Observed differences between argon- and krypton-induced reactions leading to the same compound nuclei, ^{158}Er and ^{156}Er

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Cross-bombardment experiments were carried out to produce the same compound nucleus ^{158}Er either in (^{84}Kr + ^{74}Ge) or (^{40}Ar + ^{118}Sn) reactions. Also the compound nucleus ^{156}Er was formed by using ^{72}Ge and ^{116}Sn targets. Evaporation residues ^{152}Er and ^{153}Er were detected, and excitation functions were constructed for (Kr, xn) and (Ar, xn) reactions, where x varies from 3 to 6. Some measurements were also made of (Ar, pxn) and (Kr, pxn) reactions leading to ^{152}Ho. A comparison of the absolute cross sections shows that complete fusion is more severely limited in the case of Kr ions than for Ar ions, at the same values of excitation energy and of maximum orbital angular momentum. It was deduced that the critical angular momentum is lower in the case of krypton bombardments, 52$\hbar$ instead of 76$\hbar$ for Ar at $E^* = 80$ MeV. Also, the measured excitation functions are narrower for (Kr, xn) than for (Ar, xn) reactions and the Kr thresholds are shifted to higher energies by some 15 MeV, as if more energy were necessary for emitting a given number of neutrons in the (Kr, xn) reactions than in the (Ar, xn) reactions. Such an effect cannot be explained in terms of the deexcitation of the compound nucleus. We conclude that in the case of krypton-induced reactions on germanium, some particular aspects of the formation stage of the compound system may dissipate energy prior to attainment of full equilibrium.

[NUCLEAR REACTIONS ^{70}Ge, ^{72}Ge, ^{74}Ge(Kr, xn)^{152,153}Er; ^{116}Sn, ^{118}Sn(Ar, xn)-^{152,153}Er. $\bar{E}$=110–300 MeV, measured $\sigma(\bar{E})$. Deduced complete fusion cross section and dynamical effects in the entrance channel (Kr+Ge).]

I. INTRODUCTION

There have been a great number of experiments done to verify the independence hypothesis of compound nucleus formation and decay, with identical compound nuclei being produced by different entrance channels. In principle, when the excitation energy and the angular momentum are specified, the decay processes should be entirely determined, independent of the manner in which the compound system was formed. Cross bombardment experiments, so-called Ghoshal-type tests, have been carried on by many authors who have particularly compared the excitation functions for the production of the same evaporation residues in different reactions. A typical example is shown in the work of Alexander and Simonoff[1] who found that excitation functions of the reactions ^{144}Nd(^{12}C, 6n)^{150}Dy and ^{136}Ba(^{20}Ne, 6n)^{150}Dy had the same threshold energy, the same maximum energy, and the same width. Until recently, the heaviest projectiles used in cross bombardments were neon and argon ions.

In order to explore how much heavier projectiles fuse with target nuclei and to obtain information on the compound system which might be formed, a comparison has been made between (^{40}Ar, xn) and (^{84}Kr, xn) reactions. Excitation functions were constructed for two evaporation residues, ^{152}Er and ^{153}Er, for excitation energies between 50 and 110 MeV. These two isotopes are very convenient radioactive nuclei, since they are α emitters with short half-lives. Targets were made of germanium for the bombardments with krypton ions and of tin for those with argon ions. By using different isotopes, ^{70}Ge, ^{72}Ge, and ^{74}Ge, or ^{116}Sn and ^{118}Sn, and by observing always the same residual nuclei, it was possible to explore (HI, xn) reactions for x between 1 and 6 in the case of germanium isotopes and between 3 and 6 for tin, as is shown in Table I. Also, a comparison could be made with the results obtained previously[2] for the analogous reactions of ^{16}O on ^{142}Nd.

In order to obtain precisely the same compound nucleus by different entrance channels, it is necessary to produce it at the same excitation energy and the same angular momentum. We have calculated for a large range of excitation energies E^* the maximum values of the orbital angular momentum brought into the compound system by

TABLE I. Various target-projectile combinations for producing Er compound nuclei.

Projectile	Target	Compound nucleus	Values of x in $(\mathrm{HI}, xn)^{152}\mathrm{Er}$	Values of x in $(\mathrm{HI}, xn)^{153}\mathrm{Er}$
^{84}Kr	^{70}Ge	^{154}Er	$x=2$	$x=1$
	^{72}Ge	^{156}Er	4	3
	^{74}Ge	^{158}Er	6	5
^{40}Ar	^{116}Sn	^{156}Er	4	3
	^{118}Sn	^{158}Er	6	5
^{16}O	^{142}Nd	^{158}Er	6	5

the projectile, with the simplest relationship

$$l_{\max}\hbar = (R_1 + R_2)(2\mu(\overline{E} - \overline{E}_0))^{1/2},$$

where R_1 and R_2 are the radii of the partners, μ is the reduced mass, $\overline{E}$ the center of mass kinetic energy, and $\overline{E}_0$ the energy at the total reaction threshold taken to be the Coulomb barrier. Also, $E^* = \overline{E} + Q$ where Q is the mass balance for compound nucleus formation. These results are presented in Fig. 1 and it is noticed that in the energy range under consideration, 50–110 MeV, the maximum l values are always a little higher for argon projectiles than for krypton, since the kinetic energies for argon relative to krypton are much farther above the barrier. However, they are never very different and one might assume that the compound nuclei are formed with very similar angular-momentum populations. The situation is quite different for the case of oxygen where $l_{\max}\hbar$ is always much lower than for the very heavy ions.

II. EXPERIMENTAL TECHNIQUES

A. Targets

Isotopically enriched targets of ^{70}Ge, ^{72}Ge, and ^{74}Ge and of ^{116}Sn and ^{118}Sn were prepared at Harwell (AERE). In the case of ^{70}Ge, corrections had to be made for a nonnegligible amount of another isotope (6% of ^{72}Ge).

The target thickness was of the order of 300 μg/cm^2 for all targets of germanium and tin, which were deposited on aluminium backing foils.

B. Reaction products

^{153}Er disintegrates by α emission (4.67 MeV) with a half-life of 36 s. ^{152}Er is an α emitter (4.80 MeV) with a half-life of 11 s. Because of such short decay periods, the nuclei recoiling from the target were collected with a helium jet system, and the α particles were counted with an annular surface barrier detector as described in previous publications.[3] The absolute yields were measured in a separate set of irradiations with targets put inside a Faraday cup. The cross section for ^{153}Er was obtained[4] by the measurement of the long-lived α emitter ^{149}Tb^g (4.1 h), daughter of ^{149}Dy, which itself is the daughter of ^{153}Er, in an energy range where no contribution was due to the (Kr, $2pxn$)^{149}Dy reaction. Then a comparison between ^{153}Er measured in the helium-jet apparatus and ^{149}Tb^g measured after bombardment in the Faraday cup gave the efficiency of the collecting system.

For each experiment, the range in helium of the recoiling nuclei was found to be consistent with the calibrated efficiency. When krypton ions are used, the recoil energy is of the order of 200 MeV for $^{152-153}$Er and therefore it was necessary to slow down the recoil nuclei in an aluminium foil placed at the back of the target, in order to diminish the range in the helium gas chamber.

C. Incident energy measurements

Ar^{12+}, Ar^{13+}, Kr^{23+}, Kr^{24+}, and Kr^{25+} are the ions available on the accelerator ALICE at Orsay with energies given by the relation $E = 72z^2/A$, where z and A are the charge and mass of the ion. Depending on the energy range which was studied, the ion charge was chosen and aluminium or nickel foils were used as degraders in front of the nickel foil put at the entrance of the helium chamber.

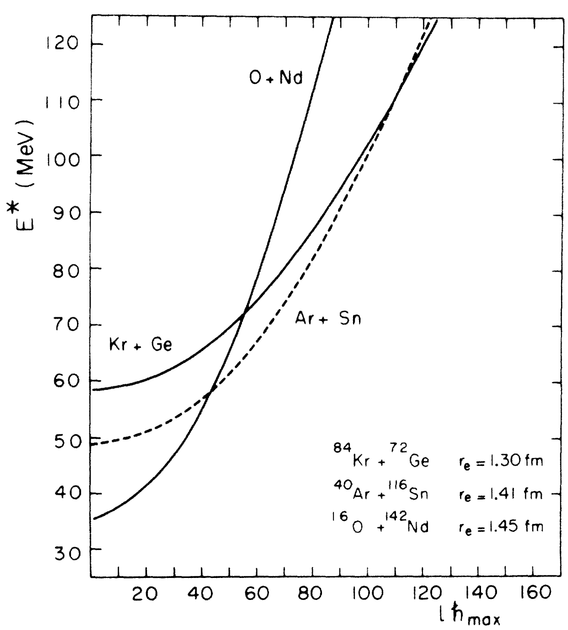

FIG. 1. Excitation energies versus maximum orbital angular momenta for the systems ^{16}O+^{142}Nd, ^{40}Ar+^{116}Sn, and ^{84}Kr+^{72}Ge. $l\hbar$ values were calculated by taking radius parameters $r_e = 1.30$ fm for ^{84}Kr, $r_e = 1.41$ fm for ^{40}Ar, and $r_e = 1.45$ fm for ^{16}O.

For a number of experiments the same energy was obtained on the target by using different charges for the incident ions and different arrangements for the degraders. The good agreement between the cross sections obtained with these different arrangements constituted a check of the energy-loss values calculated with Northcliffe's tables.[5] Also, the absolute value of the bombarding energy without degraders was measured with an accuracy better than 0.5% with a magnetic analyzer put in the direct beam. Because of the uncertainty in the energy loss in the degraders, we estimate the error of the energy on target at ±2%. In excitation energies, it corresponds to an error of the order of 1 MeV. The straggling adds an energy spread around 2 MeV. Therefore, we are strongly confident that the energy scales of the excitation functions for both argon and krypton ions are accurately determined. For most of the measured cross sections, there were four different sets of experiments done in the case of Kr ions and three in the case of Ar.

III. RESULTS: EXCITATION FUNCTIONS

Figure 2 shows the (Ar, *xn*) excitation functions for *x* between 3 and 6, obtained with ^{116}Sn and ^{118}Sn. Figure 3 shows analogous (Kr, *xn*) functions for *x* between 2 and 6. The (Kr, 1*n*) reaction was searched for with ^{70}Ge, but we did not find any evidence for it after correction for the ^{72}Ge included in the ^{70}Ge target. In the excitation energy scales, corrections were made for the fact that two different compound nuclei ^{158}Er and ^{156}Er are shown on the same figure. However, the respective neutron binding energies are so similar that the corrections do not exceed ≈1 MeV. The threshold energy was found to be ≈111 MeV (center of mass) for (Ar, 3*n*) and was ≈149 MeV (center of mass) for the reactions (Kr, 2*n*) and (Kr, 3*n*). We have assumed that such a threshold represents the Coulomb + nuclear interaction-barrier $\overline{E}_0$, which as has been noted,[6] can be given

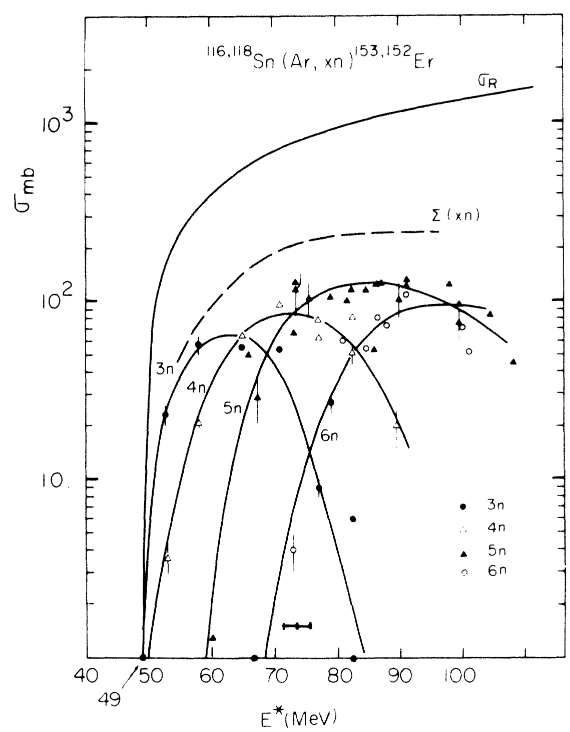

FIG. 2. Excitation functions for (Ar, *xn*) reactions on ^{116}Sn and ^{118}Sn with $x = 3$ to 6. σ_R is calculated (see text). The curves are drawn to guide the eye through the experimental points. The horizontal bar expresses an example of the width in energy due to the target thickness and the resultant energy straggling, as estimated from Alonso and Harvey (Ref. 16).

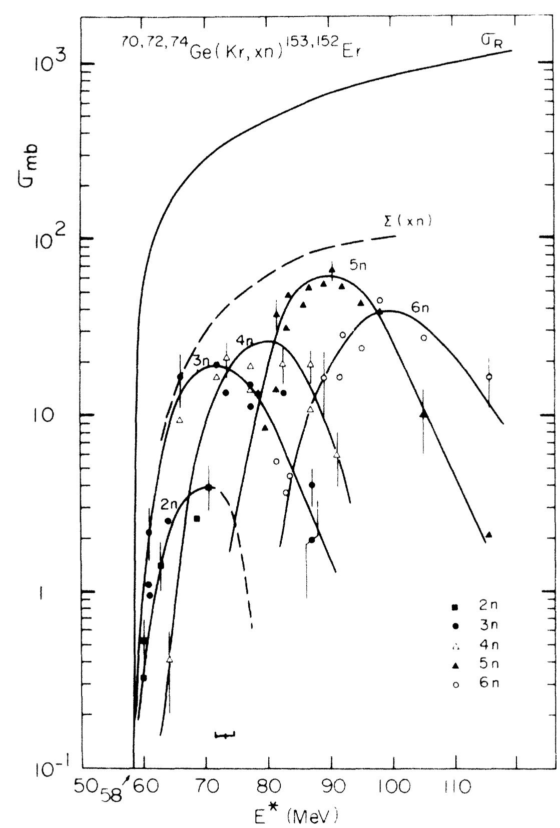

FIG. 3. Excitation functions for (Kr, *xn*) reactions on ^{70}Ge, ^{72}Ge, and ^{74}Ge with $x = 2$ to 6. σ_R calculated according to text. The curves are drawn to guide the eye through the experimental points. The horizontal bar expresses an example of the width in energy due to the target thickness and the resultant energy straggling, as estimated from Alonso and Harvey (Ref. 16).

by the relation

$$\bar{E}_0 = \frac{Z_1 Z_2 e^2}{r_e (A_1^{1/3} + A_2^{1/3})} ,$$

where r_e is an effective radius parameter (not r_0, the size radius parameter). With such a relation, we found $r_e = 1.41$ fm for the argon-induced reactions where $Z_1 Z_2 = 900$, and $r_e = 1.30$ fm for the krypton-induced reactions where $Z_1 Z_2 = 1152$. Such a difference in the r_e values corresponds to what would be expected due to the effect of the more predominant Coulomb repulsion in the case of krypton ions.[7] These results confirm entirely our previous data.[8] The total reaction cross section σ_R given on Figs. 2 and 3 has been calculated in the strongly rising part of the excitation function with the very simple relation

$$\sigma_R = \pi r_e^2 (A_1^{1/3} + A_2^{1/3})^2 \left(1 - \frac{\bar{E}_0}{\bar{E}}\right) ,$$

where r_e and $\bar{E}_0$ were taken from the above experimental determinations.

There are three important conclusions which can be drawn from Figs. 2 and 3:

(i) The total cross sections of $\sum(xn)$ reactions is roughly $\frac{1}{4}$ of σ_R for argon ions, whatever is the excitation energy between 70 and 95 MeV. It is around $\frac{1}{8}$ of σ_R for krypton ions in the same energy range. Therefore one might deduce that the complete fusion cross section is a smaller part of the total reaction cross section when krypton projectiles are used.

(ii) There is still a measurable probability of emitting only two neutrons when a compound nucleus is formed by (^{84}Kr + ^{70}Ge) at 70 MeV of excitation energy. This corresponds to a very large energy available per neutron (around 25 MeV).

(iii) The excitation function for a given reaction induced by Kr ions exhibits a threshold energy 15 MeV higher than for the same reaction induced by Ar ions, for the evaporation of the same number of neutrons (for example, five neutrons). Such a shift is not due to any Coulomb barrier effects, since both thresholds are well above the interaction barrier, and is observed for any value of x where the comparison can be made ($x = 4$, $x = 5$, and $x = 6$). These three points will be discussed in more detail in the following sections.

IV. EFFECT OF THE ENTRANCE CHANNEL ON THE COMPOUND NUCLEUS CROSS SECTION: CRITICAL ANGULAR MOMENTUM

When absolute cross sections are considered, and compared to σ_R, the ratio $[\sigma(4n)/\sigma_R]_{\mathrm{Ar}}$ is equal to 0.14 at the maximum, and $[\sigma(4n)/\sigma_R]_{\mathrm{Kr}} \sim 0.050$. There is also a larger ratio for $[\sigma(5n)/\sigma_R]_{\mathrm{Ar}}$ than for $[\sigma(5n)/\sigma_R]_{\mathrm{Kr}}$. Moreover, as we shall discuss later on, the widths of the excitation functions for Kr are narrower than for Ar ions. Thus if the sum of all the (xn) excitation functions is evaluated and plotted versus the excitation energy, $[\sum\sigma(xn)/\sigma_R]_{\mathrm{Ar}}$ is generally seen to be about twice $[\sum\sigma(xn)/\sigma_R]_{\mathrm{Kr}}$. And although the results were not very accurate, cross sections were also measured for (Ar, $p3n$) and (Kr, $p3n$) reactions leading to the evaporation residue ^{152}Ho. A ratio of about 2 was also found for $[\sigma(p3n)/\sigma_R]_{\mathrm{Ar}}/[\sigma(p3n)/\sigma_R]_{\mathrm{Kr}}$, at the maxima of the excitation functions.

Since the above results were found in the same excitation energy range for maximum orbital angular momenta that are lower for Kr ions than for Ar ions (Fig. 1), the only possible explanation is that there is an influence of the entrance channel on the limits for complete fusion. If the well-known relation

$$\frac{\sigma_{CF}}{\sigma_R} \approx \frac{l_{cr}^2}{l_{\max}^2}$$

is applied,[9] one may write

$$\frac{l_{cr}^2(\mathrm{Kr})}{l_{\max}^2(\mathrm{Kr})} = \frac{1}{2} \frac{l_{cr}^2(\mathrm{Ar})}{l_{\max}^2(\mathrm{Ar})} .$$

By measuring all the decay products from the compound nucleus, i.e., evaporation residues and fission fragments, Le Beyec, Lefort, and Peter[6] have found that l_{cr} for Ar ions was around $76\hbar$ at an excitation energy of 80 MeV. Since $l_{\max}(\mathrm{Kr})/l_{\max}(\mathrm{Ar})$ is equal to 0.9 (Fig. 1), one obtains for $l_{cr}(\mathrm{Kr})$ a value around $52\hbar$ (note that this calculation assumes that the fission cross section in the Kr reaction is also $\approx\frac{1}{2}$ that in the Ar reaction). Such a lower value is in good agreement with the concept of a constant close-contact distance that is necessary for fusion.[10] Because of the higher Coulomb repulsive potential exerted by Kr on Ge, relative to Ar on Sn, a smaller centrifugal potential results for the Kr + Ge fusion limits.

V. EFFECT OF THE ENTRANCE CHANNEL ON THE POSITIONS OF EXCITATION FUNCTIONS

Figure 4 shows the comparison of σ/σ_R versus excitation energy for the $4n$, $5n$, and $6n$ reactions. It is striking to observe exactly the same behavior for the three cases. The krypton-induced excitation functions are narrower, due to a larger value of the threshold. For example, if one takes $[\sigma(4n)/\sigma_R] = 5\times10^{-3}$ as a reference for the rising part of the curve, this value is found at 48 MeV for (Ar, $4n$) and 64 MeV for (Kr, $4n$). The same ratio for $[\sigma(5n)/\sigma_R]$ is observed at 60 MeV for (Ar, $5n$) and 75 MeV for (Kr, $5n$). There is a shift of about 15 MeV towards higher excitation energies with krypton ions, which is not at all predicted by any theoretical aspect of the compound-nuclear deexcitation process. Such a difference was so unexpected that the energy measurements were carefully rechecked and the observed energy shifts were verified.

A well known presentation[1] of the effect of angular momentum on neutron evaporation chains is to calculate the "available energy per emitted neutron," $\langle E_{xn}\rangle = (\bar{E}+Q)/x$, where Q is the mass balance. In the case of compound nuclei formed in the rare earth region by C, N, and O ions, Alexander and Simonoff found[1] that $\langle E_{xn}\rangle$ was around 5 to 6 MeV. Since $\langle E_n\rangle$ is of the order of 3 MeV per neutron when low angular momenta are involved, they deduced that a significant fraction of the excitation energy was dissipated in the form of radiation.

Using the same concept, Fig. 5 presents the results from Macfarlane and Griffioen[2] on ($^{16}O + ^{142}Nd$) and our results on ($^{40}Ar + ^{118}Sn$) and ($^{84}Ke + ^{74}Ge$) for five-neutron emission. The maximum of the ratio σ_{5n}/σ_R is located at a higher energy (≈7.3 MeV per neutron) for Ar than for ^{16}O (≈5.2 MeV per neutron), as expected, since larger angular momenta occur in the compound nucleus ^{158}Er formed by argon projectiles. Similar results have been obtained by Natowitz and Alexander[11] for the reaction $^{114}Cd(Ar, 5n)$. The fact that excitation functions are broader when high angular momenta are involved can be predicted from consideration of the angular-momentum population of the compound nucleus. For low angular-momentum (l) values, the minimum excitation energy at which a given xn reaction occurs should be essentially independent of the way the compound nucleus was formed. But when high angular momenta are reached, a large part of the excitation energy becomes rotational energy, reducing the energy available for neutron emission. Therefore, a given (xn) excitation function is broadened towards higher energies and the maximum is shifted. This change in shape and centroid of the excitation function also causes an apparent shift in the reaction threshold, for the relative number of low l waves decreases as l_{max} becomes larger.

Now if one considers the curve in Fig. 5 for the (Kr, $5n$) reaction, a puzzling result is observed. While the probability for $\langle E_{5n}\rangle$ rises from 10^{-3} at ≈1 MeV up to 10^{-1} at 7.3 MeV in the case of (Ar, $5n$), the probability of 10^{-3} for (Kr, $5n$) is observed only at ≈5 MeV. This result arises from the energy shifts of the order of 15 MeV observed in the Kr excitation functions. It is difficult to find any explanation for this difference based on angular-momentum effects. First of all, the maximum l values (Fig. 1) are lower for Kr than for Ar ions and therefore the excitation function for the (Kr, $5n$) should be in between the (O, $5n$) and (Ar, $5n$) curves. Moreover, there is no reason why low angular momenta would not exist *at all* when a compound nucleus is formed by the entrance channel Kr + Ge (see note added in proof).

Therefore, any attempt to explain the observed difference between (Kr, xn) and (Ar, xn) thresholds will be unsuccessful if made on the basis of the exit channel analysis. We are forced to reconsider the problem of the entrance channel and to try to understand why the compound systems produced are not exactly the same when Ar projectiles bombard tin targets and when Kr projectiles bombard germanium targets. There seems to be some

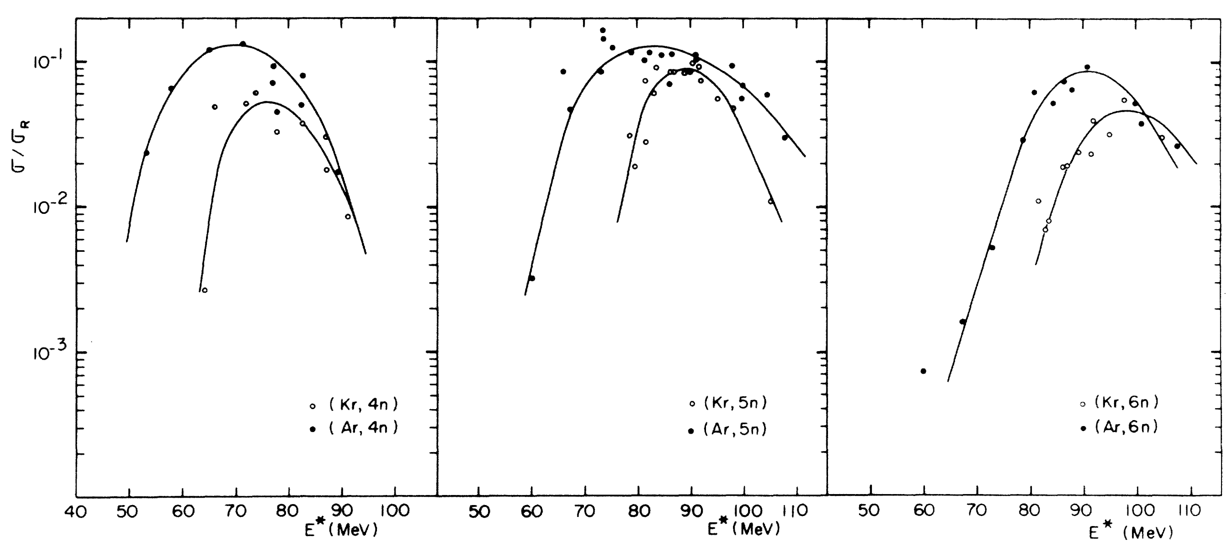

FIG. 4. $\sigma(\mathrm{HI}, xn)/\sigma_R$ as a function of excitation energy for $x = 4$, 5, and 6. ● HI is Ar, and ○ HI is Kr. (The curves are drawn to guide the eye through the experimental points.)

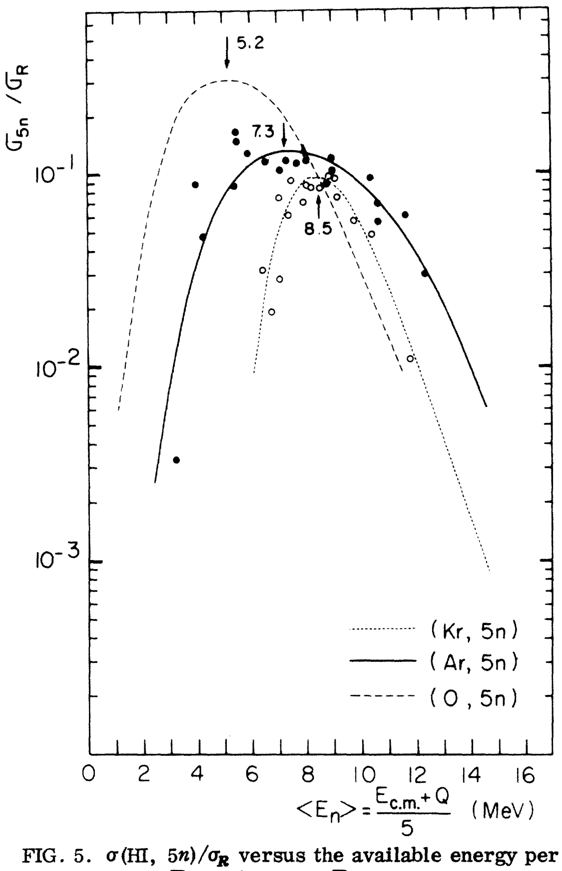

FIG. 5. σ(HI, $5n$)/σ_R versus the available energy per neutron $\langle E_{5n}\rangle = (\bar{E}+Q)/5$ where $\bar{E}$ is the center of mass energy of the bombarding projectile and Q the mass balance. --- is the curve obtained from Ref. 2 for $^{16}O + ^{142}Nd$, ● is $^{40}Ar + ^{118}Sn$, and ○ is $^{84}Kr + ^{74}Ge$.

special effect which inhibits the evaporation of nucleons from the compound system formed with Kr ions, affecting all of the reactions observed, namely (Kr, $4n$), (Kr, $5n$), (Kr, $6n$) and (Kr, $p3n$) and (Kr, $p4n$). For example, in the case of five-neutron emission, the (Kr, $5n$) yield is extremely small in the excitation energy range of 60–75 MeV, where a large probability is found for the (Ar, $5n$) reaction. We emphasize again that the energy measurements were made with great care and note that a shift of 15 MeV in excitation energy corresponds to ≈35 MeV in beam energy.

The only conclusion which we can reach at the present time is that a fairly large amount of energy is somehow dissipated in the interaction of Kr with Ge so that the compound nucleus which is formed does not share all of the excitation energy which is deduced from the $\bar{E}+Q$ balance. One possible explanation for our results, suggested by Blann,[12] could be the preequilibrium emission of one or two neutrons with large kinetic energy from the system (Kr + Ge). Then a smaller energy deposit would be left in the residual excited nucleus. For example, this could explain, at least qualitatively, why a large yield for (Kr, $3n$) is observed at $E^* \sim 75$ MeV, although the (Kr, $5n$) reaction is expected with a large probability on the basis of the (Ar, $5n$) results: The first neutron emitted, in a preequilibrium state, could carry away a large part of the available energy, so that, in a second step, *only* two additional neutrons could be evaporated under equilibrium conditions. Indeed, we have noted that with ^{70}Ge, ^{152}Er was still obtained at excitation energies between 60 and 75 MeV. Taking account of the neutron binding energy, we find an average energy available per neutron for the (Kr, $2n$) reaction of the order of 25 MeV. It seems unreasonable to try to explain these results by a deexcitation process from ^{154}Er after full equilibrium has been attained.

Other explanations of our data, involving entrance-channel effects, may also be possible. For example, consideration of the dynamical aspects of the fusion of two heavy liquid-drop nuclei,[13,14] indicates that an energy significantly higher than the usual interaction barrier is required if mass transfer (and thus fusion) is to occur. However, the fact that at energies lower than the threshold for the (Kr, $5n$) reaction, large cross sections were found for (Kr, $4n$) and (Kr, $3n$) reactions (see Fig. 3), would seem to indicate that an elevated fusion barrier is not responsible for the observed shifts in the (Kr, xn) excitation functions.

Detailed consideration of such approaches is beyond the scope of this paper. Our purpose here is to demonstrate that definite differences related to the entrance channel are observed in krypton-induced reactions, as compared to argon-induced reactions that lead to the same compound system. It would be desirable to repeat this type of cross-bombardment experiment on another system, for example ($^{40}Ar + ^{160}Dy$) and ($^{84}Kr + ^{116}Cd$) that lead to ^{200}Po. Although we have preliminary results,[8,15] the small cross sections encountered require higher intensities of krypton ions than are available at Orsay.

Note added in proof: Since this paper was submitted for publication, we have come to the conclusion that another possible explanation of the energy shift of the (Kr, xn) excitation functions is indeed a depletion of the angular momentum population for low l values. If one assumes that a lower cutoff in angular momentum also exists for forming the compound system (an "angular-momentum window"), then the low-energy part of the excitation function for a given x value is suppressed; the threshold for that reaction shifts to higher energy, and the excitation function becomes narrower. Statistical-model calculations have verified these effects. Note also that Swiatecki and Tsang,[17] in treating the dynamics of collisions of heavy nuclei, have considered the possibility that low l waves do not contribute to complete fusion reactions.

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