and for Kr+Cd. For example, at $E^*=86$ MeV, $\sigma_{\text{ER}}=0$ at $l=40$. That theory also indicates that differences in fission probabilities between the Ar and Kr reactions only occur above the l value where σ_{ER} becomes zero.

From Eqs. (1) and (2), the ratio of ER cross sections for the Ar and Kr reactions leading to $^{200}\text{Po}^*$ at constant E^* equals the ratio of the λ^2 values,

$$\lambda^2(\text{Ar})/\lambda^2(\text{Kr}) = 1.10 E(\text{Kr})/E(\text{Ar}), \quad (3)$$

where the constant, 1.10 , is obtained from the masses of projectiles and targets in the two reactions, and the energies in the laboratory system, $E(\text{Kr})$ and $E(\text{Ar})$, are selected to correspond to the same value of E^* . Our cross sections span the interval, $31 \leq E^* \leq 86$ MeV, where the ratio, $E(\text{Kr})/E(\text{Ar})$, varies from 2.15 to 1.91 , so the predicted cross-section ratio varies from 2.4 to 2.1 . These calculated ratios are comparable to the measured ratios (see above), supporting the idea that there are no major differences in the deexcitation of $^{200}\text{Po}^*$ compound nuclei formed either by ^{40}Ar or by ^{84}Kr .

To compare experimental and statistical model results, one often obtains experimental P_{xn} values by dividing the measured xn cross sections by the calculated values of σ_C . However, this procedure depends upon the accuracy of the calculated formation cross sections for the two different projectiles, which in turn depend upon values chosen for the nuclear radius parameter. We avoid this uncertainty by considering cross-section ratios for evaporating $x+1$ and x neutrons, obtained with a given projectile at constant E^* ,

$$\sigma_{(x+1)n}/\sigma_{xn} = P_{(x+1)n}/P_{xn} = R. \quad (4)$$

If the statistical model is valid for the Ar and Kr xn re-

actions, their measured R values should be equal.

Because $\sigma_{(x+1)n}$ increases steeply above the $(x+1)n$ threshold, while σ_{xn} decreases, R should increase very rapidly. The measured values of R are plotted versus energy for $3 \leq x \leq 5$ in Fig. 3, and compared with calculated ratios of emission probabilities from the ALICE (Ref. 13) and JULIAN (Ref. 14) codes. Each set of measured ratios is seen initially to increase rapidly with increasing energy, by a factor of 100 within 15 MeV above threshold; points for the Ar and Kr reactions overlap and follow the same steep rise. This agreement of the Ar and Kr data is a sensitive validation of the independence hypothesis.

Furthermore, the calculated R curves follow the rising experimental points, although the JULIAN calculation more closely reproduces the trends of the measurements. Because the JULIAN code includes γ -ray emission in addition to neutron evaporation and fission, its R values are shifted to higher energies than are those from the ALICE program. The overall agreement between calculations and data indicates that the decay of $^{200}\text{Po}^*$ is reasonably reproduced by the statistical model.

However, at higher excitation energies, > 15 MeV above the threshold of the R curve, the calculations diverge from experiment: while the calculated curves continue to increase with increasing energy, the experimental Ar and Kr points for the $4n/3n$ and $5n/4n$ ratios go through maxima and begin to decrease. This characteristic of the measured ratios reflects the trends seen in Figs. 1 and 2, where the high-energy parts of the excitation functions decrease slowly with increasing energy. One is tempted to explain these observed high-energy tails and leveling off of the R values by the dependence of γ -ray emission probabilities upon l , i.e., γ rays remove angular momentum from the compound nucleus, shifting the thresholds for emission of additional neutrons to higher energies, so that the increase of R is slowed considerably. The JULIAN code should include such effects; however, it does not reproduce the turnover of the measured R values. Also, neither the ALICE nor the JULIAN code reproduces our observation that the $(\text{HI}, 2n)$ product, ^{198}Po , is seen in the Kr reactions but not in the Ar reactions.

The high energy tails on the $(^{200}\text{Po}, xn)$ excitation functions may be related to the fact that these excited nuclei are unstable to fission. Calculations of fission-evaporation competition, done with the ALICE code, were presented in detail in our previous work.⁷ The reader will note in Figs. 7–10 of Ref. 7 that the fission barrier decreases with increasing angular momentum, J , and that the fission cross section increases with increasing excitation energy at the expense of the ER cross sections. If the fission barrier were to decrease more slowly with J than predicted by the rotating liquid-drop model, then the calculated increase of the fission cross section with energy would also be slowed, so that the xn cross sections would not decrease as rapidly with E^* . Thus the excitation functions would display high energy tails.

Two observations support these arguments. First, the

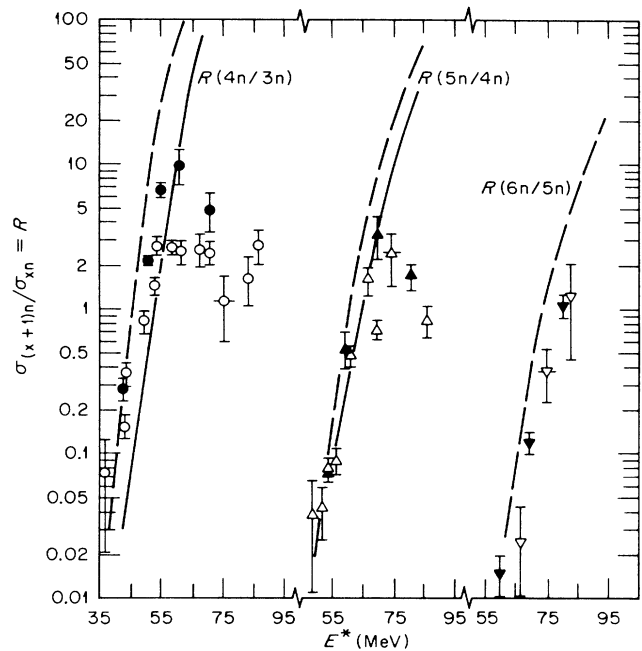


FIG. 3. Experimental points and calculated curves for the ratio R [see Eq. (4)] vs energy. Closed points are for reactions with ^{40}Ar , while open points are for ^{84}Kr reactions. Curves were calculated with the ALICE (Ref. 13) (dashed) and JULIAN (Ref. 14) (solid) codes. As in Fig. 1, data indicated by the open points at $E^* = 76$ MeV, marked by horizontal bars, were obtained with a 1.1-mg/cm^2 -thick ^{116}Cd target.

Kr and Ar data, in Figs. 1 and 2, respectively, show tailing at higher energies, but the effect is much more pronounced for Kr. The Kr cross sections are systematically lower than the corresponding ones for Ar, so that any increase in xn cross sections due to reduced fission competition in the Po compound system should be more noticeable for the Kr reactions. Second, our studies³ of Er compound nuclei produced by Ar and Kr beams did not reveal any significant high energy tailing. Because the probability of fission deexcitation in medium weight nuclei is much less than it is in ^{200}Po , we attribute the absence of high energy tailing in the excitation functions to the diminution of fission competition for the Er compound nuclei. On the other hand, effects due to deexcitation γ -ray emission in the Er and Po compound systems, as compared to neutron emission, are not too different. Thus, it is the increased probability of fission, competing with nucleon emission, that probably accounts for the tails observed in the (Po, xn) data.

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