tions for proton scattering with the loosely bound neutron in Be^9. If this model is correct, it can be stated within the experimental accuracy that the forward exchange scattering cross section for bound and free $n-p$ collisions are the same. It must be emphasized, however, that the loosely bound neutron in Be^9 is not necessarily representative of neutrons embedded in nuclear matter.

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The (α,n) and $(\alpha,2n)$ Cross Sections of Ag^{109}†

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The excitation curves for the reactions $Ag^{109}(\alpha,n)In^{112}$ and $Ag^{109}(\alpha,2n)In^{111}$ have been measured for alpha-energies up to 19.5 Mev. The threshold for the $(\alpha,2n)$ reaction is 14.8 ± 0.2 Mev. The sum of the cross sections agrees approximately with the total cross section calculated for a radius $R\sim1.6\times10^{-13}A^{\frac{1}{3}}$ cm. The energy dependence of the ratio $\sigma(\alpha,2n)/\sigma(\alpha,n)$ can be interpreted as being in agreement with either a nearly constant nuclear temperature of 1.7 Mev or with a level density $\omega(E)=\text{const}\exp[2(aE)^{\frac{1}{2}}]$ with $a=2.5$ Mev^{-1}. The corresponding temperature $\Theta=(E/a)^{\frac{1}{2}}$ varies from 1.7 Mev to 2.2 Mev for excitation energies between 7.5 and 12 Mev. These apparent temperatures are considerably higher than those found by direct measurement of (p,n) and (n,n) neutron spectra.

I. INTRODUCTION

ACCORDING to the theory of nuclear reactions, as developed on the basis of the Bohr assumption, the determination of the relative cross sections for primary and secondary reactions can furnish information about the level spacing for intermediate and heavy nuclei.[1,2] Consider the reactions $Ag^{109}(\alpha,n)In^{112}$ and $Ag^{109}(\alpha,2n)In^{111}$. The energy distribution of the primary neutrons is given by

$$I(\epsilon)d\epsilon=\text{const}\;\epsilon\sigma_C(\epsilon)\omega(\epsilon_{\max}-\epsilon)d\epsilon, \quad (1)$$

where $\sigma_C(\epsilon)$ is the cross section for the formation of the compound nucleus In^{113} from the level of the residual nucleus In^{112} reached in the reaction. If $\sigma_C(\epsilon)$ is known from the theory the level density ω of In^{112} at an excitation energy $E=\epsilon_{\max}-\epsilon$ can be computed directly from the measured intensity distribution $I(\epsilon)$. The measurement of neutron spectra, however, is rather tedious and, for higher excitation energies, made uncertain by the emission of secondary neutrons. Relative cross sections, on the other hand, can be determined by simple activity measurements. Assuming that a second neutron is evaporated whenever it is energetically possible, one obtains for the cross-section ratio

$$r(\epsilon_\alpha)=\sigma(\alpha,2n)/\sigma(\alpha,n) = \int_0^{\epsilon_{\max}-S} I(\epsilon)d\epsilon \Big/ \int_{\epsilon_{\max}-S}^{\epsilon_{\max}} I(\epsilon)d\epsilon. \quad (2)$$

Here, ϵ_α is the initial kinetic energy in the c.m. system, i.e., essentially the alpha-energy. S is the separation energy of the second neutron from In^{112}, $\epsilon_{\max}-S=\epsilon_\alpha-T_{2n}$ the maximum energy a primary neutron can have without making the escape of a secondary neutron impossible. T_{2n} is the threshold energy for the $(\alpha,2n)$ reaction.

It is obvious that the level density $\omega(E)$ is not determined uniquely by (2), even if the cross-section ratio is known as a function of ϵ_α. Neglecting the variation of $\sigma_C(\epsilon)$ one obtains, for $E=S+\epsilon_\alpha+T_{2n}$,

$$\omega(E)=\text{const}\left\{\frac{d^2r}{d\epsilon_\alpha{}^2}+B\left[2\frac{dr}{d\epsilon_\alpha}+(\epsilon_\alpha-T_{2n})\frac{d^2r}{d\epsilon_\alpha{}^2}\right]\right\},$$

with

$$B=\int_0^S\omega(E)dE\Big/\int_0^S dE\int_0^E\omega(E')dE'.$$

Since B is not known, no direct calculation of $\omega(E)$ is possible. Instead, the measurements are used to determine the parameter in some assumed level density function, e.g., the nuclear temperature Θ. By developing the logarithm of the level density in the neighborhood of $\epsilon_{\max}$, using $d(\ln\omega)/dE=1/\Theta$, one can approximate Eq. (1) by $I(\epsilon)=\text{const}\;\epsilon\sigma_C(\epsilon)e^{-\epsilon/\theta}$. Assuming $\sigma_C(\epsilon)=\text{const}$, and $\epsilon_{\max}\gg\epsilon_{\max}-S$, the cross-section ratio becomes

$$r(\epsilon_\alpha)=\sigma(\alpha,2n)/\sigma(\alpha,n)=e^x/(1+x)-1=f(x), \quad (3)$$

with $x=(\epsilon_\alpha-T_{2n})/\Theta$.

Theoretical estimates of the dependence of Θ on E vary with the model used. Blatt and Weisskopf[2] give, for a degenerate-gas model, $\Theta=(E/a)^{\frac{1}{2}}$, which leads to

† Work supported by the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
* Now at U. S. Military Academy, West Point, New York.
[1] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472, 935 (1940).
[2] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. VIII.

$\omega(E)=\text{const}\ \exp[2(aE)^{\frac{1}{2}}]$. For $A=115$ they estimate $a=8\ \text{Mev}^{-1}$, giving $\Theta=1.1$ Mev at 10-Mev excitation energy.

An investigation to determine Θ by measuring the relative cross sections of (α,n) and ($\alpha,2n$) reactions was started by Lark-Horovitz and co-workers;[3] Bradt and Tendam[4] obtained results with Ag and Rh from which they concluded that, for alpha-energies between 15 and 19 Mev, Θ is approximately 1.8 Mev.

Recently, Gugelot[5] measured the energy distribution of neutrons emitted in reactions produced by 16-Mev protons. For $A\sim 100$ it can be represented by $I(\epsilon)=\text{const}\ \epsilon\exp(-\epsilon/\Theta)$, with $\Theta=0.8$ to 0.9 Mev. Similarly, the energy spectrum of inelastically scattered neutrons, at 14-Mev primary energy, measured by Graves and Rosen,[6] appears like a Maxwellian distribution corresponding to temperatures of about 0.7 Mev for all but the lightest nuclei. In view of these discrepancies, the measurements of Bradt and Tendam were repeated with increased accuracy.

II. EXPERIMENTAL PROCEDURE

The earlier measurements with silver had been performed using stacked foils. The analysis of the decay curves, comprising half-lives of 14.5 and 20.7 min ($In^{112,112m}$), 66 min (In^{110}), 4.3 hr (In^{109}), 4.9 hr (In^{110m}), and 2.84 days (In^{111}), is somewhat uncertain, especially for the shorter periods, since several foils must be counted with the same counter. Since the activities arising from the irradiation of Ag^{107} are not well suited for the determination of excitation curves because of the nearly identical periods of In^{109} and In^{110m} it was decided to use enriched Ag^{109}.[7] A foil of 2.5 mg/cm^2 (92.16 percent Ag^{109}) was prepared by electrolysis from a cyanide solution onto a pure iron sheet. The iron backing with the silver deposit was mounted between two silver plated brass rings serving as the target holder for the bombardments. The silver was coated with polystyrene and the iron etched away with 5 percent sulfuric acid. Then the plastic coat was removed with chloroform. The thickness of the foil was determined by comparing the reduction in range of Po alpha-particles with that by a natural Ag foil of known weight.

The same foil was used for the entire excitation curves, a separate bombardment being performed for each energy. The range of the cyclotron beam was measured by a remotely controlled absorption apparatus[8] patterned after that of Kelly.[9] The energy was reduced to the desired value by a monitor foil of 2.85 mg/cm^2 natural silver and suitable aluminum absorbers. The beam current integrator was read every minute so that, for each activity produced, the equivalent number of alpha-particles at the end of the irradiation ($t=0$) could be computed,

$$Q_\lambda=\frac{1}{2e}\int_{-\infty}^{0} i(t)e^{\lambda t}dt.$$

The 66-min activity of the monitor foil was used to check the reliability of the current integrator; the agreement was within 2 percent, i.e., within the accuracy of the decay-curve analysis.

The activities were measured in a standard arrangement with a thin-window beta-counter. The absolute efficiency for the radiations of In^{111} was determined by measuring the decay rate of a strong sample of the same thickness by means of gamma-gamma-coincidences (see decay scheme, Fig. 1). Corrections for the maximum angular correlation of In^{111}, $f(\vartheta)=1.071(1-0.20\cos^2\vartheta)$, were applied, since the In^{111} was embedded in the silver target.[10]

The decay rate of the isomeric state of In^{112} (see decay scheme, Fig. 1)[11] was determined by measuring the intensity of the conversion line of the isomeric transition in a lens spectrometer whose geometrical factor was found, with the aid of the K conversion lines of the In^{111} sample whose strength was known. The conversion coefficients measured by McGinnis[12] (for In^{111}) and calculated by Rose *et al.*[13] were used.

The relative cross sections for the production of the two states of In^{112} were obtained by setting the spectrometer at 330 kev and following the decay of the beta-radiation, emitted from the ground state only. The initial activities, A_g and A_m, of the two components of the decay curve are related to the cross sections by

$$\frac{\sigma_g}{\sigma_m}=\frac{\lambda_m}{\lambda_g-\lambda_m}\left(1+\frac{A_g/Q_g}{A_m/Q_m}\right),$$

where the indices g and m refer to the ground state and metastable state, respectively, and Q_g, Q_m are the cor-

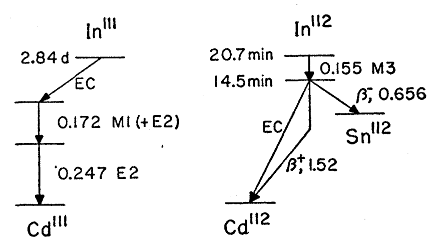

FIG. 1. Decay schemes of In^{111} (see reference 12) and In^{112} (see reference 11). Energies in Mev, not drawn to scale.

[3] Lark-Horovitz, Risser, and Smith, Phys. Rev. **72**, 1117 (1947).
[4] H. L. Bradt and D. J. Tendam, Phys. Rev. **72**, 1117 (1947).
[5] P. C. Gugelot, Phys. Rev. **81**, 51 (1951), contains a rather complete list of references.
[6] E. R. Graves and L. Rosen, Phys. Rev. **87**, 239 (1952).
[7] Obtained from the Isotopes Division of the U. S. Atomic Energy Commission, Oak Ridge, Tennessee.
[8] Gailar, Seidlitz, Bleuler, and Tendam, Rev. Sci. Instr. **24**, 126 (1953).
[9] E. L. Kelly, Phys. Rev. **75**, 1006 (1949).
[10] Aeppli, Frauenfelder, and Walter, Helv. Phys. Acta **24**, 335 (1951).
[11] Bleuler, Blue, Chowdary, Johnson, and Tendam, Phys. Rev. **90**, 464 (1953).
[12] C. L. McGinnis, Phys. Rev. **81**, 734 (1951).
[13] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

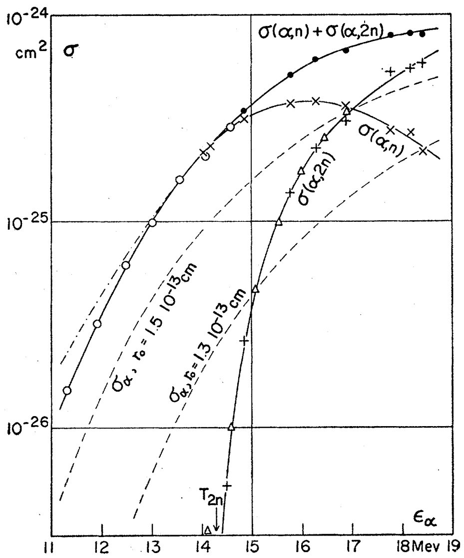

FIG. 2. Excitation curves of the alpha-particle reactions with Ag^{109}. Present, absolute measurements: $+=\sigma(\alpha,2n)$, $\times=\sigma(\alpha,n)$, $\bullet=\sigma(\alpha,n)+\sigma(\alpha,2n)$. Adjusted relative measurements by Bradt and Tendam (reference 4): $\triangle=\sigma(\alpha,2n)$, $\bigcirc=\sigma(\alpha,n)$, assuming constant σ_g/σ_m, —·—·— estimated maximum values of $\sigma(\alpha,n)$, assuming increase of σ_g/σ_m from 1/1.3 at 14 Mev to 2 at 11 Mev. — — — — — theoretical total alpha-particle cross sections (reference 2).

rected irradiation strengths. At all energies a growth curve was obtained ($A_g<0$) such that the cross section for the production of the metastable state is larger than that for the ground state. The ratio varies from $\sigma_m/\sigma_g=1.3$ at 14-Mev alpha-energy to $\sigma_m/\sigma_g=2.6$ at 18 Mev. This energy dependence is to be expected because of the increasing contribution of alpha-particles with high angular momentum.

III. RESULTS AND DISCUSSION

The cross sections obtained are given in Fig. 2 together with the adjusted results of Bradt and Tendam.[4] For the latter the energy scale has been shifted by slightly more than one Mev because of corrections for the density of the air in which the beam range was measured, for half the energy loss in the silver foils, and for the center-of-mass motion. The threshold for the $(\alpha,2n)$ process is thereby shifted from the earlier value of 15.5 Mev to 14.8±0.2 Mev in the laboratory system, 14.3 Mev in the c.m. system. There exists some uncertainty in the (α,n) cross section below 14 Mev, because the ratio σ_m/σ_g is not known, only the 20.7-min period having been measured. For the points indicated by circles a constant ratio has been assumed, while the broken curve indicates an estimate of a reasonable upper limit of $\sigma(\alpha,n)$.

The total cross section, taken as $\sigma=\sigma(\alpha,n)+\sigma(\alpha,2n)$, neglecting proton emission, can be compared with theoretical estimates[2] calculated for different values of the nuclear radius $R=r_0A^{\frac{1}{3}}$. From the *shape* of the excitation curve, Bradt and Tendam had found agreement with $r_0=1.3\times10^{-13}$ cm. For the present, *absolute* measurements, a value of $r_0\sim1.6\times10^{-13}$ cm seems more appropriate. This value is in good agreement with the results obtained by Blaser *et al.*[14] who, from the excitation curves for (p,n) reactions, find values of r_0 between 1.5 and 1.7×10^{-13} cm around $A=100$.

Assuming the validity of the approximations leading to Eq. (3), a value of $x=(\epsilon_\alpha-T_{2n})/\Theta$ can be calculated for each energy. The function $f(x)$ used has been modified graphically to take into account the finite thickness of the Ag^{109} foil and the straggling of the beam energy. The total width of the effective energy distribution at half maximum was about 0.5 Mev. Nevertheless, the corrections are appreciable only at energies less than 400 kev above the $(\alpha,2n)$ threshold. Figure 3 shows the dependence of x, determined from the measured cross-section ratio, on the alpha-energy. The broken line represents the best fit for a constant temperature, which would be 1.68 Mev, somewhat lower than the 1.8-Mev value reported by Bradt and Tendam. The solid line is the best fit using an energy dependent temperature $\Theta=(E/a)^{\frac{1}{2}}=(\epsilon_\alpha-T_n)^{\frac{1}{2}}/a^{\frac{1}{2}}$. An approximate value for T_n, the threshold for the (α,n) process has been obtained by adjusting the mass formula used by Harvey[15] so as to give the observed $(\alpha,2n)$ threshold of ~14.3 Mev (original value obtained from the formula: 15 Mev). The binding energy of the last neutron in In^{112} is about 7.5 Mev, the (α,n) threshold, about 6.8 Mev. The constant a, then, would be 4.25 Mev^{-1}, yielding temperatures varying from 1.34 Mev at 14.5-Mev alpha-energy to 1.66 Mev at 18.5 Mev.

Actually the application of Eq. (3) is not justified if the temperature varies since in evaluating (2) one has to use the level density over a range of energies which is rather large compared to nuclear temperature. Figure 4 shows the direct comparison of the experi-

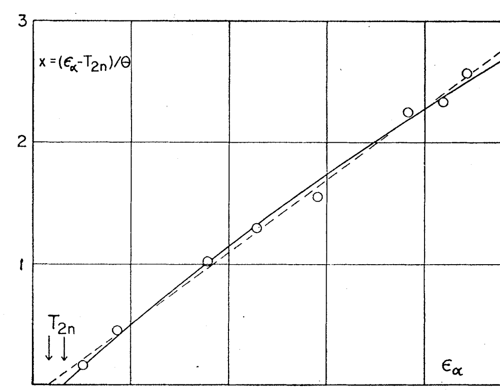

FIG. 3. Dependence of the nuclear temperature on the alpha-particle energy (c.m.), according to Eq. (3). — — — — — $\Theta=\text{const}=1.68$ Mev, ———— $\Theta=(\epsilon_\alpha-T_n)^{\frac{1}{2}}/a^{\frac{1}{2}}$, with $T_n=6.8$ Mev and $a=4.25$ Mev^{-1}.

[14] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta 24, 441 (1951).

[15] J. A. Harvey, Phys. Rev. 81, 353 (1951).

mental cross-section ratio, corrected for the finite beam width, with that calculated according to Eq. (2), putting $\sigma_C(\epsilon)=\text{const}$ and $\omega(E)=\text{const}\ \exp[2(aE)^{\frac{1}{2}}]$, and assuming $S=7.5$ Mev and $T_{2n}=14.25$ Mev. The best value of a would be 2.5 Mev^{-1}, corresponding to temperatures increasing from 1.7 Mev to 2.2 Mev for excitation energies between about 7.5 and 12 Mev (alpha-energies between 14.3 and 18.8 Mev).

The probable error in the cross-section ratio is estimated to be about 10 percent, that of the temperatures somewhat less.

CONCLUSIONS

The results of Bradt and Tendam have been confirmed inasmuch as the nuclear temperatures deduced from the ratio of the cross sections for the (α,n) and the (α,$2n$) reactions with Ag^{109} are appreciably higher than those found by Gugelot from the (p,n) reactions and by Graves and Rosen from the inelastic scattering of neutrons. The constant a in the expression $\Theta=(E/a)^{\frac{1}{2}}$ is found to be 2.5 Mev^{-1}, while Gugelot obtained about 13 Mev^{-1} for Rh, and the estimate of Blatt and Weisskopf is about 8 Mev^{-1}.

The difficulty in the measurement of the neutron spectra would seem to lie in the proper subtraction of the secondary neutrons and also, as remarked by Gugelot, in the possibility of neutrons being emitted in a direct interaction with the incident particle rather than evaporated from the compound nucleus. The latter process, however, would be expected to increase rather than decrease the apparent temperature.

In the case of the present measurements, any process which reduces the probability of the evaporation of the second neutron will increase the apparent temperature.

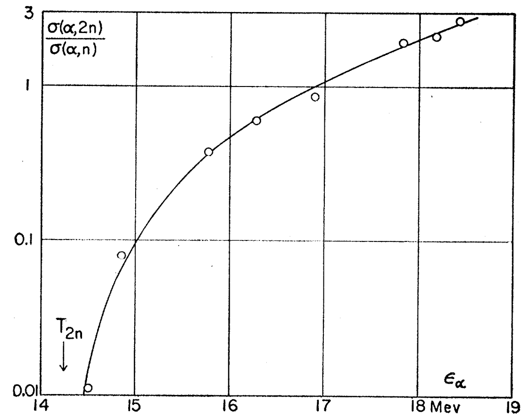

FIG. 4. Cross-section ratio $\sigma(\alpha,2n)/\sigma(\alpha,n)$ as a function of the alpha-particle energy (c.m.). Curve calculated for $\omega(E)=\text{const}\ \exp[2(aE)^{\frac{1}{2}}]$, with $a=2.5\ \text{Mev}^{-1}$.

It appears that the theoretical probability of gamma-emission or evaporation of a secondary proton is very small. Whether any process involving an "accelerated" proton emission after the evaporation of the first neutron could be invoked, is not known. In view of such possible complications of the method here employed, it seems desirable to measure the distribution of the neutrons emitted in the (α,n) process using the direct method applied in the case of the (p,n) and (n,n) neutrons.

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