strengths of the previously known 2^+ levels at 1276 and 1496 keV. The former was proposed as a β vibrational level. From the γ-ray yields, these values are $B(E2)_{exc} \leq 2\times10^{-51}\ e^2\text{cm}^4$ for the 1276-keV level, and $B(E2)_{exc} \leq 10^{-50}\ e^2\text{cm}^4$ for the 1496-keV level. The ratio of these values to the single-particle estimates are ≤ 0.07 and ≤ 0.34, respectively. Since these values are considerably less than the single-particle estimate, the levels do not appear to be collective. If the three 0^+ excited levels in ^{178}Hf as well as the 2^+ levels at 1276 and 1496 keV are all interpreted as two-quasiparticle states, the β-decay feedings[10] agree well with the predictions of Soloviev.[17] Also, $M1$ admixtures can be expected, since $M1$ transitions to the ground-state band then are not hindered in general, nor are the $E2$'s enhanced as for quadrupole vibrational states.

In conclusion, we have definitely established the $2^+\ \gamma$ vibrational state in ^{178}Hf and shown that there is no evidence for β vibrational states around 1.3 MeV, as earlier suggested.[7] This work thus confirms the conclusion of the previous paper[5] that the proposed[6,7] β vibrational states in ^{178}Hf are not such collective states and removes the one case thought to agree with Mottelson's suggestion.[4]

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Behavior of the Cross Sections for Polonium Production in Nuclear Reactions of Ar^{40} with Dy^{104}

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Excitation functions are reported for the reactions of ^{164}Dy with ^{40}Ar to produce ^{200}Po and ^{199}Po. The cross sections are much smaller than the calculated values and it is concluded that this is due to an angular momentum cutoff and to a large fission width. The reaction threshold at a laboratory energy of 4.2 MeV per nucleon indicates a low Coulomb barrier ($r_0 = 1.45$ fm).

The argon ion beam recently available from the heavy-ion accelerator ALICE has been used for bombardment of dysprosium at various energies between 168 and 185 MeV. The determination of the energy has been made very precisely by measurements with a magnetic spectrometer of magnetic rigidity (BR) corresponding to the scattered Ar beams with electronic charges 16, 17, and 18.

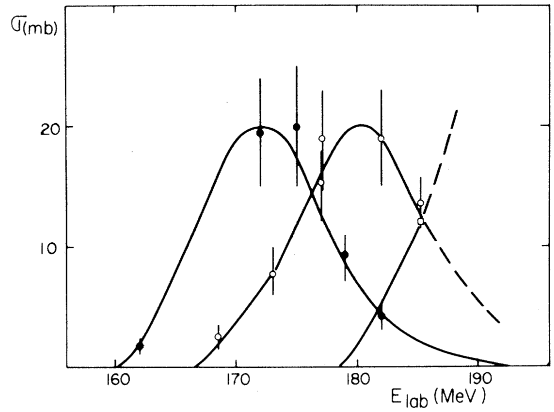

FIG. 1. Excitation functions for the reactions: ^{164}Dy-(Ar, $4n$)^{200}Po O, from Sikkeland *et al.*, Ref. 1; ^{164}Dy-(Ar, $4n$)^{200}Po ○, present work; ^{164}Dy(Ar, $5n$)^{199}Po □, present work. The curves have been drawn through the experimental points.

The main purposes of this preliminary study were as follows: (1) to determine the reaction threshold and therefore the Coulomb barrier for the reactions of Ar with Dy and (2) to obtain the excitation function for the heaviest product from the compound-nucleus process ^{164}Dy(Ar, $4n$)^{200}Po. A secondary purpose was to compare the experimental cross sections with the calculated values of the total cross section in order to estimate the ratio of evaporation width to fission width. These results are of some interest for the evaluation of possibilities for production of superheavy elements by heavy-ion bombardments of heavy targets. In the course of this work, similar experiments were made by Sikkeland *et al.*[1] Although our results are in fairly good agreement with theirs, we have found that the energy range of the excitation function differs by 6 to 8 MeV and therefore our reaction threshold is correspondingly higher.

1. EXPERIMENTAL RESULTS

The target foils, DyF_3, were 0.29 mg/cm^2, with an isotopic composition as follows: 98.6% 164, 1.1% 163, 0.18% 162, and 0.12% 161. Polonium nuclei that recoiled from the target were detected by the α radiation from the Al collectors placed behind the target.

The reaction chamber in which the irradiation was carried out was also a Faraday cup for the measurement of beam intensity. ^{201}Po, ^{200}Po, and ^{199}Po were searched for. The cross section for ^{201}Po is smaller by at least a factor of 10 than that for ^{200}Po; this shows that the evaporation process from the compound nucleus ^{204}Po gives a chain of at least four neutrons. In Fig. 1, the excitation function is given for ^{200}Po. We have observed that the threshold of the reaction Dy(Ar, $5n$)^{199}Po is at about 180 MeV, essentially the energy of the maximum yield for ^{200}Po. The Coulomb barrier obtained from these data is equal to 167 MeV in the laboratory system and corresponds to a radius parameter r_0 of 1.45×10^{-13} cm, in good agreement with the results for the fission of uranium induced by argon ions.[2]

2. REMARKS ON THE SIGNIFICANCE OF THE RESULTS

(a) The value given above for the Coulomb barrier (135 MeV in the center of mass) shows clearly that the effect of nuclear deformation on the Coulomb barrier, as suggested by Beringer[3] is not observed experimentally. For most heavy-ion reactions, regardless of whether the projectile is ^{12}C, ^{16}O, or ^{20}Ne, it has been found that the Coulomb barrier can be approximated by taking $Z_1Z_2e^2/r_0(A_1^{1/3}+A_2^{1/3})$ with r_0 of 1.5 fm. This appears to be still valid for heavier projectiles like Ar ions.

(b) A second interesting point is that a ^{204}Po compound nucleus excited to 61 MeV (bombarding energy 180 MeV) emits on the average only four neutrons, which corresponds to an average avail-

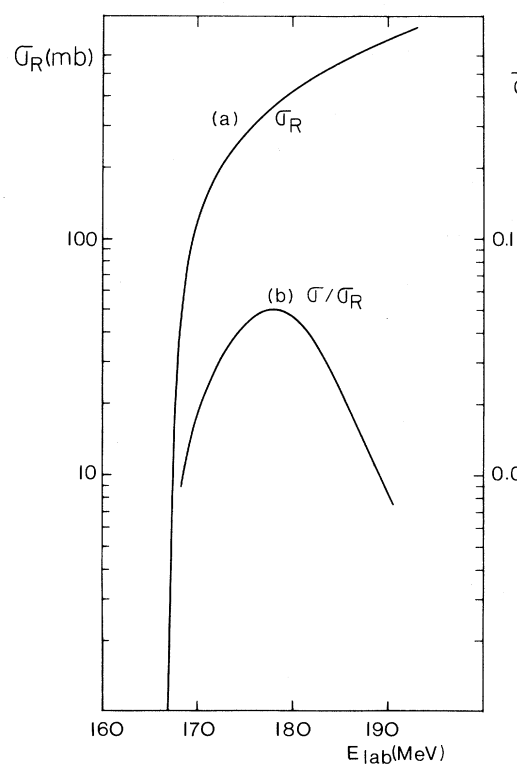

FIG. 2. (a) Total reaction cross section σ_R vs bombarding energy, left scale, calculated from Ref. 6. (b) Fraction of total reaction cross section σ/σ_R vs bombarding energy, right scale.

able energy $(E^*-B)/4$ of ~6 MeV neutron emitted (E^* is the excitation energy, B the sum of the binding energies). This large value has been attributed by Alexander and Simonoff[4] and others to an angular momentum effect. This is very similar to the results obtained by Natowitz and Alexander[5] for the reaction $\mathrm{Cd}(^{40}\mathrm{Ar}, xn)\mathrm{Dy}$, but it was not expected to be so large in the case of polonium products where deexcitation might proceed with high probability by fission, especially for the states of high angular momentum.

(c) It may also be noted that the peak cross section is small if one assumes that $^{200}\mathrm{Po}$ is the major product of the compound-nucleus reaction between 168 and 180 MeV. The total reaction cross section can be calculated either by the optical model, or in a more classical way by $\sigma = \pi R^2(\bar{\epsilon} - V/\bar{\epsilon})$, where $\bar{\epsilon}$ is the energy in the center of mass and V is the Coulomb barrier. Riesenfeld and Thomas[6] and also Natowitz,[7] have shown that the two methods are comparable providing an appropriate adjustment of the radius parameter is made. We have calculated σ_R, the total reaction cross section, and the ratio $\sigma(\mathrm{Ar}, 4n)/\sigma_R$. The highest ratio is found at 180 MeV and is of the order of 0.05, a very small value indeed (see Fig. 2). Therefore, if the calculated total reaction cross section is correct the question arises, "What are the other reaction channels?" The maximum angular momentum for Ar ions on Dy target nuclei is $l = 47\hbar$ at 180 MeV. It is often assumed that the cutoff value is about 45 in this mass region,[5,7] with most of the l values lower than 45 leading to a compound nucleus. It therefore seems likely that a very large fraction of the fusion cross section goes into fission. Also, because of the difficulty of dissipating much angular momentum by neutron emission, the ratio Γ_α/Γ_n might be enhanced considerably, leading to Pb residual nuclei instead of Po.

The last possibility is that, because of the large rotational energies (around 8 to 10 MeV), a large fraction of the fusing nuclei might be formed in such a deformed shape that, after a close approach, the Ar partner does not stick for a very long time but is scattered away either after some loss of kinetic energy or after a loss of a certain number of nucleons. Such a process could be understood as a very short and peculiar sort of compound-nucleus mechanism, in which the memory of the formation step is conserved, and favors a preferential fission.

We hope to obtain further enlightment on these questions by experiments with krypton beams.

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