Cross Sections for Production of In^{115m} and Au^{197m} by Inelastic Scattering of Neutrons*†

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Cross sections for the reactions $In^{115}(n,n')In^{115m}$ and $Au^{197}(n,n')Au^{197m}$ have been measured from the reaction thresholds to 5.5 Mev. The lowest mean energy for which the In^{115m} excitation was observed was 440 kev with an energy spread of ±100 kev; the cross section rises to a peak value of 0.36 barn at 2.5 Mev. The lowest mean energy for which the Au^{197m} excitation was observed was 420 kev with an energy spread of ±40 kev; the cross section rises to a peak value of 1.3 barns at 2.5 Mev. Both cross sections show irregularities which are evidence of energy levels in the target nuclei.

INTRODUCTION

EXCITATION of metastable states of nuclei by inelastic scattering of neutrons should be a useful means for investigating the nature of the inelastic scattering process in a rather large group of nuclides, particularly near the energetic threshold where other methods are poor.[1,2] At present the method is perhaps the only one capable of giving information on differences in inelastic scattering of isotopes. Because of their isotopic abundance and the ease of detecting the gamma radiations arising from the decay of their metastable states, the nuclides In^{115} and Au^{197} are well suited for such an investigation.

The abundance of In^{115} is 95.8 percent, that of In^{113} is 4.2 percent, and In^{114} is unstable. Several levels in In^{115} below 1.5 Mev have been proposed from investigations of the beta decay of Cd^{115}.[3] No levels are known of energies lower than the 4.5-hour metastable state at 335 kev. The isomer has two modes of decay: a 94-percent branch to the ground state of In^{115} by emission of a single 335-kev gamma ray, and a 6-percent branch to the ground state of Sn^{115} by emission of a 0.83-Mev beta.

Gold has only one isotope, Au^{197}, and the half-life of its metastable state is 7.5 seconds. The threshold for excitation of Au^{197m} by inelastic scattering of neutrons gives an unequivocal maximum value for the excitation energy of the metastable state which may be of assistance in determining the exact decay scheme for the lower levels of Au^{197}.[4]

Relative excitation curves for both In^{115m} and Au^{197m} have been obtained by Ebel and Goodman[5] using neutron energies up to almost 2 Mev; their curves show discontinuities which correspond to energy levels in In^{115} at 0.96 and 1.37 Mev and in Au^{197} at 1.14 Mev. They find excitation thresholds for In^{115m} and Au^{197m} at 0.60 Mev and 0.53 Mev, respectively. Cross sections for the production of In^{115m} by inelastic scattering of neutrons have been measured at several points between 2 and 4 Mev by Cohen,[6] who reports values of about 0.36 barn over this energy range.

The present experiments were undertaken for the purpose of measuring the absolute cross sections for both reactions, $In^{115}(n,n')In^{115m}$ and $Au^{197}(n,n')Au^{197m}$, from the reaction thresholds to 5.5 Mev. In addition to yielding information about energy levels in the target nuclei, absolute measurements may be compared with theoretical predictions of the cross section for excitation of the metastable state.[7]

In the case of the single isotope Au^{197} it may also be possible to compare experimentally the total inelastic collision cross section, as obtained by other methods, with that part of the inelastic scattering cross section which here leads to the 7.5-second state Au^{197m}.

EXPERIMENTAL PROCEDURES

Measurement of Relative Excitation Curves

Monoergic neutrons were made by accelerating either protons or deuterons with the Los Alamos 2.5-Mev electrostatic accelerator to produce the reactions $T(p,n)He^3$ or $D(d,n)He^3$.[8] For both reactions, neutrons were produced by the monatomic beam passing through a 3-cm-long gas target[9] filled to a pressure of approximately 25-cm Hg. Proton or deuteron beams of about three microamperes were used, and with the resulting neutron intensities it was necessary to irradiate the samples at about 10 cm from the source. This limited the neutron energy resolution with which the data could be taken.

Indium samples were prepared by folding strips of

* Work done under the auspices of the U. S. Atomic Energy Commission.
† H. C. Martin, thesis, University of Texas, 1953 (unpublished).
[1] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, *Final Report of the Fast Neutron Data Project*, NYO-636 (Technical Information Service, Oak Ridge, 1951), Sec. 4.
[2] Francis, McCue, and Goodman, Phys. Rev. **89**, 1232 (1953).
[3] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[4] J. W. Mihelich and A. de-Shalit, Phys. Rev. **91**, 78 (1953).
[5] A. A. Ebel and C. Goodman, Phys. Rev. **93**, 197 (1954) (this issue).
[6] S. G. Cohen, Nature **161**, 475 (1948).
[7] B. Margolis, Phys. Rev. **93**, 204 (1954) (this issue).
[8] Hanson, Taschek, and Williams, Revs. Modern Phys. **21**, 635 (1949).
[9] Jarvis, Hemmendinger, Argo, and Taschek, Phys. Rev. **79**, 929 (1950).

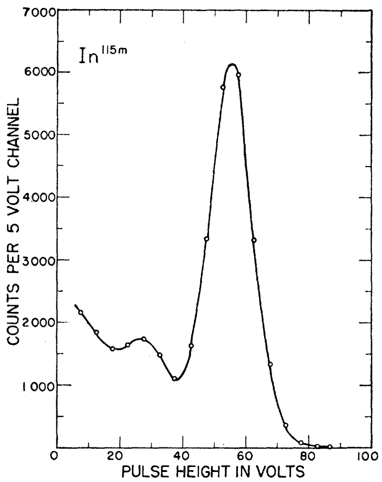

FIG. 1. Scintillation spectrum of gamma radiation from In^{115m}.

foil into rectangular blocks about $1\times1\times0.1$ cm. These blocks were held in small clips on a light aluminum ring which positioned them at equal distances and accurately known angles from the center of the gas target. Four irradiations with $T(p,n)He^3$ neutrons were made at different proton energies to obtain the section of the relative excitation curve from 440 kev to 1.6 Mev.

A $1\frac{1}{2}$-in. diameter$\times$2-in. long NaI(Tl) cylinder mounted in a mineral-oil filled container on a 5819 photomultiplier was used for counting the gamma rays from the activated samples. The samples were placed directly on the surface of the container with 0.002 in. of aluminum separating the samples and the crystal. Pulses from the photomultiplier were fed to a linear pulse preamplifier and amplifier, out of which they went to the input of an 18-channel pulse-height analyzer.[10] The gain of the amplifier was adjusted by observing the photopeak due to the 323-kev gamma ray from a Cr^{51} source, and the activities of the samples were measured by taking the number of counts in the photopeak due to the 335-kev In^{115m} gamma ray (Fig. 1). The observed activities were corrected for the angular distribution of the $T(p,n)He^3$ neutrons,[9] and a self-consistent curve was obtained by normalizing the four sets of data to each other at the highest neutron energy in each set, which was near 1.6 Mev. Samples irradiated by the lower energy neutrons had an appreciable number of 430-kev gamma rays from In^{116} produced by neutron capture. It was necessary to wait several hours for the 54-minute In^{116} activity to decay since the 335-kev and 430-kev gamma rays were not completely resolved by the scintillator. In^{113} has a 1.73-hour metastable state which decays to the ground state by a 390-kev transition, but no appreciable amounts of this activity were detected.

Nineteen samples placed at 7.5° intervals around the source were irradiated with $D(d,n)He^3$ neutrons to obtain the high-energy section of the relative excitation curve; a deuteron energy of 2.13 Mev was used. The observed activities of the samples were corrected for the angular distribution of the $D(d,n)He^3$ neutrons,[11,12] and this portion of the excitation curve was normalized to the $T(p,n)He^3$ section by extrapolating the $T(p,n)He^3$ section 200 kev. To check the validity of the structure observed in the high-energy section of the indium curve, a second short irradiation of the samples was made using a deuteron energy of 1.83 Mev. The resulting relative excitation curve agreed with the curve obtained using the higher deuteron energy within ±10 percent, which is about equal to the relative errors in the neutron angular distributions.

A special technique was devised for excitation and counting of the 7.5-second Au^{197m} activity. To avoid large background activities which were induced in the materials of the gas target assembly, the scintillator described above was placed on its side on the floor, eight feet directly below the neutron source, and an arrangement was used which allowed the irradiated sample to slide down a rod into position near the scintillator. By means of a system of relays and timers interlocked with the accelerator's beam shutter and the pulse-height analyzer, the gold sample was irradiated 40 seconds, was allowed 2.3 seconds to slide down the rod, and was counted for 10 seconds. Variation in the beam current was held to within about 4 percent during each irradiation. After each run the sample could be reactivated without delay since the half-life involved was so short.

The relative Au^{197m} excitation from 420 kev to 1.7 Mev was measured by irradiating the sample at 0° with $T(p,n)He^3$ neutrons. At each energy the relative neutron intensity was monitored by a flat-response long counter[13] placed at 0° and about 4 meters from the source. At least four irradiations were made at each energy. Figure 2 shows the pulse-height spectrum of the excited gold sample; the two photopeaks correspond to gamma-ray energies of about 280 and 70 kev. Although the metastable state decays by a 130-kev transition, the internal conversion coefficient for this transition is so large ($\sim$24) that no photopeak corresponding to a 130-kev gamma ray was observed.[14] Therefore, the Au^{197m} excitation was measured by the number of counts in the photopeak of the 279-kev prompt gamma ray which follows the 130-kev transition.

The relative excitation curve obtained with $D(d,n)He^3$ neutrons was measured by irradiating the sample at 7.5° intervals around the source while maintaining a constant accelerating voltage; the deuteron energy was

[10] C. W. Johnstone, Nucleonics **11**, 36 (1953).

[11] E. T. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949).
[12] Blair, Freier, Lampi, Sleator, and Williams, Phys. Rev. **74**, 1599 (1948).
[13] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[14] We are indebted to Dr. M. Goldhaber for clarifying the connection between the results of these experiments and the decay scheme of Au^{197}.

again 2.13 Mev. A beam-current integrator[15] was used to monitor the beam current for each irradiation. The excitation of the sample was again corrected for the angular distribution of the $D(d,n)He^3$ neutrons.

When deuterons were accelerated, neutrons were produced by the deuterons striking various materials in the target tube and vacuum system of the accelerator. This neutron background prohibited the use of the long counter as a monitor, but apparently was negligible so far as the samples placed near the gas target were concerned. The continuity of the slopes of the $T(p,n)He^3$ and $D(d,n)He^3$ sections of the excitation curves is evidence that no troublesome background was present. It was also observed that when deuterons were accelerated on the gas target when it was filled with tritium, the excitation of the gold sample was less than 10 percent of that caused by $D(d,n)He^3$ neutrons. Since the neutrons at 0° from the $D(t,n)He^4$ reaction have energies near 18 Mev, this observation is evidence for the validity of the negative slope of the gold excitation cross section above 3 Mev, and also indicates that the neutron background arising from deuterons striking materials other than the target gas was not troublesome.

Measurement of Absolute Cross Sections

In order to measure the absolute cross sections, the efficiency of the scintillator for counting the 335-kev In^{115m} gamma ray and the 279-kev Au^{197} gamma ray had to be determined. This was accomplished by calculating the efficiency of the crystal for photopeak counting of these gamma rays and also 411-kev gamma rays. The calculated 411-kev photopeak efficiency was then compared to an experimentally measured value to check the validity of the calculated values.

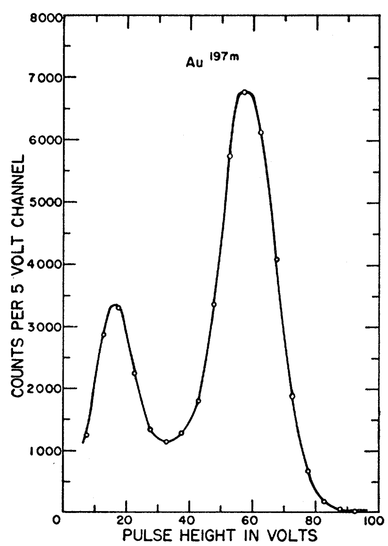

FIG. 2. Scintillation spectrum of gamma radiation from Au^{197m}.

[15] H. T. Gittings, Rev. Sci. Instr. **20**, 325 (1949).

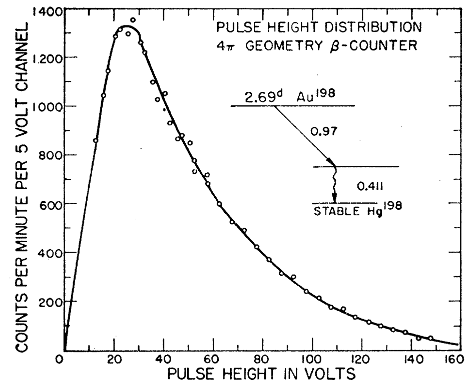

FIG. 3. Pulse-height distribution from the 4π-geometry beta counter.

2.69-day Au^{198} decays solely to the 411-kev excited state of Hg^{198} by emitting a beta of 0.97-Mev maximum energy;[16] the 411-kev gamma ray was chosen for calibrating the scintillator because a thin intense source could be prepared by thermal neutron bombardment of gold, the disintegration rate of the source could be measured by beta counting, and the total internal conversion coefficient of the 411-kev transition is only 0.043.

In calculating the efficiencies, it was assumed that the source was a point at one end and on the axis of the cylindrical crystal. Published values of calculated NaI absorption coefficients[17] were used, and no attempt was made to calculate the effect of secondary absorption. Calculated efficiencies for 279, 335, and 411-kev radiations were 0.251, 0.196, and 0.137, respectively.

A Au^{198} source was prepared by irradiating a 200 μgram/cm^2 gold leaf in the thermal neutron flux of the Los Alamos Water Boiler. A 1×1-cm sample was cut out of this leaf, and the disintegration rate of the sample was measured by absolute counting of the 0.97-Mev betas. The beta counter consisted of two ½ mm thick×4-cm diameter stilbene crystals in Lucite mounts on 5819 photomultipliers. These crystals were butted together with the sample sandwiched between them, giving a 4π geometry. Figure 3 shows the pulse-height spectrum from this counter; from the extrapolation of this spectrum to zero pulse height, it appears that all but about 5 percent of the pulses from the scintillator were above noise level. Using this counter it was possible to check within the experimental error of about 7 percent the 14-Mev neutron cross sections reported by Forbes for copper and aluminum.[18] After being counted in the beta counter, the gold sample was placed on the NaI cylinder with 0.062 in. of aluminum absorber to eliminate the 0.97-Mev betas; the counting rate for the 411-kev photopeak was observed, and a measured efficiency of 0.150 was obtained.

[16] D. Saxon and R. Heller, Phys. Rev. **75**, 909 (1949).
[17] W. H. Gordon, Ann. Rev. Nuclear Sci. **1**, 221 (1952).
[18] Stuart G. Forbes, Phys. Rev. **88**, 1309 (1952).

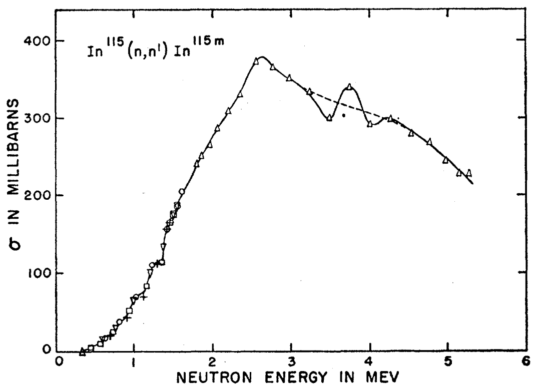

FIG. 4. Cross section for the production of In^{115m} by inelastic scattering of neutrons. Points indicating a small peak in the cross section near 4 Mev (solid curve) also appeared on an excitation curve obtained by making a second short irradiation of the indium samples using a different deuteron bombarding energy.

The measured efficiency for 411-kev gamma rays was about 9 percent larger than the calculated efficiency, which is reasonable since some scattered quanta from Compton collisions must be reabsorbed to give photopeak pulses. In view of this comparison, the efficiencies for 279 and 335-kev gamma rays were increased 9 percent over the calculated values by assuming that the ratios of the actual to calculated efficiency for the three gamma rays were equal; respective photopeak efficiencies of 0.275 and 0.215 were used for the 279 and 335-kev gamma rays.

For 279-kev radiation, the total absorption coefficient of gold is 14 per cm; a sample $1\times1\times0.05$ cm was used in measuring the cross section, and the sample was counted with its surface almost in contact with the surface of the scintillator. With this geometry, self-absorption was quite large; it was calculated that 52 percent of the gamma rays that would have been counted by the scintillator were self-absorbed.[19] In indium, the total absorption coefficient for 335-kev gamma rays is about 1.1 per cm; a sample $1\times1\times0.1$ cm was used, and the self absorption was calculated to be 22 percent.

Reported values of the total internal conversion coefficients for the transitions involved were used to calculate the number of excited nuclei corresponding to the observed number of nuclear gamma rays from the activated samples. For the 335-kev In^{115m} transition, $\alpha=0.98$,[20,21] and for the 279-kev Au^{197} transition, $\alpha=0.3$.[4] In the case of indium, it was also necessary to make a correction for the 6-percent beta-decay branch of In^{115m}. These betas were absorbed in the 0.062 in. of aluminum placed on the scintillator for the absolute cross section measurements.

[19] A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935), Appendix IX, p. 513.
[20] J. L. Lawson and J. M. Cork, Phys. Rev. **57**, 982 (1940).
[21] Langer, Moffat, and Graves, Phys. Rev. **86**, 632 (1952).

A neutron energy of 1.28 Mev was selected for measuring the cross section for indium because the excitation curve has a flat section at that point. The gold excitation curve has no flat section for $T(p,n)He^3$ neutron energies, and the energy of 1.42 Mev chosen for measuring the gold cross section was governed by the maximum proton energy conveniently attainable at the time of the measurement. The flat response long counter was used in determining the absolute neutron intensity by comparing the flux from the $T(p,n)He^3$ reaction to the flux from a standard RaBe source, calibrated to ±5 percent, placed at the gas target.

RESULTS

Figure 4 shows the cross sections obtained for In^{115m}. Very approximate average values of the total energy spread at various neutron energies are given in Table I. The lowest mean neutron energies for which excitation of the metastable state was observed were 0.44, 0.57, 0.60 Mev with approximate cross sections of 6, 11, and 17 millibarns respectively. The neutron-energy spread for these points was about 0.2 Mev. This is in agreement with the decay scheme for In^{115} proposed from the beta decay of Cd^{115}.

The energy dependence of the cross sections below 1.8 Mev is in good agreement with the relative curve obtained by Ebel and Goodman,[5] and the absolute cross section between 2 and 4 Mev agrees very well with the values measured by Cohen.[6] At 1.3 Mev, the probable error in the absolute cross section is estimated to be ±10 percent; relative errors in the cross section from 1 to 1.6 Mev are estimated to be ±5 percent. From 1.8 to 5.5 Mev, relative values of the cross section depend on accuracy of the knowledge of the very asymmetric angular distribution of the $D(d,n)He^3$ neutrons; relative errors for this section of the excitation curve are about ±10 percent.

Flat sections appear in the excitation curve at about 1 Mev and 1.35 Mev; x-ray excitation functions[22–24] for In^{115m} also show discontinuities at about these energies. Levels in In^{115} at 0.96 and 1.3 Mev which do not decay by way of the metastable state

TABLE I. Approximate total energy spreads at various mean neutron energies for the In^{115m} excitation curve. The energy spreads are largely caused by poor angular resolution.

Mean neutron energy in Mev	Total energy spread in Mev
0.3 to 1.2	0.18
1.2 to 1.4	0.13
1.4 to 1.7	0.05
1.8 to 2.4	0.18
2.4 to 3.6	0.45
3.6 to 5.0	0.40
5.0 to 5.5	0.12

[22] B. Waldman and M. L. Wiedenbeck, Phys. Rev. **63**, 60 (1943).
[23] W. C. Miller and B. Waldman, Phys. Rev. **75**, 425 (1949).
[24] Waldman, Miller, and Gideon, Phys. Rev. **76**, 181 (1949).

have also been proposed on the basis of the beta decay of Cd^{115}; the flat sections in the excitation curve at these energies are apparently caused by the competitive excitation of these levels. In the present experiment the shape of the curve near these levels is probably entirely determined by the neutron energy resolution.

Figure 5 shows the excitation curve for Au^{197m}. For each datum below 1.7 Mev the total neutron energy spread is about 70 kev. Above 1.8 Mev the energy spreads are the same as for the indium data.

The lowest mean energy for which the Au^{197m} excitation was observed was 420 kev; for this datum the maximum energy of the neutrons was not more than 460 kev. This result is energetically incompatible with the Au^{197} decay scheme quoted in reference 3, in which a 130-kev, a 279-kev, and a 77-kev gamma-ray cascade in series from the metastable level at 486 kev.[14] Because of the threshold obtained in the present experiment, in the decay scheme for Au^{197m} recently proposed by Mihelich and de-Shalit[4] it is assumed that the 77-kev gamma ray is not in the cascade with the 130-kev and 279-kev gamma rays; the metastable state is then at 409 kev. The low-energy photopeak in the Au^{197m} pulse-height distribution (Fig. 2) can be accounted for by conversion K x-rays from gold if the 77-kev nuclear gamma is omitted from the cascade.[14] The energy of the metastable state could probably be determined to within 10 kev by measuring the neutron excitation threshold using $Li^7(p,n)Be^7$ neutrons.

In measuring the absolute cross section, the large correction for self-absorption in the gold sample may cause a large error. At 1.4 Mev the measured value of the cross section was 0.6 barn; the probable error is estimated at ± 25 percent. Relative errors in the curve below 1.7 Mev are about ± 5 percent, and above 1.8 Mev, about ± 10 percent.

Below 1.7 Mev the gold curve is in general agreement with the relative curve obtained by Ebel and Goodman, although there are no marked increases in slope at 1.14 and 1.44 Mev such as they report. The curve of Fig. 5 shows general increases in slope at about 1.2 and 2 Mev and a peak at 2.6 Mev, and these energies correspond roughly with the activation levels for x-ray excitation of Au^{197m} found at 1.22, 2.15 and 2.56 Mev.[25]

The sections of the indium and gold cross section curves obtained with $D(d,n)He^3$ neutrons are remarkably similar in shape. Both curves show peaks near 2.5 Mev and fall off rapidly above 4 Mev. Since the energy of 4 Mev corresponds closely to an angular position at which the neutron intensity changes rapidly with angle, it might be suspected that these features were caused by errors in the angular distribution of the $D(d,n)He^3$ neutrons, but this seems unlikely in view of the very good agreement of the angular distributions obtained by Hunter and Richards[11] with those obtained by Blair *et al.*[12]

[25] M. L. Wiedenbeck, Phys. Rev. **68**, 1 (1945).

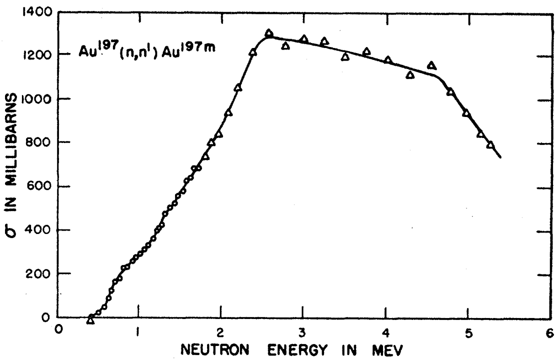

FIG. 5. Cross section for the production of Au^{197m} by inelastic scattering of neutrons.

The following explanation for the large difference in the indium and gold cross sections at energies near 2.5 Mev has been pointed out by Dr. B. Margolis. At high energies many states of the target nucleus can be excited, and, statistically, the number of these states cascading to the ground state through the metastable state as opposed to the number bypassing the metastable state should be roughly in the ratio $(2I_m+1)$: $(2I_g+1)$, where I_m and I_g represent the spins of the metastable state and ground state. The quantity

$$\frac{(2I_m+1)}{(2I_m+1)+(2I_g+1)}$$

then represents the fraction of inelastic-scattering events which should give rise to excitation of the metastable state. For gold and indium, this fraction is $\frac{3}{4}$ and $\frac{1}{6}$, respectively. If the cross sections at peak values are multiplied by 4/3 for gold and 6 for indium, values of 1.7 and 2.2 barns respectively are obtained which should represent the total inelastic scattering cross sections and hence should be similar in value.

The value of 2.2 barns for the total inelastic-scattering cross section of indium is reasonable in view of the total cross section, which is about 5 barns near 3 Mev. For gold, a total inelastic-scattering cross section of about 2.5 or 3 barns might be expected near 3 Mev. Since gold also has three levels between the metastable level and the ground state by way of which high excited states may decay, the value of 1.7 barns should be somewhat lower than the total inelastic scattering cross section. Cross sections for the excitation of isomeric states by bombardment with high-energy photons have a similar dependence on the spins of the ground state and isomeric state.[26]

A comparison of the cross section for excitation of the metastable state with the inelastic collision cross section as a function of neutron energy would be of interest. For gold this could be accomplished by the method of

[26] J. Goldemberg and L. Katz, Phys. Rev. **90**, 308 (1953).

measuring the transmission of a spherical shell with a threshold detector.[27,28]

We are indebted to the personnel of the Los Alamos Water Boiler for the irradiation of the gold leaf, and we wish to thank Dr. Goldhaber for his information concerning the decay scheme of Au^{197m}. It has been a pleasure to exchange communications with Dr. Margolis, Dr. Ebel, and Dr. Goodman in regard to these experiments.

[27] H. H. Barshall, Revs. Modern Phys. **24**, 120 (1952).
[28] Phillips, Davis, and Graves, Phys. Rev. **88**, 600 (1952).

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Inelastic Scattering of Neutrons near Threshold*

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Using the compound nucleus model, and assuming a statistical distribution of levels of the compound state, the inelastic neutron scattering cross sections for excitation of metastable states of Cd^{111} and In^{115} are calculated. The energy range just above threshold is considered. The sensitivity of the cross sections to the spin and parity of the metastable state is demonstrated in the case of Cd^{111}. Comparison is made with experiment, and the calculations are seen to be useful in learning about spins and parities of excited states of nuclei.

INTRODUCTION

Hauser and Feshbach[1] have pointed out that just above threshold energy the cross section for production of an excited state of a target nucleus by inelastic neutron scattering is particularly sensitive to the spins of the ground and excited states and to a lesser extent to the parities of these states. It is clear then that measurements of cross sections for the inelastic scattering of neutrons are of interest in nuclear spectroscopy. In particular, if the target nucleus has an excited state with a fairly long lifetime, it is possible to measure the cross section for excitation of this state by measuring its radioactivity. This is precisely the case when the cross sections are most sensitive to spin and parity difference. The larger the spin difference between the ground and excited states the more sensitive is the cross section to these spins and parities. Experiments of this type have been carried out by Francis, Goodman, and McCue[2] and by Martin, Diven, and Taschek.[3]

In this paper cross sections will be computed for excitation of metastable levels of Cd^{111} and In^{115} having energies 0.396 Mev, and 0.335 Mev, respectively.

THEORY

Using the compound-nucleus model and assuming a statistical distribution of levels for the compound states, Hauser and Feshbach[1] derive the following expression for direct excitation of an excited state of spin i' and energy above ground E' by inelastic scattering of neutrons of energy E and wavelength $2\pi\lambda\!\!\!^{-}$ from a target of spin i:

$$\sigma(i|i')=\frac{\pi\lambda\!\!\!^{-2}}{2(2i+1)}\sum_{l=0}^{\infty}T_l(E)\sum_{J=0}^{\infty}\epsilon_{jl}{}^J(2J+1)\frac{\sum_{l'}\epsilon_{j'l'}{}^J T_{l'}(E-E')}{\sum_{E'',l''}\epsilon_{j''l''}{}^J T_{l''}(E-E'')}. \quad (1)$$

The expression (1) takes into account competition due to elastic scattering and inelastic scattering of the neutrons by other levels. The competition from the (n,γ) process is omitted since, in the energy range under consideration, the radiation width is at most only a few percent of the total neutron width. This competition can be included easily when necessary.[4]

In formula (1) the energies and spins of the levels of the target nucleus that can be excited by a neutron of energy E are denoted by E'' and i'', respectively. J represents the possible spins of the compound nucleus; l, l', and l'' are the orbital angular momentum quantum numbers of an incoming neutron, of an outgoing neutron leaving the residual nucleus in the metastable state E', and of any outgoing neutron, respectively. The sum over the l'' must be taken so as to include only those terms that conserve the parity as well as the angular momentum of the system. $j_{1,2}''=i''\pm\frac{1}{2}$ and

$$\epsilon_{jl}{}^J=\begin{cases}2 \text{ if both } j_1 \text{ and } j_2\\ 1 \text{ if } j_1 \text{ or } j_2\text{, not both}\\ 0 \text{ if neither } j_1 \text{ nor } j_2\end{cases} \quad \text{satisfy } |J-l|\leq j_i\leq J+l. \quad (2)$$

* Research carried out at Massachusetts Institute of Technology, Cambridge, Massachusetts.
[1] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[2] Francis, McCue, and Goodman, Phys. Rev. **89**, 1232 (1953).
[3] Martin, Diven, and Taschek, preceding paper [Phys. Rev. **93**, 199 (1954)].
[4] B. Margolis, Phys. Rev. **88**, 327 (1952).