close to the center of gravity of the electron distribution.

Both e,γ and e,β^+ coincidences were measured for two different thin Sc^{44} sources, with compatible results. The average coincidence fractions are $f_\gamma = 40 \pm 9\%$, $f_{\beta^+} = 84 \pm 12\%$. This means that 60% of the electrons, not being in coincidence with the full-energy gamma rays, must have been produced by the gamma ray, presumably by Compton effect in the neighborhood of the source or in the baffle system. 93% of these, or a fraction of 56% of the total number, would be preceded by positron emission and thus be in coincidence with the positrons. This leaves $84-56=28\pm15\%$ of the electrons coincident with both the positrons and the gamma ray, as they should be if emitted in the process of positron decay. Even this fraction of the electrons, however, could be produced by inelastic scattering of the positrons such that the positrons still have an energy in excess of 0.9-Mev and can be recorded in the crystal.

(4) Summary

The number of low-energy electrons between 30 kev and 150 kev which might be attributed to atomic excitation during the positron decay of Sc^{44} has been reduced from 4% to about 0.4% $(1.3\% \times 0.28)$. At these low intensities the techniques employed here are unreliable and there is, thus, no evidence for an electron intensity higher than predicted by the theory.

ACKNOWLEDGMENTS

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Production of Y^{89m}, Ba^{137m}, and Hg^{199m} by Inelastic Neutron Scattering*

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Isomeric states in Y^{89} (913 kev), Ba^{137} (661 kev), and Hg^{199} (527 kev) have been excited by inelastic scattering of monoenergetic neutrons. The shape of the excitation curves agrees rather well with the prediction of the strong interaction theory, but the theoretical cross sections are, at least in the cases with simple decay schemes, considerably larger than the experimental ones.

INTRODUCTION

ONE of the many different ways of studying the inelastic scattering of neutrons is through the measurement of the excitation of metastable states of nuclei. The cross section for the production of a metastable state by inelastic neutron scattering depends strongly on the angular momentum difference between this state and the ground state and depends to some extent on the relative parity of these two states. In addition, the cross section depends on the presence of other excited states.

If spin and parity of the metastable state are known from other studies, especially from measurements of the internal conversion of the gamma-ray transition, an investigation of the absolute cross section for excitation with monochromatic neutrons represents a test of the available nuclear models as applied to reaction theory.

If, on the other hand, a theory exists which successfully explains experiments of this kind, the study of the energy dependence and of the absolute value of the cross section will enable one to assign spin values to the metastable states and to other levels affecting the excitation of the metastable state by their competition. Breaks in the excitation curve indicate levels above the metastable state, and the sign of the change of slope at these breaks indicates whether the deexcitation of these levels proceeds through the metastable state or whether it bypasses this level.

As long as one is interested in a test of theoretical predictions, one would like as simple a level scheme as possible. The metastable state should preferably be the first excited state. This would eliminate all of the uncertainties stemming from the competition of other levels, the properties of which are often not very well known.

Previous investigations on Cd^{111}, In^{115}, and Au^{197} [1–3] involved relatively complicated level schemes. Margolis[4] compared the predictions of the strong-interaction theory[5] with these experimental data and, in view of

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* Supported by the U. S. Atomic Energy Commission.

[1] Francis, McCue, and Goodman, Phys. Rev. **89**, 1232 (1953).
[2] A. A. Ebel and Clark Goodman, Phys. Rev. **93**, 197 (1954).
[3] Martin, Diven, and Taschek, Phys. Rev. **93**, 199 (1954).
[4] B. Margolis, Phys. Rev. **93**, 204 (1954).
[5] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

the preliminary character of the data and of the uncertainties of the level schemes, considered the agreement satisfactory. Recently Stelson and Campbell[6] studied the 0.8-sec isomeric level in Pb^{207} and found good agreement between experiment and theory using a radius of 8×10^{-13} cm and assuming reasonable spins and parities for the four levels involved in this case.

After first experiments with Hg^{199}, which clearly demonstrated to us the ambiguity created by many additional levels with uncertain properties, we decided to investigate the isomeric states in Y^{89} and Ba^{137}, which fulfill the requirement of a very simple decay scheme. It should, however, be pointed out that both isotopes have properties which might reduce their value for an effective test of the theory. In the case of Y^{89} the ground state is magic ($N=50$), whereas for Ba^{137} the compound nucleus is magic ($N=82$). In spite of this, however, a comparison with Pb^{207} should be useful, because in this case the compound nucleus is the doubly magic Pb^{208}.

EXPERIMENTAL METHOD

A. Neutron Source

Monoenergetic neutrons were produced by bombarding thin lithium targets with protons accelerated in the Bartol-ONR electrostatic generator. This generator was built at Bartol and produces an analyzed beam of several microamperes with energies up to 5 Mev. A radio-frequency ion source described previously in the literature[7] is used as the source of protons. A 90° magnet serves both as the analyzer and as the energy stabilizer, the field of the magnet being determined by a proton magnetic moment resonance magnetometer. Slits at the object and image points of the magnet define the resolution, and error signals are taken from the exit slits to control a corona load on the central electrode of the generator, thus stabilizing the generator voltage. The energy resolution throughout these experiments was about 0.1%, although appreciably better resolution can be obtained.

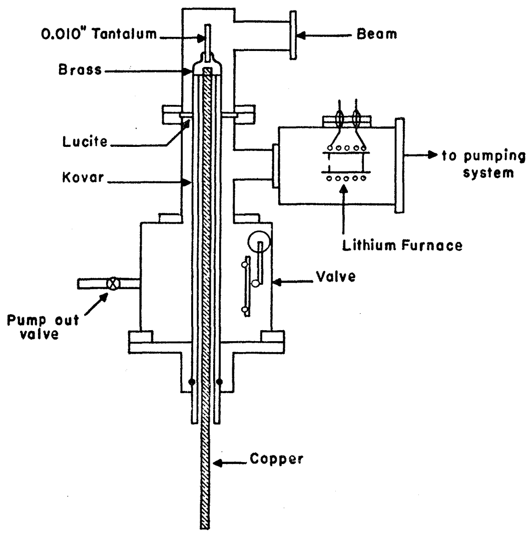

FIG. 1. Target chamber for cooled lithium targets.

Energy measurements were based on the Li(p,n) threshold calibration which was taken as 1.882 Mev.[8] The threshold as determined over periods of weeks did not vary by more than 0.1%.

In the early stages of this work, the lithium targets were prepared in an auxiliary evaporating system and then exposed to air prior to insertion in the generator system. A rotating target scheme was used to prevent deterioration of the target while under bombardment.

The target thickness was determined by measuring the geometrical peak at the (p,n) threshold. A comparison of the yield of Au^{197m} with the absolute measurements of the Los Alamos group[3] indicated that the neutron yield from our lithium targets was one-third to one-fourth of the yield expected for a pure lithium target.

Consequently, in the later stages of the work, targets were prepared directly in the generator system. The arrangement for doing this and also for cooling the targets is shown in Fig. 1. The cooling is accomplished by inserting the copper rod into either a dry ice—acetone mixture or into liquid air. With this cooling no apparent deterioration of the targets took place under several microampere-hours of bombardment. The targets are evaporated at the level of the furnace to prevent contamination of the beam chamber. Target thicknesses of 30 to 50 kev were used in the course of this work. Neutrons emitted at angles up to 30 degrees with the forward direction were intercepted by the scatterers. The total neutron energy spread due to target thickness and finite acceptance angle varied from ~60 kev at 0.5-Mev neutron energy to ~90 kev at 1.5-Mev neutron energy. Monitoring was accomplished with a neutron "long counter"[9] positioned at the forward direction.

B. Neutron Yield Calibration

In order not to depend on the intercomparison via Au^{197m}, we proceeded to determine the neutron yield by measuring the Be^7 activity induced in the lithium target, assuming $11.0\pm0.6\%$[10] of the Be^7 disintegrations to be accompanied by a 478-kev gamma ray. The absolute counting of this gamma ray was done with a calibrated sodium iodide crystal (see Sec. C). As Be^7 decays with a half-life of 52.9 ± 0.2 days,[11] the induced activity was followed for several days. This, together with the pulse-height selection, excluded any other activity.

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[6] P. H. Stelson and E. C. Campbell, Phys. Rev. **97**, 122 (1955).
[7] C. P. Swann and J. F. Swingle, Rev. Sci. Instr. **23**, 636 (1952).
[8] Herb, Snowdon, and Sala, Phys. Rev. **75**, 246 (1949).
[9] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[10] J. M. Dickson and T. C. Randle, Proc. Phys. Soc. (London) **A64**, 902 (1951).
[11] E. Segrè and C. Wiegand, Phys. Rev. **75**, 39 (1949).

The calibration of the monitor counts in terms of total neutron yield was carried out at 1.2-Mev mean neutron energy. A fresh lithium target was bombarded with 3-Mev protons, corresponding to 1.2-Mev mean neutron energy, for about 2 microampere-hours. The total number of monitor counts was recorded for this bombardment, the monitor being kept in the same position in which it was used during the Y, Ba, and Hg irradiations. The subsequent determination of the absolute Be^7 activity enables one then to express monitor counts in terms of total neutron yield. In order to calculate the number of neutrons actually striking the scatterers under study, it is necessary to know the angular distribution of the $Li(p,n)$ neutrons. At 1.2-Mev neutron energy we measured this distribution and found its shape to agree with that expected from an extrapolation of the coefficients determined by Taschek and Hemmendinger[12] at lower neutron energies.

Near the thresholds for the excitation of the metastable states the second neutron group present in the $Li(p,n)$ reaction does not contribute to the production of the isomers but is detected in the monitor. Consequently, a 10% correction[13] was applied to the monitor readings.

C. Calibration of Gamma-Ray Detector

For the determination of the absolute Be^7 activity, as well as of the Y^{89m} and Ba^{137m} activities, gamma-ray sources of known strengths and covering the energy range from 0.4 to 1.3 Mev were necessary. For this purpose sources of Tl^{202} (0.439 Mev), Na^{22} (0.511 Mev and 1.28 Mev) and Co^{58} (0.81 Mev) were calibrated by standard x-γ and γ-γ coincidence techniques. With the scintillation spectrometer adjusted for each line to bring the photopeak to 30 volts pulse height, the counting rate per disintegration per minute in a 28.5+3 volt channel was determined for the Be^7 geometry. The resulting curve of counts per disintegration versus gamma-ray energy was then used to determine the absolute source strengths of Cs^{137} and Y^{88} sources and, of course, the absolute Be^7 activity.

The Cs^{137} γ ray is identical with the isomeric transition in Ba^{137}, and one of the Y^{88} gamma rays agrees to within 10 kev with the gamma ray from Y^{89m}. Therefore, the detection efficiency for the two isomeric transitions in the special geometries used could be measured using the calibrated sources of Cs^{137} and Y^{88}.

The ultimate error in the absolute value of the Be^7 activity as well as of the Y^{89m} and Ba^{137m} activities is estimated to be less than 10%. In the case of Hg^{199}, where the 159-kev transition was used, the special counting geometry was studied with a source of Au^{199}, the strength of which was based on the calculated absorption coefficient of the sodium iodide crystal. The uncertainty in the over-all detection efficiency in this case is estimated at 30%, i.e., it is still smaller than the uncertainty in the number of metastable states stemming from the errors in the measurements of the conversion coefficient of the 159-kev transition.[14]

MEASUREMENTS, RESULTS, AND DISCUSSIONS

A. Y^{89m}

A half-life of 14±2 sec has been reported[15] for the 913-kev $M4$ transition which leads from the $9/2+$ metastable state to the $1/2-$ ground state of Y^{89}. For the analysis of our data, a more accurate value for $T_{\frac{1}{2}}$ was needed. We, therefore, redetermined it and found $T_{\frac{1}{2}}=16.1\pm0.3$ sec.

For the measurement of the (n,n') excitation curve a sample of Y_2O_3 pressed into a thin aluminum container of $1\frac{1}{2}$ inches diameter and $\frac{1}{4}$ inch thickness was used. Each run consisted of a 70-second bombardment, 14 seconds for the transfer of the sample to the scintillation spectrometer, and 70 seconds of gamma counting. The excitation curve obtained in this way is given in Fig. 2. The uncertainty in the absolute cross sections is estimated at 20%. Since Y^{89} is the only stable yttrium isotope, the metastable state cannot be produced by neutron capture. No activity is therefore observed below the threshold for direct excitation, i.e., below 910 kev. At the threshold, however, the production of Y^{89m} sets in immediately, i.e., direct excitation of the metastable level takes place. The sharp break at 1.2 Mev indicates a level which, at least partially, decays to the metastable state. The 1.53-Mev level, known from the disintegration of Zr^{89m},[16] manifests itself by a slightly negative slope of the excitation curve. This is in accord with the observation of the 1.53-Mev gamma ray[16]

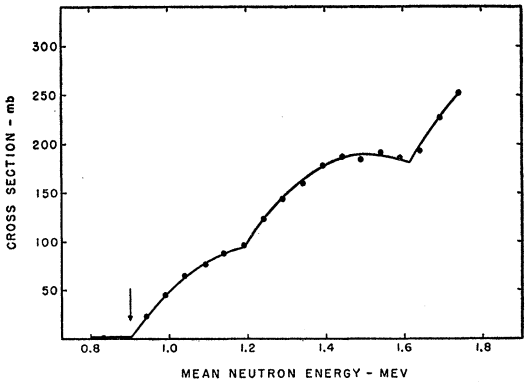

FIG. 2. Cross section for the production of the 913-kev metastable level of Y^{89} as a function of the mean neutron energy. Arrow indicates threshold expected for direct excitation. Statistical errors ~5%.

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[12] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

[13] *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 2, p. 380.

[14] P. M. Sherk and R. D. Hill, Phys. Rev. **83**, 1097 (1951).

[15] Goldhaber, der Mateosian, Scharff-Goldhaber, Sunyar, Deutsch, and Wall, Phys. Rev. **83**, 661 (1951).

[16] Shore, Bendel, Brown, and Becker, Phys. Rev. **91**, 1203 (1953).

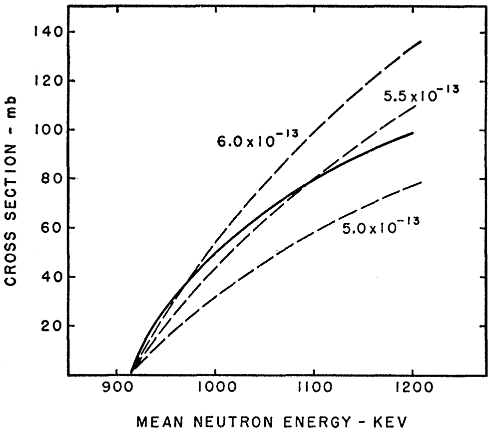

FIG. 3. Comparison of the experimental cross section (solid curve) for direct excitation of Y^{89m} with the predictions of the strong-interaction theory for different radii and for the known spin of the metastable state (9/2+).

going to the ground state and with the absence of an ~620-kev transition to the metastable state. No attempt has been made to analyze the curve at higher energies.

A comparison with the predictions of the strong-interaction theory for different values of the nuclear radius has been made, assuming the known spins and parities for the metastable state and the ground state. Figure 3 shows that a radius of 5.5×10^{-13} cm gives a reasonably good fit in shape as well as in the magnitude of the cross section. This value of the radius appears to be somewhat low when compared with the radii tabulated by Feshbach and Weisskopf.[17]

B. Ba^{137m}

The 661-kev metastable level of Ba^{137} has a half-life of 2.6 minutes.[18] The $M4$ transition[19] leads from the $h_{11/2}$ isomeric level to the $d_{3/2}$ ground state. The 661-kev state is the only excited state of Ba^{137} involved in the disintegration of Cs^{137}. From the known spin of Cs^{137} [20] and from the selection rules for beta decay as well as from the absence of a gamma-ray cascade competing with the 661-kev transition, one can conclude that there exists no level with spin $\geq 3/2$ between the ground state of Ba^{137} and the metastable level at 661 kev. The only possibilities not excluded by the disintegration scheme of Cs^{137} are levels with spin 1/2− and 1/2+. However, such levels would not affect the behavior of the cross section, because for any level in the compound nucleus which would feed the 11/2 metastable state, the branching to the 3/2+ ground state would be much larger than the branching to a 1/2± state.

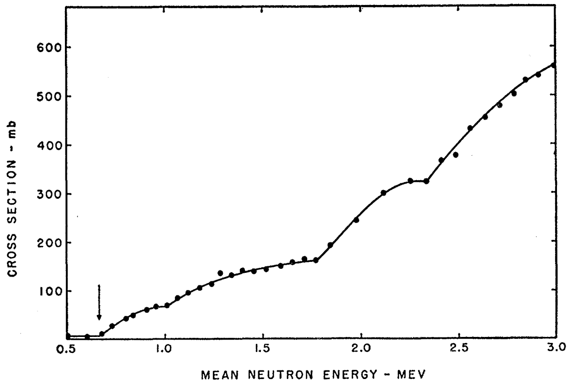

FIG. 4. Cross section for the production of the 661-kev metastable level of Ba^{137} as a function of the mean neutron energy. Arrow indicates threshold expected for direct excitation. Statistical errors ~5%.

Disks of Ba metal, $1\frac{5}{8}$ inch in diameter and $\frac{1}{8}$ inch thick, were used for the measurement of the (n,n') excitation curve. Each run consisted of a 10-minute bombardment, 20 seconds for the transfer of the sample to the scintillation spectrometer, and 5 minutes of gamma-ray counting. Figure 4 shows the excitation curve obtained in this manner. The sharp rise of the excitation curve at ~660 kev mean neutron energy indicates direct excitation of the metastable state. The residual counting rate below the (n,n') threshold is attributed to fast neutron capture in Ba^{136} (7.81% abundant).

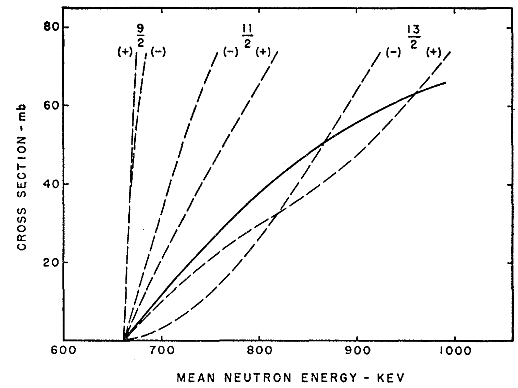

FIG. 5. Cross section for the direct excitation of Ba^{137m}. Comparison of the experimental cross section (solid curve) with the theoretical cross sections assuming different spin assignments for the metastable level.

The breaks in the excitation curve indicate the presence of excited states decaying to the metastable state. The energies of these levels are 1.05, 1.78, and 2.38 Mev. The abrupt flattening out beginning at 2.25 Mev might indicate another level at about this energy, which, however, decays principally to the ground state.

Using a radius of 8×10^{-13} cm, we calculated on the basis of the strong-interaction theory[5] the excitation curves assuming different values of spin and parity for the metastable level. The results are shown in Fig. 5,

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[17] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).

[18] A. C. G. Mitchell and C. L. Peacock, Phys. Rev. **75**, 197 (1949).

[19] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).

[20] L. Davis, Jr., Phys. Rev. **76**, 435 (1949).

together with the experimental curve. The theoretical curves for spins 9/2± and 11/2± have the correct shape, but give too large a cross section. The assignment 13/2+ gives the closest agreement with the experimental results. Figure 6 shows that with a radius of 5.3×10^{-13} cm and with the correct spin and parity, a good fit to the experimental points is obtained. Although our original choice of 8×10^{-13} cm might be considered somewhat large, the value of 5.3×10^{-13} cm is certainly smaller than one might expect[17] in this region of the periodic table.

C. Hg^{199m}

The $p_{1/2}$ ground of Hg^{199} and the $i_{13/2}$ metastable level at 527 kev differ by 6 units of angular momentum. The 44-min[21] isomeric level does not decay directly to the ground state, but is deexcited by a 368-kev $M4$ transition in cascade with a 159-kev $E2$ transition.

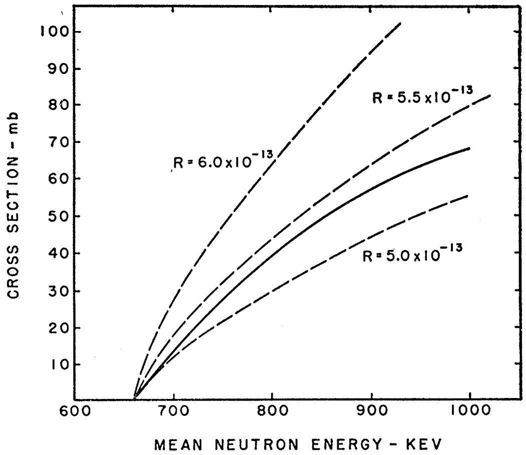

FIG. 6. Comparison of the experimental cross section (solid curve) for direct excitation of Ba^{137m} with the predictions of the strong-interaction theory for different radii and for the known spin of the metastable state (11/2−).

The scatterer consisted of liquid mercury contained in a thin-walled steel cylinder with 3 inches diameter and $\frac{1}{16}$ inch length. The bombarding times ranged from 30 minutes at the low energies to 5 minutes at the high energies. After the bombardment the mercury was poured into a plastic container surrounding the sodium iodide crystal, and counting commenced 1 minute after the end of the bombardment and lasted for 10 minutes. In Fig. 7 is shown the excitation curve. Direct excitation of the metastable level does not occur with a cross section greater than ~2 millibarns; the fast-neutron capture in Hg^{198} tends to conceal any small direct excitation.

The first definite break in the excitation curve occurs at 610-kev neutron energy. By using the level scheme of Hg^{199} proposed by Bergström and co-workers[22] and assuming a radius of 8×10^{-13} cm, a good fit could be obtained for the region from 610 to 980 kev, if the 610-kev level was assigned spin 9/2, even parity. The complexity of the level scheme and the uncertainty of some of the spin assignments makes this fit appear somewhat fortuitous. In addition to the 610-kev level, other excited states feeding the metastable level are indicated at 980, 1280, and 1840 kev.

CONCLUSION

In conclusion, it appears that, while the radius giving the best fit for Y^{89m} is, in view of the general fluctuation in the radii, reasonably close to the expected value,[17] the radius necessary in the case of Ba^{137m} is definitely low. One might use the magic character of the compound nucleus Ba^{138} as an excuse for this deviation; however, this argument is weakened by the good fit obtained by Stelson and Campbell[6] for Pb^{207m}, in which case the compound nucleus is even doubly magic. Unless the good fit for Pb^{207m} is due to the complex level structure and must be considered fortuitous, the disagreement in the case of Ba^{137m} might indicate that the fit obtained with the strong interaction theory[5] is poor in some regions of the periodic table while it is satisfactory in others. One certainly has to be very cautious in trying to use excitation curves of metastable states for the determination of unknown spins.

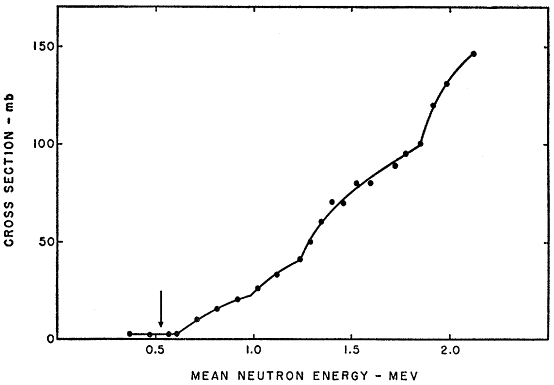

FIG. 7. Cross section for the production of the 527-kev metastable level of Hg^{199} as a function of the mean neutron energy. Arrow indicates threshold expected for direct excitation. Statistical errors ~5%.

ACKNOWLEDGMENTS

We are grateful to Mr. W. C. Porter for assistance in taking the data and to Mr. D. Schildknecht for computing some of the transmission coefficients.

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[21] N. Hole, Arkiv. Mat. Astron. Fysik **34B**, No. 19 (1947).

[22] Bergström, Hill, and Pasquali, Phys. Rev. **92**, 918 (1953).