Population Ratios of Be^7, Li^7, and B^{10} States from Li^6 on Li^6 and Be^9 as Functions of Bombarding Energy*

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The populations of the Be^7 (0.431 MeV), Li^7 (0.478 MeV), and B^{10} (0.717 MeV) states have been compared in the bombardment of Li^6 by Li^6 over energies from 1.2 to 2.8 MeV. The populations of the same Li^7 and B^{10} states have been compared in the Li^6+Be^9 reactions over energies from 1.5 to 2.9 MeV. It is found that the ratios of these populations are constant within experimental error. A simple tunneling model and a compound-nucleus model do not appear compatible with the data; however a "surface" interaction is consistent with the results.

INTRODUCTION

LITHIUM–LITHIUM reactions under 4 MeV have been treated with some success as simple Butler stripping where lithium is considered to have an alpha plus deuteron structure or alpha plus triton structure.[1] Indeed the low photodissociation energies for breakup into these configurations make the analogy to deuteron stripping seem close. However, reactions involving relatively more tightly bound structures such as Li^5+n or He^5+p do not exhibit the characteristic stripping angular distributions.[2]

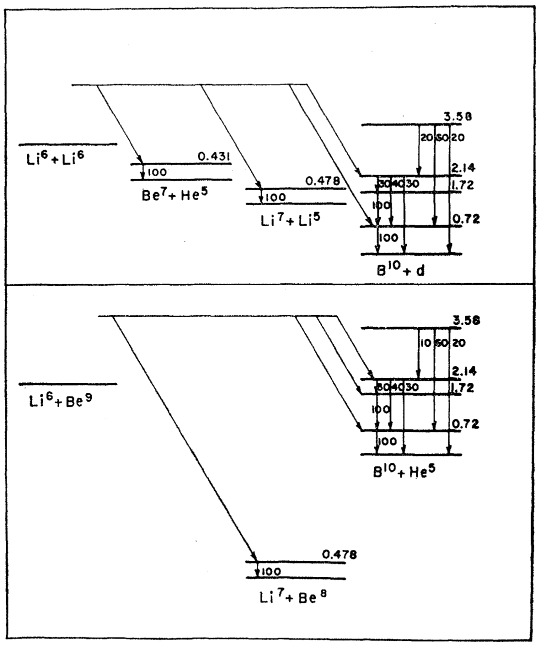

FIG. 1. Energy level diagrams for the reactions under study. Arrows indicate reactions and gamma rays under study. Energy levels are given in MeV and are drawn to scale. Branching ratios are given in percentages. Both diagrams are to the same scale. The upper line in each diagram represents center-of-mass energy resulting from bombardment.

It has been suggested that reactions of the latter kind in which a nucleon is emitted require compound-nucleus formation.[2] *A priori*, this mode would seem unlikely since, at 3-MeV bombarding energy, the classical distance of closest approach is 10 F which is considerably larger than the Li^6 nucleus ($r=1.5A^{1/3}$ F). The classical distance of closest approach is taken as $Z_1Z_2e^2/E$, where E is the kinetic energy in the center-of-mass system.

A plausible alternative mechanism which this experiment investigates is tunneling of a nucleon or cluster between the nuclear potential wells. Nucleon tunneling has been treated by Breit and Ebel[3] for the $N^{14}+N^{14}\rightarrow N^{13}+N^{15}$ reaction. The nuclei are assumed to follow classical orbits which are essentially undisturbed by the transfer of the neutron requiring, therefore, that the transferring mass and Q value be small. In a second paper[4] they conclude that virtual Coulomb excitation is important at low bombarding energies. However, for lithium this effect ought to be considerably less than in the nitrogen reactions at comparable distances of approach since the excitation probability is proportional to Z^2.

The following reactions have been studied:

$$Li^6+Li^6 \rightarrow Li^{7*}+Li^5, \quad \text{Ground state } Q=1.75 \text{ MeV};$$
$$\rightarrow Be^{7*}+He^5, \quad 0.95 \text{ MeV};$$
$$\rightarrow B^{10*}+d, \quad 2.92 \text{ MeV};$$
$$Li^6+Be^9 \rightarrow Li^{7*}+Be^8, \quad 5.58 \text{ MeV};$$
$$\rightarrow B^{10*}+He^5, \quad 1.93 \text{ MeV}.$$

Figure 1 shows energy level diagrams for these reactions. Excitation energies and branching ratios are taken from previous work.[5] Populations of the 0.431-MeV state in Be^7, the 0.478-MeV state in Li^7, and the 0.717-MeV state in B^{10} were compared by measuring the intensities of gamma-ray decays of these states. Cascade corrections must be made in the case of the B^{10} level. The bombarding energy ranged from 1.2 to 2.8 MeV. If the reactions take place via a tunneling

* Work supported in part by the U. S. Atomic Energy Commission.

[1] G. C. Morrison, Phys. Rev. **121**, 183 (1961).

[2] G. C. Morrison and M. N. Huberman, *Proceedings of the Second Conference on Reactions between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 246.

[3] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1956).

[4] G. Breit and M. E. Ebel, Phys. Rev. **104**, 1030 (1956).

[5] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

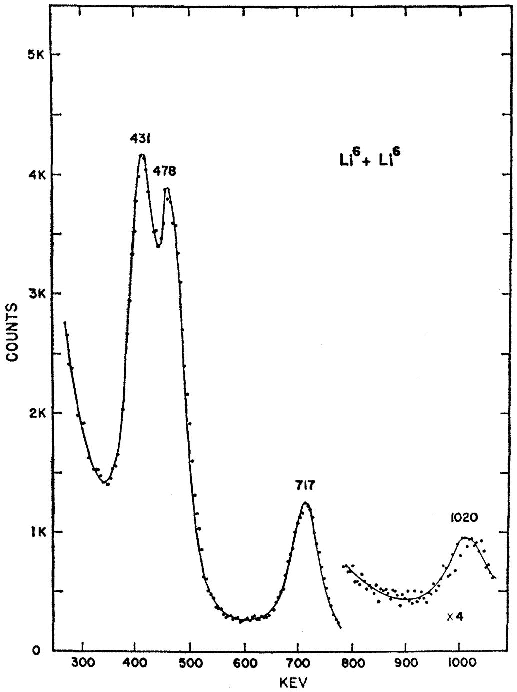

FIG. 2. Pulse-height distribution of gamma rays from the bombardment of Li^6 by Li^6 at 2.6 Mev. Be^7 (0.431 MeV), Li^7 (0.478 MeV), B^{10} (0.717 MeV), and B^{10} (1.02 MeV) peaks are present.

process, the population ratios are expected to change as the bombarding energy is varied due to unequal barriers for transfer of two dissimilar clusters or nucleons.

EXPERIMENTAL PROCEDURE

The State University of Iowa Van de Graaff was used to accelerate singly charged Li^6 ions. The beam energy was known to about 3%. The ion source and extraction system have been described elsewhere.[6]

Evaporated Li^6F and Be^9 targets on gold backings were used. Three-MeV lithium ions lost 0.17 MeV and 3 MeV in the targets, respectively.

A 2 in. long by 2-in. diam NaI(Tl) crystal was placed 3 in. from the target at 90° to the beam. Standard electronics plus a 256-channel pulse-height analyzer gave the gamma-ray pulse-height distributions at various bombarding energies.

Except for several lead bricks 1.5 ft from the crystal which shielded the crystal from machine background, no other shielding material was used in order to minimize neutron inelastic scattering in the crystal. This was considered important because high-energy neutrons are produced in these lithium reactions so that I^{127} and Na^{23} de-excitation gamma rays might contribute to the peaks produced by reaction gamma rays. In fact, the 0.625- and 0.640-MeV levels in I^{127} were never observed. Since these states have $(n,n'\gamma)$ cross sections of similar magnitude to those of other I^{127} and Na^{23} states,[7] neutron-induced gamma rays are negligible.

The amount of annihilation radiation from higher energy reaction gamma rays relative to the Li^7 0.478-MeV peak was ascertained from the Li^6+Li^7 reaction in which the gamma rays having energies greater than 1.5 MeV were monitored and the annihilation radiation yield measured. The high-energy gamma-ray spectra of the two sets of reactions are similar. The contribution to the spectrum in the 0.5-MeV region at every bombarding energy represented less than 1% of the Li^{7*} peak produced in the Li^6+Li^6 reactions. Annihilation radiation from C^{11} and N^{13} decay was subtracted using background readings taken after each gamma-ray spectrum. This subtraction was always less than 5% of the total Li^{7*} peak produced in the Li^6+Li^6 reactions.

RATIOS OF Be^{7*} AND Li^{7*} TO B^{10*} PRODUCED IN Li^6+Li^6 REACTIONS

Figure 2 shows a typical pulse-height distribution obtained from the Li^6+Li^6 reactions. Since the Be^{7*}, Li^{7*}, and the 0.41-MeV B^{10} peaks overlapped, peak intensities were computed from peak heights using measured crystal resolutions (10.8% at 0.41 MeV; 10.4% at 0.51 MeV; 8.7% at 0.61 MeV) and efficiencies. The contribution of the Be^7 peak height from the

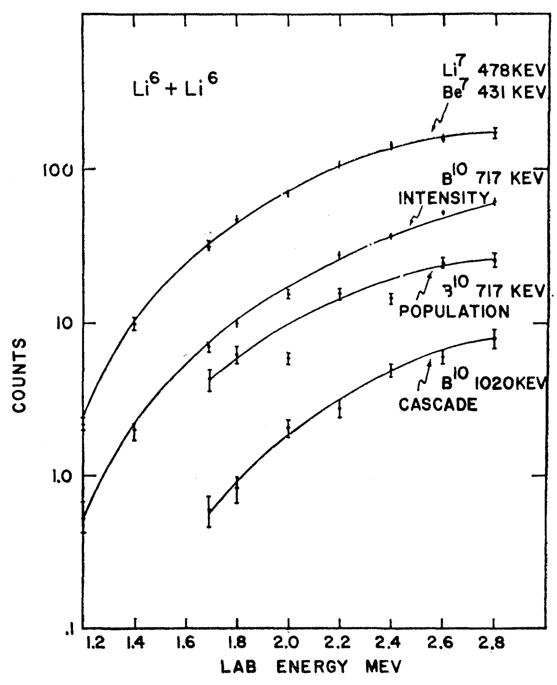

FIG. 3. Gamma-ray peak heights per microcoulomb from Li^6+Li^6 as a function of bombarding energy. The B^{10} (0.717 MeV) population peak height is obtained by subtraction of cascades as discussed in text. The Li^7 and Be^7 points lie on the same curve. Curves are based on penetrabilities of the Li^6 nuclei (see text).

[6] E. H. Berkowitz, thesis, State University of Iowa, 1961 (unpublished).

[7] *Nuclear Data Sheets*, National Academy of Sciences (National Research Council, Washington, D. C., 1960).

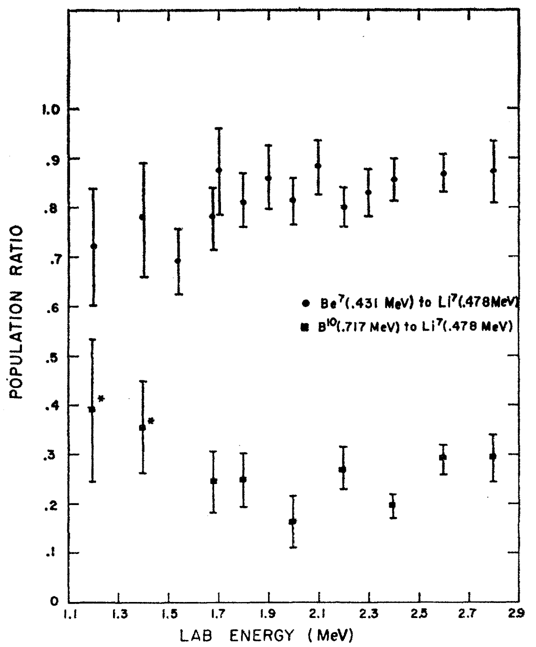

FIG. 4. Population ratios of Be^7 (0.431 MeV) to Li^7 (0.478 MeV) and B^{10} (0.717 MeV) to Li^7 (0.478 MeV) from Li^6+Li^6. The error bars represent statistical error only. The points with asterisks in the latter set are to be regarded as upper limits since no cascade correction was made to the B^{10} (0.717 MeV) population.

0.410-MeV cascade was calculated to be about $(5\pm3)\%$ and the overlap of the Be^7 peak on the Li^7 peak height, and vice versa, was about $(7\pm3)\%$. These percentages were the same at 1.68 and 2.6 MeV (bombarding energy) so the overlap was not an important source of error in measuring the change in population ratios. Figure 3 shows the yield curves for the relevant gamma rays. The Li^7 and Be^7 points lie so close together that a single line has been drawn through them.

In determining the population of the 0.717-MeV B^{10} state, the cascade from the 3.58-MeV state was ignored. The threshold for production of this level is 1.3 MeV so that its relative strength is expected to be small. This was substantiated by three-crystal pair spectrometer data at 2.6 MeV.[8] These data give the ratio of the intensities of the 3.58- to the 2.15-MeV gamma ray to be $(6\pm2)\%$ which, using the branching ratios, implies the ratio of cascades to the B^{10} 0.717-MeV state from these two states is 9%.

The 1.02-MeV peak from transitions between the 1.74- and 0.717-MeV states is considered to measure 30% of the 2.15-MeV production. This assumption is based on experiments by Morrison at 2.1 MeV,[9] and by Bromley *et al.* at 6 MeV.[10] They observed deuterons

[8] E. H. Berkowitz, S. Bashkin, R. R. Carlson, S. Coon, and E. Norbeck, Phys. Rev. (to be published).

[9] G. C. Morrison, Phys. Rev. Letters **5**, 565 (1960).

[10] D. A. Bromley, K. Nagatani, L. C. Northcliffe, R. Ollerhead, and A. R. Quinten, *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961* (Academic Press Inc., New York, 1961).

TABLE I. Cross sections (lower limits) for Li^6+Li^6 reactions.

Lab energy (MeV)	Total cross section (mb) Li^7 (0.478 MeV)	B^{10} (0.717 MeV)	B^{10} (2.15 MeV)
1.2	1.3 ± 0.4	0.5 ± 0.2	
2.6	80 ± 16	24 ± 6	39 ± 10

from the Li^6+Li^6 reaction. Direct production of the 1.74-MeV state is negligible compared to that of the 2.15-MeV state. The total cascade contribution to the 0.717-MeV peak is, therefore, equal to the 1.02-MeV peak intensity plus 4/3 this intensity which represents the cascade going directly to the 0.717-MeV state from the 2.04-MeV state. The population ratios as functions of machine energy are shown in Fig. 4. The error bars represent statistical fluctuations only.

Cross sections may be calculated for the Li^6+Li^6 reactions using the known target thickness and calculated efficiencies for NaI(Tl) crystals. These cross sections should be regarded as lower limits because of possible contamination of the target surface. Results are given in Table I.

RATIOS OF Li^{7*} TO B^{10*} PRODUCED IN THE Li^6+Be^9 REACTIONS

Figure 5 shows a typical pulse-height distribution from Li^6 bombardment of Be^9. The cascade analysis is less accurate than in the above section since there is now no restriction on the production of the 1.76-MeV

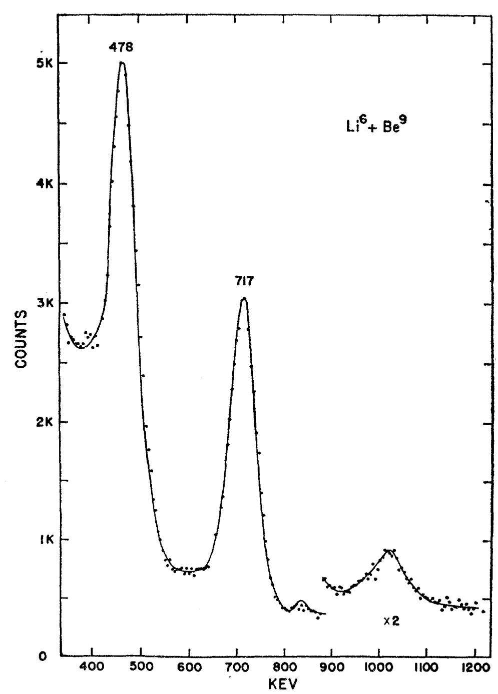

FIG. 5. Pulse-height distribution of gamma rays from the bombardment of Be^9 by Li^6 at 2.9 MeV. Li^7 (0.478 MeV), B^{10} (0.717 MeV), and B^{10} (1.02 MeV) peaks are present.

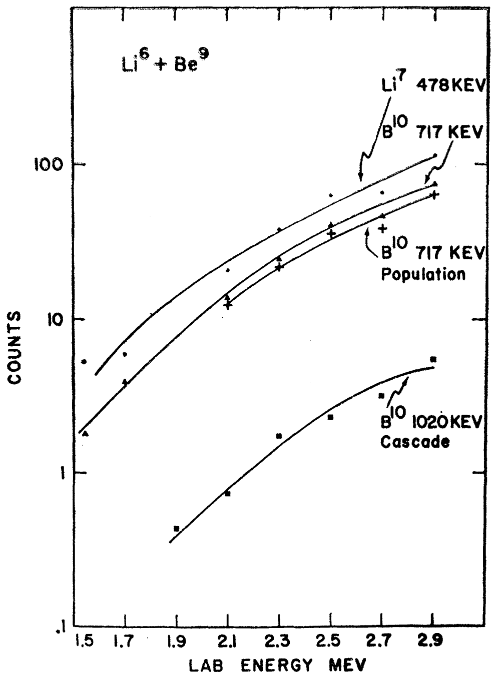

FIG. 6. Gamma-ray peak heights per microcoulomb from Li^6+Be^9 as a function of bombarding energy. Curves are based on penetrabilities of Li^6 with Be^9.

state in B^{10} so that the intensity of the 1.02-MeV gamma ray no longer indicates the amount of production of the 2.15-MeV state. Therefore two sets of 0–3.0 MeV gamma-ray spectra, taken at 2.1- and 3.2-MeV bombarding energy, were analyzed to determine the percentage of direct cascade to the 0.717-MeV state from the 2.15-MeV state compared to the cascade from the 1.74-MeV state. The percentages were 16 ± 4 at 2.1 MeV and 28 ± 6 at 3.2 MeV. Since the largest cascade correction from the 1.74-MeV state to the 0.717-MeV peak intensity is about 8%, the largest error in the 717-MeV population resulting from the neglect of direct cascade to this state from the 2.15-MeV state is 2.4%. The yield curves and ratios are shown in Figs. 6 and 7.

DISCUSSION

Within experimental error the population ratios observed do not change over bombarding energies which give classical distances of closest approach from 22 to 9 F for Li^6+Li^6 and 21 to 11 F for Li^6+Be^9. Lemeille *et al.* have observed the same result in Li^6+Be^9 from 32 to 16 F.[11]

These data are inconsistent with predictions based on a one-dimensional W.K.B. penetrability calculation for tunneling between the nuclear surfaces. The method is identical to that used by Breit and Ebel to estimate the cross-section ratios for proton and neutron transfer in $N^{14}+N^{14}$.[4] The transfer cross section is proportional to

$$\exp\left(-2\left(\frac{2M}{\hbar^2}\right)^{\frac{1}{2}}\int_a^{2a'-a}(V-E)^{\frac{1}{2}}dr\right),$$

where $(V-E)$ is the binding energy plus Coulomb and centrifugal barrier terms where applicable, $2a'$ is the separation of Li^6 nuclei at distance of closest approach, and a is the Li^6 radius. (See reference 4 for a complete explanation of the method and a discussion of its shortcomings.) Assuming equal reduced widths for neutron and proton emission, the above formula gives Be^{7*} to Li^{7*} ratios of 1.35, 0.92, and 0.87 at 1.2-, 2.0-, and 2.6-MeV bombarding energy (both transfers are assumed to be p wave). The data show that this ratio is approximately 0.83 ± 0.1. Furthermore, since the one-dimensional model exaggerates the Coulomb barrier (see reference 4) the implication is that a more accurate calculation would give larger ratios. However, these predicted ratios are already too large and also show an energy dependence in disagreement with the data.

An application of this expression to the alpha-particle transfer is of dubious validity; however, if this is done it is found that the predicted ratio of B^{10} to Li^7 in the Li^6+Li^6 reaction changes by an order of magnitude over the 1.2- to 2.6-MeV bombarding energy range. Again, the data show that the ratio is approximately constant.

Since the barrier thickness for tunneling depends on the bombarding energy, the constancy of all observed

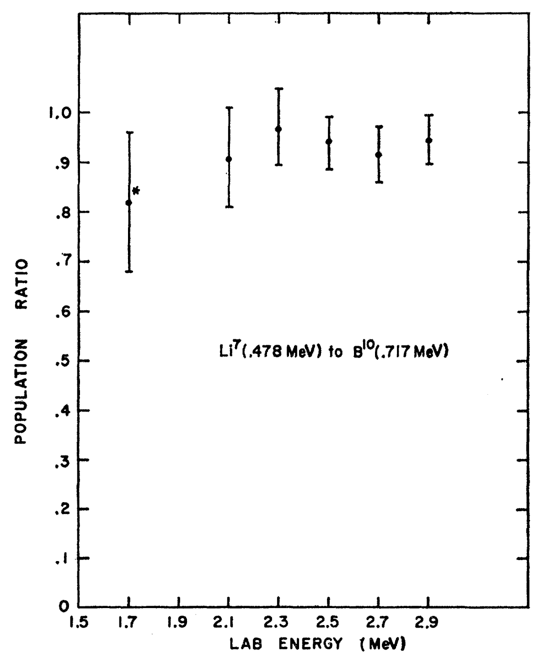

FIG. 7. Population ratios of Li^7 (0.478 MeV) to B^{10} (0.717 MeV) from Li^6+Be^9. Error bars represent statistical error only. The first point is a lower limit because no cascade correction was made to the B^{10} (0.717 MeV) population.

[11] C. Lemeille, L. Marquez, and N. Saunier, J. phys. et radium **22**, 349–352 (1961).

ratios makes an interpretation in terms of tunneling difficult. On the other hand, the preference for neutron transfer compared to alpha transfer in the Li^6+Li^6 reactions argues against compound nucleus formation since the outgoing particles are a He^5 and a deuteron, respectively, and penetrability considerations favor deuteron emission.

On the basis of the above disagreements with the data of the simple tunneling theory, and compound-nucleus formation, it is suggested that the reactions proceed by a surface interaction between the long-range nuclear tails. This would require that the population ratios remain constant with change in bombarding energy. At the same time, no contradiction with the data ensues from the larger cross section Li^{7*} compared to B^{10*}. The yield curves are well fitted (see Figs. 3 and 6) by assuming the yield is a function of the penetrability of the Coulomb barrier of the Li^6 nuclei by the other nucleus, with the nuclear radius given by $r=1.75A^{1/3}$ F. Penetrabilities were taken from published graphs of Coulomb functions.[12] The present results do not establish this interpretation, but they are consistent with it.

ACKNOWLEDGMENT

The author appreciates the advice and encouragement of Professor R. R. Carlson.

[12] W. T. Sharp, H. E. Gove, and E. B. Paul, "Graphs of Coulomb Functions," Chalk River Project, 1955 (unpublished).

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Effects of Angular Momentum and Gamma-Ray Emission on Excitation Functions*

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Excitation functions for many compound nucleus reactions are strongly dependent on the competition between gamma-ray and particle emission in the final particle-emission step. This competition depends, in turn, mainly on the energies and spins of a relatively few levels in the product nucleus, namely, on the lowest energy level at every angular momentum J (these energies are herein designated by E_J). A method for making approximate calculations is described in which the influence of the competitive gamma-ray emission on excitation functions well above threshold is estimated, using assumed plausible distributions of the E_J's. It is found that larger values of the level density parameter a are required to achieve agreement of calculations with experimental data when the competitive gamma-ray emission is included than when it is neglected (i.e., practically equivalent to setting $E_J=0$ for all angular momenta). An approximate analysis of experimental excitation functions for the reaction-pair $Ag^{109}(\alpha,n)In^{112}$ and $Ag^{109}(\alpha,2n)In^{111}$ suggests that $a>12$ MeV^{-1}, assuming the level density expression $\omega(E)\propto E^{-2}\exp[2\sqrt{(aE)}]$, or $a>7$ MeV^{-1} assuming $\omega(E)\propto\exp[2\sqrt{(aE)}]$. Alternatively, assuming $a\approx 16$ MeV^{-1} (in the first formula), consistent with values calculated by Lang from level spacings observed near neutron binding energies, it appears that the average value of the E_J's for angular momenta of $(11/2)\hbar$ to $(17/2)\hbar$ in In^{111} is roughly 2 to 2.5 MeV. It is suggested that instead of trying to extract a from excitation functions, it is perhaps more appropriate to try to extract information on the E_J distribution, using for this purpose values of a from other types of experiment.

INTRODUCTION

EXCITATION functions for compound nucleus processes are expected to provide data from which a knowledge of the variation of nuclear state density with excitation energy may be obtained. In analyses of such data, it is necessary to include the effects of angular momentum, and of gamma-ray emission in competition with particle emission[1]; this, in turn, requires a knowledge of the energies, spins and parities of all levels populated in the product nuclei. For most medium to heavy nuclei this information is known only for the first few levels, so that the calculations can seldom be carried beyond one or two MeV above threshold.

* Research performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. R. Grover, Phys. Rev. **123**, 267 (1961).

An extension to many MeV above threshold is described in this report, in which the influence of the unknown levels is estimated. These approximate calculations are applied to experimental data, to find whether the required information about the product levels is also obtainable from excitation function data, or whether the lack of this information blocks extraction of the desired knowledge about the energy variation of the nuclear state density.

DESCRIPTION OF THE PROBLEM AND AN APPROXIMATE SOLUTION

Emission of charged particles is neglected, for it would complicate the discussion while adding nothing essential. Parity is omitted for the same reason. Symbols used in this paper for nuclei important in the reactions