ment of the high-frequency transition can be met by a moderate-power magnetron feeding a horn radiator or a klystron feeding a resonant cavity (within which the atomic flame could be operated). The necessary klystron power depends on the quality factor (Q) and volume (V) of the resonant cavity, according to the approximate relation

$$P = 2\pi S_0 V \nu_0 / cQ. \quad (10)$$

For the typical values $V = 10^2$ cm^3 and $Q = 5\times10^3$, the klystron power required for a 10% transition probability at 9.6 kMc/sec is 125 mW. This is easily obtained from standard X-band klystrons.

Finally, a word about hyperfine structure. The CN microwave transitions should show a well-resolved splitting into three major hyperfine components, especially at the lower J values, because of magnetic interactions between the uncompensated electronic angular momenta and the magnetic moment of the nitrogen nucleus. (N^{14} also possesses an electric quadrupole moment, and the resulting quadrupole interaction may also be detectable through small line shifts.) The intensities of the three hyperfine components should be more or less equal, so, to be on the safe side, one should multiply the results of the minimum power calculations by three. Thus, a 375-mW klystron might be necessary for an investigation of the 9.6-kMc/sec spectrum.

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Recoil Studies of Reactions of Indium with Medium Energy Protons and Alpha Particles*

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Recoil ranges projected along the beam direction have been measured for the $(\alpha,\alpha\gamma)$, $(\alpha,\alpha n)$, (α,pn), and $(p,p\gamma)$ reactions on In^{115} and for the $In^{113}(p,n)$ reaction, with 5 to 10 MeV protons and 20 to 40 MeV alpha particles. The results have been compared with values expected for compound-nucleus formation and reasonable agreement is obtained for the (α,pn), $(p,p\gamma)$, and (p,n) reactions. The measured range for the $(\alpha,\alpha n)$ reaction agrees with calculation at the lowest energy studied but is somewhat low at the highest bombarding energy. In the case of the $(\alpha,\alpha\gamma)$ reaction the measured ranges are a factor of 3 to 6 smaller than the calculated values, indicating a direct interaction process. The recoil ranges expected for Coulomb excitation have been computed for the $(\alpha,\alpha\gamma)$ and $(p,p\gamma)$ reactions and are substantially smaller than the experimental values. Excitation function measurements for the (α,pn) reaction are also presented.

I. INTRODUCTION

EXCITATION-FUNCTION measurements for reactions of In^{115} with medium-energy alpha particles, deuterons, and protons have been reported recently.[1] In particular, cross sections for the formation of In^{115m} were obtained for all the above bombarding particles. The cross sections for the $(\alpha,\alpha\gamma)$ reaction were compared in detail with the statistical theory and a definite disagreement was found for bombarding energies above 25 MeV. The contribution of the Coulomb excitation process was estimated and found to be substantial, particularly below 25 MeV. It was impossible to draw definite conclusions about the mechanism responsible for the other reactions leading to the formation of In^{115m}. This same uncertainty also applied to the $In^{115}(\alpha,\alpha n)\,In^{114m}$ reaction whose excitation function was also obtained in that study.

In order to obtain additional information about some of the above reactions, an investigation of the recoil properties of the reaction products has been carried out.[2] The fraction of activity recoiling in the forward direction out of a target thick compared with the recoil range has been measured for the following reactions: $In^{115}(\alpha,\alpha\gamma)In^{115m}$, $In^{115}(\alpha,\alpha n)In^{114m}$, $In^{115}(\alpha,pn)Sn^{117m}$, $In^{115}(p,p\gamma)In^{115m}$, and $In^{113}(p,n)Sn^{113}$. In addition, the excitation function for the (α,pn) reaction has also been obtained. Previous measurements of this type have been carried out in this energy range for reactions of alpha particles with aluminum,[3] potassium,[4] bismuth,[5] as well as for a number of heavy ion induced reactions.[6]

II. EXPERIMENTAL PROCEDURE AND RESULTS

The target foils consisted of natural indium evaporated to a thickness of 1 to 2 mg/cm^2 onto high-purity

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0.001-in. thick aluminum. The recoil catcher foils were of this same aluminum and were positioned in contact with the target so that recoils emitted along the beam direction were collected. In several instances the orientation of the foils was reversed and recoils emitted in the backward direction were collected. Several additional aluminum foils were included in the stack for the determination of activity resulting from the activation of impurities. The number of target foils included in the foil stack varied from 2 to 6.

Irradiations were performed with the deflected proton and alpha beams of the Brookhaven 60-in. cyclotron. The foils were irradiated in a previously described[7] Faraday-cup assembly. The cross-sectional area of the beam was smaller than that of the foils so that there was no recoil loss due to edge effects. The assembly was evacuated in all but one of the irradiations. In this irradiation, in which the $(\alpha,\alpha n)$ and (α,pn) recoil ranges were measured, the results do not appear to be different from a second irradiation with the foils in vacuum. The energy of the incident beam was determined by the copper-ratio method[8] or by range measurements. A range-energy relation based on Bichsel's[9] measurements of proton ranges was used. In the course of this work a total of seven bombardments was performed. The duration of these bombardments ranged from 1 to 7 h, with beam currents of 1 to 7 μA of fully ionized particles.

After irradiations designed for study of the $(\alpha,\alpha\gamma)$ reaction the various foils were dissolved in HBr. The In was extracted[10] with bis 2-chloroethyl ether and back extracted with HCl. After a scavenging precipitation of antimony sulfide, the solution was neutralized and In_2S_3 was precipitated and mounted for assay. No chemical separations were perfromed for all the other reactions studied.

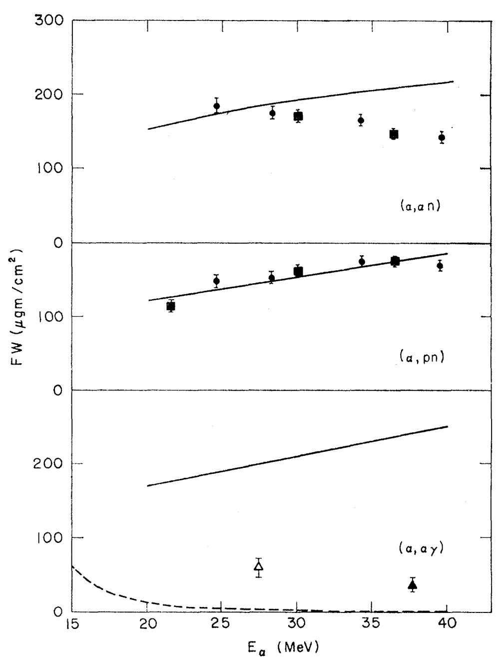

FIG. 1. Projected ranges for alpha-induced reactions. The solid curves are calculated for compound-nucleus formation. The dashed curve for the $(\alpha,\alpha\gamma)$ reaction refers to estimates for Coulomb excitation. The different symbols indicate different bombardments.

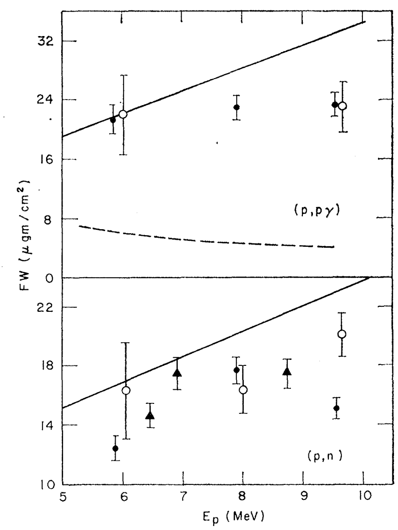

FIG. 2. Projected ranges for proton-induced reactions. The solid curves are calculated for compound-nucleus formation. The dashed curve is the estimate for Coulomb excitation. The different symbols indicate different bombardments.

The activity of the samples was determined in a variety of ways. In most cases a calibrated 3- × 3-in. NaI(Tl) crystal connected to a 100-channel pulse-height analyzer was used. The radiations detected from 49-day In^{114m}, 14-day Sn^{117m}, and 4.5-h In^{115m} were the 192, 160, and 335 keV gamma rays,[11] respectively. In the case of 115-day Sn^{113} the 392-keV gamma ray of the In^{113m} daughter was detected. In some cases a 6-mm thick NaI crystal was used in order to obtain a lower background rate. In the case of In^{115m} formed in the $(p,p\gamma)$ reaction the x rays resulting from the internal conversion of the isomeric transition were detected by a 2-mm thick NaI crystal with pulse-height analysis. This procedure gave sufficiently low backgrounds to permit the detection of the low activity rates of the catcher foils. The activity of the activation blanks was always less than 1% of that of the forward recoil catcher except in the case of one of the $(p,p\gamma)$ experiments where a 25% correction was determined. The formation of In^{115m} and In^{114m} in reactions of In^{113} with alpha particles has been investigated previously[1] at these energies and found to be negligible in comparison with the formation of these nuclides from In^{115}.

The results for In^{115m} suffer from the fact that this isomer is produced with very high cross section by the

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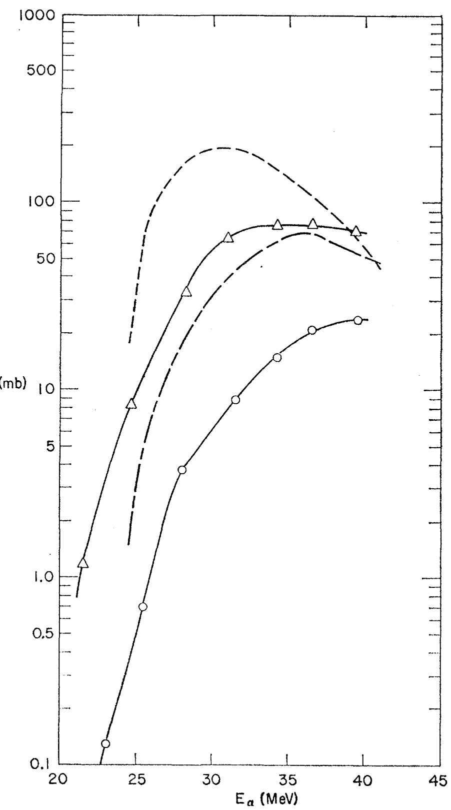

FIG. 3. Excitation functions for the $In^{115}(\alpha,\alpha n)In^{114m}$ (○) and $In^{115}(\alpha,pn)Sn^{117m}$ (△) reactions. The long- and short-dashed curves are evaporation calculation estimates for the $(\alpha,\alpha n)$ and (α,pn) reactions, respectively.

$(n,n\gamma)$ reaction[12] on In^{115}. The effect of this reaction on the measured cross sections for the $(\alpha,\alpha\gamma)$ and $(p,p\gamma)$ reactions was previously investigated,[1] and it was found that the flux of secondary neutrons was sufficiently high to account for a substantial fraction of the observed yields below 18 and 7 MeV, respectively. Thus, the results reported for the $(p,p\gamma)$ reaction at this lowest bombarding energy are quite uncertain. For the $(\alpha,\alpha\gamma)$ reaction the observed excitation function was used to correct the ranges at the higher bombarding energies. It was assumed that the $(n,n\gamma)$ contribution is constant through the foil stack[1] and that the range of the $(n,n\gamma)$ recoils is negligible compared to that of the $(\alpha,\alpha\gamma)$ recoils. The latter is justified if it is assumed that the neutrons responsible for the $(n,n\gamma)$ reaction have an energy of 2.5 MeV, corresponding to the peak of the $(n,n\gamma)$ excitation function.[12] This correction raised the $(\alpha,\alpha\gamma)$ ranges reported in Fig. 1 by 25%.

The experimental results may be expressed in terms of the variation of FW with bombarding energy, as shown in Figs. 1 and 2. F is the fraction of the total activity of a given nuclide found in the forward recoil catcher, W is the target thickness, and FW is the average projected recoil range along the beam direction in the target material. It is seen that the ranges are much larger in the case of the alpha-induced reactions than in the case of the proton-induced reactions. This fact reflects the larger momentum of the incident alpha particle. It is also seen that the ranges of the various alpha-induced reactions differ from each other by substantial factors and show different trends with bombarding energy. A detailed analysis of these results is presented in the following section. The ratios of forward to backward emission were measured for all the reactions of interest and were found to be greater than 100 for the (α,pn) and $(\alpha,\alpha n)$ reactions at 35 MeV and the (p,n) reaction at 8 MeV. The ratio was about 20 for the $(\alpha,\alpha\gamma)$ reaction at 35 MeV and the $(p,p\gamma)$ reaction at 9 MeV. If compound-nucleus formation is assumed then backward recoil emission is forbidden by momentum conservation considerations. However, when the recoil ranges are small and the laboratory angular distributions are expected to be broad, it appears that backward emission does become significant, probably because of scattering effects.

The excitation functions for the (α,pn) and $(\alpha,\alpha n)$[1] reactions are shown in Fig. 3. In both cases only the cross section for the formation of the isomeric state has been measured. These results are compared with evaporation calculations in the following section.

III. DISCUSSION

The procedure in this section will be to compare the measured projected ranges with values expected for the complete transfer of momentum of the incident particle to the struck nucleus, which we shall call compound-nucleus formation. This definition is equivalent to the statement that in the center-of-mass system the outgoing particles are emitted symmetric about 90° to the beam direction. It should be noted that the recoil properties of the reactions which have a large ratio for the mass of the outgoing particles to the mass of the bombarding particle, are more sensitive to the angular distribution and energy spectra of the emitted particles.

In calculating projected ranges assuming compound-nucleus formation Winsberg and Alexander[6] pointed out that although FW is mainly a measure of the velocity imparted to the struck nucleus along the beam direction, (v), there is a correction due to the velocity imparted to the recoil by particle evaporation, (V). This correction is only important when range is not proportional to velocity. Winsberg and Alexander give the relationship

$$FW=R_0(1+(2/3)\mu^2-(1/15)\mu^4), \qquad (1)$$

where $\mu=V/v$. The range-velocity relationship is $R=k|\mathbf{v}+\mathbf{V}|^N$, where k and N are constants and R_0 is the recoil range corresponding to v only, i.e., $R_0=kv^N$. Equation (1) assumes that the fragment range is proportional to its energy $(N=2)$, that the angular dis-

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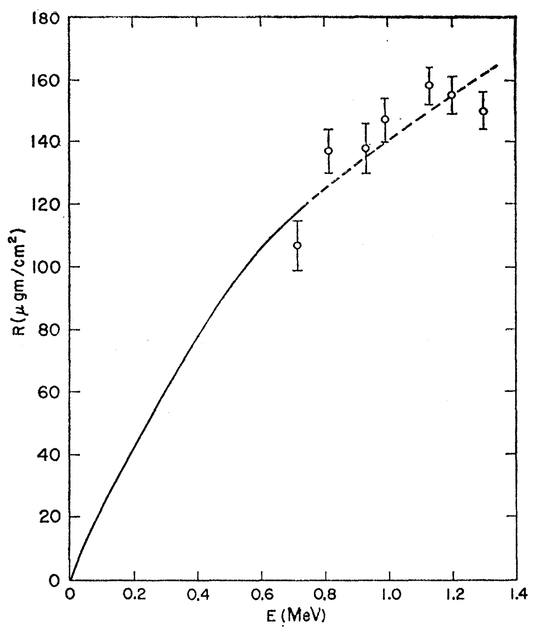

FIG. 4. Range projected along the beam axis for $\approx In^{115}$ recoils in In. Solid curve from Lindhard and Scharff. Points from (α,pn) recoil data.

tribution of the evaporated particles is isotropic in the center-of-mass system, that V has a unique value which is less than v, and that the production rate is constant over the target thickness. The situation for a nonconstant production rate has been considered by Porile.[3] In the present experiment the effect of the change in production cross section over an energy corresponding to the target thickness is less than 3% and can be neglected. The values of μ were obtained from the expression

$$\mu^2=(M_{CN}^2/M_R^2M_PE_P)\sum M_eE_e, \qquad (2)$$

where M and E are mass and kinetic energy and the subscripts CN, R, P, and e, refer, respectively, to the compound nucleus, the residual fragment, the bombarding particle, and the emitted particles. The summation is carried out over all the emitted particles. The values of E_e were estimated from the reaction kinematics as follows. It was assumed that the charged particles were evaporated with an energy equal to that of the Coulomb barrier when energetically possible. The neutrons were assumed to have an energy of 2 MeV when energetically possible. If with these conditions, more than 6 MeV was left behind for gamma-ray emission, the excess was divided between the outgoing particles. The values of FW/R_0 thus calculated for the $(\alpha,\alpha n)$, (α,pn), $(\alpha,\alpha\gamma)$, $(p,p\gamma)$, and (p,n) reactions were approximately 1.33, 1.09, 1.48, 1.57, and 1.18, respectively, and were not very sensitive to bombarding energy.

We wish to compare the measured values of FW with values calculated on the assumption of compound-nucleus formation. In order to obtain R_0 from the kinetic energy of the compound nucleus, or from that of the bombarding particle, a range-energy relation is needed. A universal range-energy relation for low-energy recoils has been proposed by Lindhard and Scharff.[13] This relation applies in the region where energy loss is due mainly to atomic collisions. In the case of indium recoils in indium the relation is expected to be valid for recoil energies up to about 0.75 MeV and is shown in Fig. 4 as the solid curve. At higher energies it is expected that the ionization mechanism will become more important than the 20% effect estimated by Lindhard and Scharff at 0.75 MeV. Since the recoil energy for complete momentum transfer of a 40-MeV alpha particle is about 1.3 MeV, it is clear that the calculated range-energy relation must be extended. Assuming that the mechanism of the (α,pn) reaction involves full momentum transfer, the experimental FW values for this reaction were converted to R_0 values and plotted in Fig. 4. The agreement with the Lindhard and Scharff curve at the lowest bombarding energy indicates that this assumption is correct at 22 MeV. The generally rising shape of the curve indicates that there is probably no large deviation from full momentum transfer even at the highest bombarding energy. The best curve through the points and the Lindhard and Scharff calculation was adopted as the range-energy relation and used together with the FW/R_0 values derived above to calculate projected recoil ranges. These values of FW, calculated assuming compound-nucleus formation, are shown as the solid curves in Figs. 1 and 2.

The ranges of the $(\alpha,\alpha\gamma)$ reaction recoils are much smaller than the values expected for compound-nucleus formation and indicate that this mechanism is of little importance for the reaction. This result is in agreement with the conclusions based on the excitation function measurements.[1] It has been previously pointed out[1] that Coulomb excitation may make a substantial contribution to the cross section for the $(\alpha,\alpha\gamma)$ reaction. The recoil range for this process may be computed from the calculated differential cross section[14] on the assumption that an $E2$ process is primarily responsible.[1] The projected ranges obtained in this fashion are indicated by the dashed line in Fig. 1. While it is seen that the experimental ranges are considerably larger, it is clear that a small admixture of a process involving compound-nucleus formation could account for the experimental results. The situation is complicated by the fact that, in addition to the above two mechanisms, inelastic scattering can also contribute to the formation of In^{115m}. The recoil range expected for this process depends on the scattering angle. The experimental range at 37 MeV is consistent with an average scattering angle of about 45°. This value seems somewhat too large for a direct

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interaction process and again indicates a small admixture of an evaporation process. The present results thus do not discriminate between Coulomb excitation and inelastic scattering, but do indicate that the contribution of compound-nucleus formation is small.

The results for the $(\alpha,\alpha n)$ reaction are consistent with compound-nucleus formation at 25 MeV but appear to reflect an increasing contribution of a direct interaction process in comparison to the (α,pn) reaction as the bombarding energy is increased. However, the values of FW/R_0 used to draw the solid curve were calculated assuming range proportional to energy. It is known that at higher energies range becomes proportional to velocity and there appears to be some indication of this effect at the top of Fig. 4. If this were true the calculated curve for FW would be somewhat lower and the discrepancy not as great. However it is unlikely that the shape of the range-energy curve changes as drastically as from range-proportional-to-energy at 0.8 MeV to range-proportional-to-velocity at 1.3 MeV. Thus, low momentum transfer is indicated at the higher bombarding energies. It is reasonable to assume that the mechanism responsible for this result is inelastic scattering followed by neutron evaporation because of the large $(\alpha,\alpha n)$ to $(\alpha,\alpha p)$ cross-section ratio obtained in this mass region.[15] The direct knockout of a neutron by the incident alpha particle would lead to smaller $(\alpha,\alpha n)/(\alpha,\alpha p)$ cross-section ratios.

The excitation functions for the $(\alpha,\alpha n)$ and (α,pn) reactions are compared with the results of an evaporation calculation in Fig. 3. The calculation was performed by the Monte Carlo technique[16] for a radius parameter $r_0 = 1.7$ F and with a level density parameter $a = A/30$. The calculated values are larger than the experimental cross sections, as expected from the fact that the latter refer only to the formation of the isomeric states. The over-all fit to the shape of the excitation functions is about the same for both reactions and it would thus be impossible to ascribe to them differences in mechanism on this basis. It can thus be seen that the recoil measurements yield more definitive information than the excitation function measurements.

The results for the (p,n) and $(p,p\gamma)$ reactions are slightly lower than the curves calculated assuming compound-nucleus formation. This may merely reflect the uncertainty in the range-energy relation. The dashed line for the $(p,p\gamma)$ reaction refers to the ranges expected for Coulomb excitation. It is seen that the experimental values are much larger than these calculated values indicating that the contribution from this process is small.

In conclusion, it is seen that the results of the present study corroborate the conclusions based on excitation function measurements on the same system,[1] and in several instances actually yield more definitive information on the reaction mechanism. We believe that the use of both techniques will give the most useful information about reactions in this energy range. Obviously, it would also be very desirable to correlate these results with measurements on the particles emitted in the same reactions.

The cooperation of Dr. C. P. Baker and the operating crew of the 60-in. cyclotron is greatly appreciated. The chemical-yield measurements were performed by the analytical chemistry group. The cooperation of R. Withnell in the preparation of the target foils is appreciated.

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