Neutron Activation Cross Sections for Mercury Isotopes at 14.1 MeV

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Fast-neutron activation cross sections for the mercury isotopes have been measured relative to the $^{56}Fe(n, p)^{56}Mn$ cross section. Enriched and natural-isotopic-abundance samples of Hg compounds were irradiated with 14.1±0.5-MeV neutrons. The activities produced were determined by observing the γ radiation with a Ge(Li) detector. The following cross sections (in millibarns) were determined: $^{196}Hg(n, 2n)^{195m}Hg$, 1060±70; $^{198}Hg(n, 2n)^{197m}Hg$, 900±70; $^{198}Hg(n, 2n)^{197g}Hg$, 940±100; $^{198}Hg(n, p)^{198}Au$, 4.7±0.3; $^{199}Hg(n, p)^{199}Au$, 4.6±0.6; $^{200}Hg(n, 2n)^{199m}Hg$, 880±60; $^{200}Hg(n, \alpha)^{197}Pt$, 0.2±0.1; $^{201}Hg(n, p)^{201}Au$, 1.5±0.7; and $^{204}Hg(n, 2n)^{203}Hg$, 2060±190.

I. INTRODUCTION

ALTHOUGH numerous activation cross sections have been determined at neutron energies near 14 MeV, the mercury isotopes have not been extensively investigated. Values of the (n, p) cross section for ^{200}Hg and ^{201}Hg, and of the (n, α) cross section for ^{200}Hg and ^{202}Hg, have been reported by Coleman *et al.*[1] Vandenbosch and Huizenga[2] measured the ratio of the $^{198}Hg(n, 2n)$ cross sections leading to ^{197m}Hg and ^{197g}Hg. Ward *et al.*[3] have reported values of the (n, p) cross section for ^{202}Hg and ^{204}Hg. Apparently no other cross-section measurements have been reported for Hg in the 14-MeV region.

In the present investigation, samples of HgO with natural isotopic abundance as well as two enriched samples were used to measure the activation cross sections. The yield of the reactions was determined by an absolute measurement of the γ activities of the products. A Ge(Li) detector was used to resolve the numerous γ rays emitted by the product radioisotopes. The high resolution of the detector also increased the possibility of identifying very weak γ rays, especially in the low-energy region.

The cross section for an activity produced directly by a neutron reaction is given by the well-known relation

$$\sigma=[\lambda N|_0/f(\lambda T)](1/\phi N), \quad (1)$$

where N is the number of target nuclei in the sample, ϕ is the neutron flux, and $\lambda N|_0$ is the decay rate of the product at the end of the irradiation period. The function $f(\lambda T)$, for the simple case of constant flux during an irradiation of duration T, is given by

$$f(\lambda T)=1-e^{-\lambda T}, \quad (2)$$

where λ is the decay constant of the activity produced in the reaction. In the majority of our irradiations the sample was irradiated with constant flux for a time T_1, the accelerator was turned off for a time t to allow replacement of the target, and irradiation was then continued at the same flux for a time T_2. Under these conditions the appropriate expression for $f(\lambda T)$ is

$$f(\lambda T)=1-\exp(-\lambda T_2)+\exp[-\lambda(T_2+t)]-\exp[-\lambda(T_2+t+T_1)]. \quad (3)$$

II. EXPERIMENTAL PROCEDURE

Neutrons were produced via the $T(d, n)He^4$ reaction by bombarding thick TiT targets with 550-keV deuterons in the USANDL Cockcroft-Walton facility. The flux was maintained constant to ±5% by continuous monitoring of the associated α-particle counting rate. Since the energy of the neutrons is relatively independent of incident deuteron energy at an angle of 90° with respect to the incident deuteron beam,[4] this position was chosen for the samples. The largest angle subtended by any sample at the neutron source was ±30°, for which case over 90% of the neutrons incident on the sample have energies within the range 14.1±0.5 MeV.

In three of the irradiations, the absolute neutron flux was determined by measuring the amount of ^{56}Mn activity produced in iron foils placed in front of and in back of the HgO samples. The activity was determined by observing the 845-keV γ ray, which occurs in 98.8% of the ^{56}Mn decays.[5] The cross section for the $^{56}Fe(n, p)^{56}Mn$ reaction was taken to be 106±7 mb, as reported by Liskien and Paulsen.[6] This value is in agreement with measurements made by Bormann *et al.*,[7] by Santry and Butler,[8] and by Terrell and Holm.[9] In a recent paper, Cuzzocrea *et al.*[10] report a value of 124±9 mb. Cuzzocrea *et al.*, however, determined this value relative to the $^{63}Cu(n, 2n)^{62}Cu$ cross section which they had previously measured, whereas Liskien

[1] R. F. Coleman, B. E. Hawker, L. P. O'Connor, and J. L. Perkin, Proc. Phys. Soc. (London) **73**, 215 (1959).
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[3] T. E. Ward, H. Inochi, M. Karras, and J. L. Meason, Phys. Rev. **164**, 1545 (1967).
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[5] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D.C. 20025, 1959), NRC 59-04-051.
[6] H. Liskien and A. Paulsen, J. Nucl. Energy Pt. AB, **19**, 73 (1965).
[7] M. Bormann, S. Cierjacks, R. Langkau, and H. Neuert, Z. Physik **166**, 477 (1962).
[8] D. C. Santry and J. P. Butler, Can. J. Chem. **42**, 1030 (1964).
[9] J. Terrell and D. M. Holm, Phys. Rev. **109**, 2031 (1958).
[10] P. Cuzzocrea, E. Perillo, and S. Notarrigo, Nuovo Cimento **54B**, 53 (1968).

and Paulsen performed an absolute measurement. Since the Liskien-Paulsen value is in better agreement with the results of other investigators, this older measurement was used as the standard in the present work.

From the three irradiations in which the neutron flux was measured with Fe foils, the value of the ^{204}Hg$(n, 2n)^{203}$Hg cross section (among others) was determined. The 279-keV γ ray emitted in the decay of ^{203}Hg was then utilized as an internal flux monitor in all subsequent irradiations. There were several reasons for this choice: (a) Because of the high cross section for ^{204}Hg$(n, 2n)$, the 279-keV γ was prominent in the spectra of all samples irradiated; (b) since ^{203}Hg has a half-life of 47 days, the ^{203}Hg activity could be conveniently determined after other γ rays had decayed; (c) the 279-keV transition occurs in 100% of the ^{203}Hg decays[11] and its internal conversion coefficient,[12] $\alpha_T = 0.2262 \pm 0.0019$, has been measured with good accuracy; and (d) the γ ray is of sufficiently high energy to permit any necessary self-absorption corrections to be made without difficulty.

The absolute intensity of the γ rays in all samples was determined by following the decay of the photopeaks with a 6-cm^2×5-mm Ge(Li) detector. The resolution of the detector and associated electronics was approximately 3.5 keV (FWHM) in the energy region of interest. The samples were counted in a standard geometry for which the absolute photopeak efficiency of the detector had been previously determined by calibration with standard γ-ray sources of known activity. Photopeak areas at different times were obtained by a least-squares fit of a Gaussian to the experimental photopeaks. These areas were in turn fitted by an exponential function of time to obtain the initial activities.

Eight samples were irradiated. Six of these contained HgO of natural isotopic abundance. In addition, two samples of enriched isotopic content were obtained on loan from Oak Ridge National Laboratory. One of these consisted of 2.28-g HgS enriched to 74.90% in ^{200}Hg; the other consisted of 1.08-g HgO enriched to 80.44% in ^{201}Hg. To obtain good counting statistics for some of the weaker γ's, four of the natural-abundance samples were prepared with a thickness of $\sim$1 g cm^{-2}. The remaining samples were prepared with a thickness of $\sim$0.2 g cm^{-2} to avoid extreme corrections for self-absorption of the lowest-energy γ rays. In calculating the cross sections, no γ-ray data were used for which the correction for self-absorption was greater than about 20%.

III. RESULTS

The values of the cross sections measured in this experiment are listed in Table I. Relevant data concerning the γ rays whose intensities were used to determine the cross sections have been included. The experimental errors indicated for the cross sections include the uncertainty in the neutron flux and in the absolute γ-ray activities. They do not include uncertainties in internal conversion coefficients or in γ-ray branching. The cross-section values reported here are obviously subject to revision if better measurements of these quantities become available. In some cases it was possible to calculate a meaningful upper limit for the cross section even though a definite value could not be obtained. For the sake of completeness these limits are included in the table.

A. ^{196}Hg

Although ^{196}Hg is only 0.146% abundant, a yield from the $(n, 2n)$ reaction was observed. The amount of 40-h ^{195m}Hg produced was determined by following the decay of the 262-keV γ ray, which is emitted in 31.2% of the ^{195m}Hg decays.[13] The 262-keV γ also occurs in the decay of 9.5-h ^{195g}Hg, but has only a 2.2% intensity[13] in this decay. No contribution from the 9.5-h activity was observed, which indicates that the value of the $(n, 2n)$ cross section for production of ^{195g}Hg is less than, or of the same order of magnitude as, that of the cross section for production of ^{195m}Hg. A value of 1060 ± 70 mb was obtained for $\sigma_m(n, 2n)$ from an average of four measurements. Because of the very low abundance of ^{196}Hg, no other reaction products from this isotope were observed.

B. ^{198}Hg

The $(n, 2n)$ reaction on ^{198}Hg produces both 24-h ^{197m}Hg and 65-h ^{197g}Hg. The 134-keV transition, which occurs in 93.5% of the ^{197m}Hg decays,[14] was used to determine the amount of ^{197m}Hg produced. The internal conversion coefficient of this transition has been reported[15] to be $\alpha_T = 2.1 \pm 0.5$. This result, however, was published in 1951, and since the transition is $E2$ in nature, it was decided that less error would be introduced by using the theoretical internal conversion coefficient. Accordingly, the value was taken to be[16] $\alpha_T = 1.61$. From neutron irradiation of two thin samples of HgO, the value of the cross section for the reaction ^{198}Hg$(n, 2n)^{197m}$Hg was determined to be 900 ± 70 mb. A 279-keV transition occurs in (6.5 ± 1.0)% of the ^{197m}Hg decays,[14] with an internal conversion coefficient[17] $\alpha_T = 0.44 \pm 0.10$. The cross section computed from this transition agreed with that calculated from the 134-keV

[11] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed., p. 391.
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[17] F. Smend, W. Weirauch, W.-D. Schmidt-Ott, and A. Flammersfeld, Z. Physik **191**, 1 (1966).

TABLE I. Cross-section results.

Reaction	Q value[a] (MeV)	σ (mb)	Half-life of product	E_γ (keV)	α_T	Transition intensity (%)
^{198}Hg$(n, 2n)^{197m}$Hg	−8.99	1060±70	40 h	262	···	31.2[b,c]
^{198}Hg$(n, 2n)^{197g}$Hg	−8.81	≲1100	9.5 h	262	···	2.2[b,c]
^{198}Hg$(n, 2n)^{197m}$Hg	−8.93	900±70	24 h	134	1.61[d]	93.5±1.0[e]
^{198}Hg$(n, 2n)^{197g}$Hg	−8.63	940±100	65 h	191	0.82±0.08[e]	2[e]
^{198}Hg$(n, p)^{198}$Au	−0.59	4.7±0.3	64.8 h	412	···	96.0±0.5[b,f]
^{199}Hg$(n, n')^{199m}$Hg	−0.53	≲80	44 min	158	0.9±0.1[g]	100[h]
				375	5.45±0.25[g]	100[h]
^{199}Hg$(n, p)^{199}$Au	+0.32	4.6±0.6	3.15 days	158	0.9±0.1[g]	77.1[i]
^{200}Hg$(n, 2n)^{199m}$Hg	−8.56	880±60	44 min	158	0.9±0.1[g]	100[h]
				375	5.45±0.25[g]	100[h]
^{200}Hg$(n, p)^{200}$Au	−1.43	<12	48 min	368	···	30[b,j]
^{200}Hg$[(n, np)+(n, pn)+(n, d)]^{199}$Au	−7.70					
	−5.48	<0.2	3.15 days	158	0.9±0.1[g]	77.1[i]
^{200}Hg$(n, \alpha)^{197}$Pt	+6.56	0.2±0.1	18 h	191	0.82±0.08[e]	13[k]
^{201}Hg$(n, p)^{201}$Au	−0.72	1.5±0.7	22 min	532	···	5[b,l]
^{201}Hg$[(n, np)+(n, pn)+(n, d)]^{200}$Au	−7.65					
	−5.43	<1	48 min	368	···	30[b,j]
^{202}Hg$(n, \alpha)^{199}$Pt	+5.71	<1	30 min	544	···	17[b,m]
^{204}Hg$(n, 2n)^{203}$Hg	−7.50	2060±190	47 days	279	0.2262±0.0019[n]	100[o]

[a] Reference 31.
[b] Number of photons per 100 decays of parent.
[c] Reference 13.
[d] Reference 16.
[e] Reference 14.
[f] Reference 19.
[g] Reference 20.
[h] Reference 23.
[i] Reference 21.
[j] Reference 24.
[k] Reference 18.
[l] Reference 25.
[m] Reference 22.
[n] Reference 12.
[o] Reference 11.

transition to within the error limits introduced by the uncertainties in intensity and in α_T.

The case of ^{197g}Hg is less straightforward. It can be produced directly by the $(n, 2n)$ reaction on ^{198}Hg, and is also the daughter nuclide in 93.5% of the decays[14] of ^{197m}Hg. Furthermore, the γ transitions observed in ^{197}Au following the decay of ^{197g}Hg are also observed following the decay[14] of 18-h ^{197g}Pt, which can be produced via the (n, α) reaction on ^{200}Hg. The situation is further complicated by the fact that the strongest γ ray emitted has an energy of 77 keV. Since the Au $K\beta_1$ x rays have an energy of 77.9 keV, we were unable to resolve the γ ray satisfactorily even with a Si(Li) detector with a resolution of about 1 keV (FWHM) at these energies. This cross-section measurement was therefore based on the observation of the 191-keV γ ray which occurs in about 2% of the ^{197g}Hg decays[14] and in about 13% of the ^{197g}Pt decays.[18] In this case, then, the area under the 191-keV photopeak is determined by the expression

$$a_1 \exp(-\lambda_1 t) - a_2 \exp(-\lambda_2 t) + a_3 \exp(-\lambda_3 t), \quad (4)$$

where λ_1 is the decay constant of ^{197g}Hg, λ_2 is that for ^{197m}Hg, and λ_3 is that for ^{197g}Pt. In terms of the parameters a_i, the ratio of the $(n, 2n)$ cross sections is given by

$$\frac{\sigma_g}{\sigma_m} = k_{br}{}^m \left(\frac{a_1}{a_2} \frac{\lambda_1}{\lambda_2 - \lambda_1} \frac{f(\lambda_2 T)}{f(\lambda_1 T)} - \frac{\lambda_2}{\lambda_2 - \lambda_1} \right), \quad (5)$$

where $k_{br}{}^m$ is the percentage of ^{197m}Hg nuclei which decay to ^{197g}Hg, and $f(\lambda_i T)$ is given by Eqs. (2) or (3), whichever is appropriate. The (n, α) cross section is calculated from Eq. (1), where $\lambda N|_0$ is obtained in a straightforward manner from a_3, and the cross section is that for production of 18-h ^{197g}Pt both directly by the (n, α) reaction and indirectly by decay of 80-min ^{197m}Pt.

A typical decay curve for the 191-keV photopeak is

[18] R. G. Helmer and L. D. McIsaac, Phys. Rev. 137, B223 (1965).

shown in Fig. 1. A computer fit of expression (4) to these curves indicated that the contribution from ^{197g}Pt in the natural-abundance samples was negligible, as might be expected. It was necessary to use a three-component fit only in the case of the sample enriched in ^{200}Hg. This case is discussed below. Note that Eq. (5) is independent of the relative intensity and internal conversion coefficient of the 191-keV transition, and also does not depend on the self-absorption of this γ ray in the sample. Hence, thick samples could be used to obtain better counting statistics. From an average of five measurements we obtain $\sigma_g/\sigma_m = 1.03 \pm 0.08$, which yields a value of the cross section $\sigma_g(n, 2n) = 940 \pm 100$ mb.

The ^{198}Hg(n, p) cross section was calculated from the intensity of the 412-keV transition, which yields 96.0 ± 0.5 photons per 100 decays[19] of ^{198}Au. The only complication present in this measurement is the possibility of production of ^{198}Au via the $(n, d) + (n, np) + (n, pn)$ reactions on ^{199}Hg. [In the following, this combination is abbreviated to (n, np).] Such a contribution could have been searched for by irradiating a sample highly enriched in ^{199}Hg. Unfortunately, such a sample could not be obtained. There may therefore be some contribution to this cross section from the (n, np) reaction, although the (n, np) cross section is, in general, expected to be much smaller than the (n, p) cross section for heavy nuclides.[1] From an average of three measurements a value $\sigma = 4.7 \pm 0.3$ mb was obtained.

C. ^{199}Hg

Activation of ^{199m}Hg by inelastic neutron scattering is certainly expected. The isomer is also produced by the $(n, 2n)$ reaction on ^{200}Hg. An attempt to estimate the (n, n') cross section was made by comparing the activation produced in the natural samples with that produced in the sample enriched in ^{200}Hg. The difference between them was less than the experimental error. As stated above, it was not possible to obtain a sample enriched in ^{199}Hg. From the comparison of the natural and enriched samples which were available, it is only possible to say that $\sigma(n, n') \lesssim 80$ mb.

The (n, p) cross section was obtained from observation of the 158-keV transition, which has an internal conversion coefficient[20] of 0.9 ± 0.1 and occurs in 77.1% of the ^{199}Au decays.[21] The ^{199}Au isotope could also be produced by (n, np) on ^{200}Hg and by decay of ^{199}Pt resulting from (n, α) on ^{202}Hg. A comparison of the ^{199}Au activity produced in the natural samples with that produced in the sample enriched in ^{200}Hg indicated that any contribution to the ^{199}Au activity from the (n, np) reaction was negligible. A search was made for the 544-keV γ ray which occurs in about 17% of the ^{199g}Pt decays.[22] Since this γ was not observed, we placed an upper limit of 1 mb on the ^{202}Hg(n, α) cross section. A value of 1.01 ± 0.1 mb for this cross section has been reported by Coleman *et al.*[1] Our value of the (n, p) cross section calculated from an average of three measurements is 4.6 ± 0.6 mb. However, this may be as low as 3 mb if the ^{202}Hg(n, α) cross section is 1 mb.

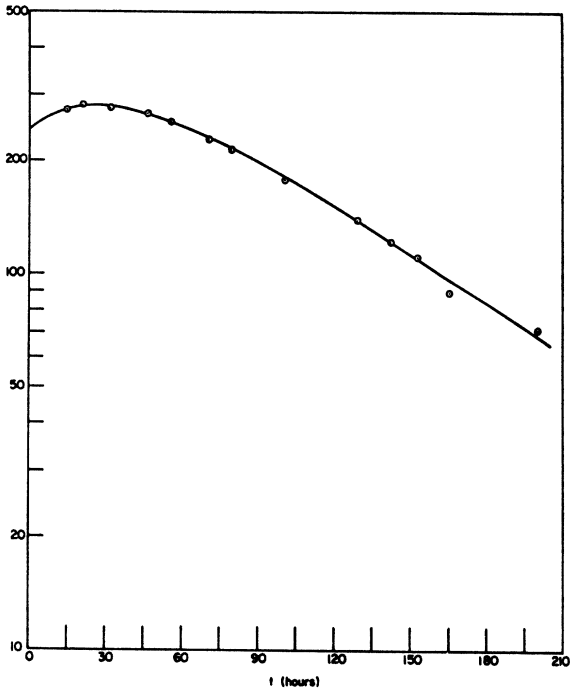

FIG. 1. Computed fit to the decay of the 191-keV peak. (The ordinate gives the activity in arbitrary units.) Natural-isotopic-abundance sample. The solid line is the expression (4) with the computed parameter values $a_1 = 583 \pm 4$ and $a_2 = 344 \pm 7$, and with $a_3 = 0$.

D. ^{200}Hg

The value of the cross section for production of ^{199m}Hg via the $(n, 2n)$ reaction on ^{200}Hg was calculated from the 375- and 158-keV transitions. Both transitions occur in 100% of the decays[23] of ^{199m}Hg. As pointed out above, this cross section may include some contribution from the (n, n') reaction on ^{199m}Hg; however, any such contribution is less than the experimental error. An average of five determinations gave $\sigma = 880 \pm 60$ mb.

The (n, p) cross section could not be measured during the course of this investigation. The only γ ray emitted in the decay[24] of ^{200}Au, which is of high enough intensity and low enough energy to be observed with the Ge(Li)

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[22] K. G. Prasad, R. P. Sharma, and B. V. Thosar, Phys. Rev. **149**, 980 (1966).
[23] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed., p. 385.
[24] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed., p. 387.

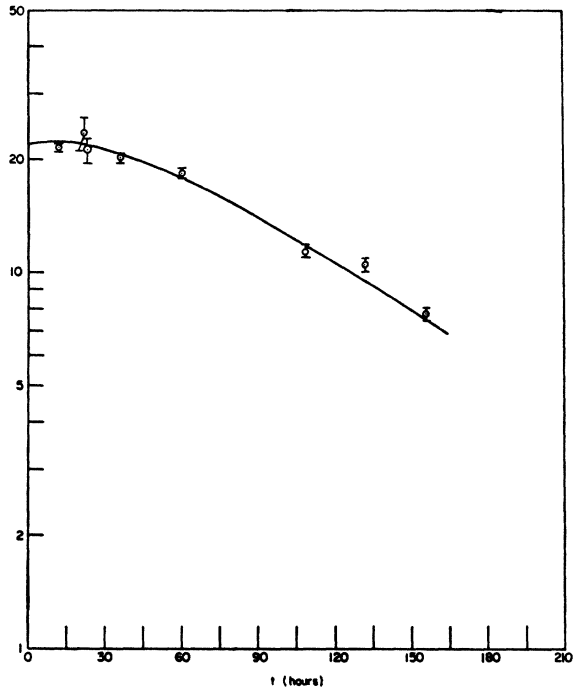

FIG. 2. Computed fit to the decay of the 191-keV peak. (The ordinate gives the activity in arbitrary units.) Sample enriched to 74.90% in ^{200}Hg. The solid line is expression (4) with the computed parameter values $a_1=40.8\pm1.9$, $a_2=23.2\pm1.1$, and $a_3=4.3\pm2.3$.

detector, is the 368-keV γ, which was not well resolved from the very intense 375-keV γ resulting from the decay of ^{199m}Hg. The half-lives of ^{200}Au and ^{199m}Hg are nearly equal. The intensity of the 368-keV peak was less than $\sim$3% that of the 375-keV peak, which yields an upper limit for the ^{200}Hg(n, p) cross section of 12 mb. Again, this may contain some contribution from the (n, np) reaction on ^{201}Hg.

The ^{199}Au activity obtained by irradiation of the sample enriched in ^{200}Hg was compared with that produced in the natural-abundance samples in order to estimate the contribution from the ^{200}Hg(n, np) reaction. An upper limit of 0.2 mb was calculated for this cross section.

The ^{200}Hg(n, α) reaction could be observed only by searching for a contribution to the 191-keV peak from the ^{197g}Pt activity, as discussed above. The least-squares fit indicated a significant contribution from ^{200}Hg(n, α) only for the data obtained from the sample enriched in ^{200}Hg. These data and the three-component computer fit to the points [see expression (4)] are shown in Fig. 2. Using Eq. (1) and assuming an internal conversion coefficient[14] of 0.82 and a relative transition intensity[18] of 13%, we obtain a value of 0.2 ± 0.1 mb for the (n, α) cross section.

E. ^{201}Hg

The (n, p) reaction on ^{201}Hg produces ^{201}Au. The decay scheme for this isotope is not well known, although it is generally agreed that the half-life is about 22 min and that a γ ray of approximately 530-keV energy is emitted in some fraction of the decays.[25–27] A γ ray of 532 ± 1-keV energy, which exhibited a half-life of about 20 min, was observed in all the natural-abundance samples, but was too weak to permit an intensity determination. It was possible to measure its intensity in the sample enriched in ^{201}Hg. From this measurement, assuming that the 532-keV γ occurs in 5% of the ^{201}Au decays,[25] we obtain for the (n, p) cross section a value of 1.5 ± 0.7 mb. Since ^{202}Hg and ^{204}Hg were only 7.95 and 1.14% abundant in this sample, any contribution from the (n, np) reaction on ^{202}Hg or from the decay of ^{201}Pt resulting from (n, α) on ^{204}Hg should be well within the error limits.

Any observation of ^{200}Au resulting from the (n, np) reaction on ^{201}Hg was again hindered by the proximity of the 375-keV γ from ^{199m}Hg. It was possible, however, to place an upper limit of 1 mb on the value of the (n, np) cross section.

F. ^{202}Hg

No products from reactions on ^{202}Hg could be definitely identified. As discussed above in connection with the (n, p) reaction on ^{199}Hg, an upper limit of 1 mb was calculated for the (n, α) cross section on ^{202}Hg.

G. ^{204}Hg

The ^{204}Hg$(n, 2n)^{203}$Hg cross section was chosen as the internal flux monitor for those irradiations in which iron foils were not used. The ^{203}Hg activity was determined by following the decay of the 279-keV γ ray for approximately two months. These data were fitted by a sum of two exponentials, since a 279-keV γ ray is also emitted in the decay of 24-h ^{197m}Hg. Since the (n, np) cross sections in this region are apparently less than 1 mb, any contribution to the ^{203}Hg activity from the decay of ^{203}Au produced via the (n, np) reaction on ^{204}Hg should be completely negligible. An average of three measurements yielded a value of 2060 ± 190 mb for the $(n, 2n)$ reaction on ^{204}Hg.

IV. DISCUSSION

A. Comparison with Earlier Results

The ratio σ_g/σ_m for the $(n, 2n)$ reaction on ^{198}Hg has been measured by Vandenbosch and Huizenga.[2] They obtained $\sigma_g/\sigma_m=1.25\pm0.16$, as compared with our value $\sigma_g/\sigma_m=1.03\pm0.08$. The values agree to within the experimental error, and the value obtained in the present investigation does not alter the conclusion of Vandenbosch and Huizenga that the value of the

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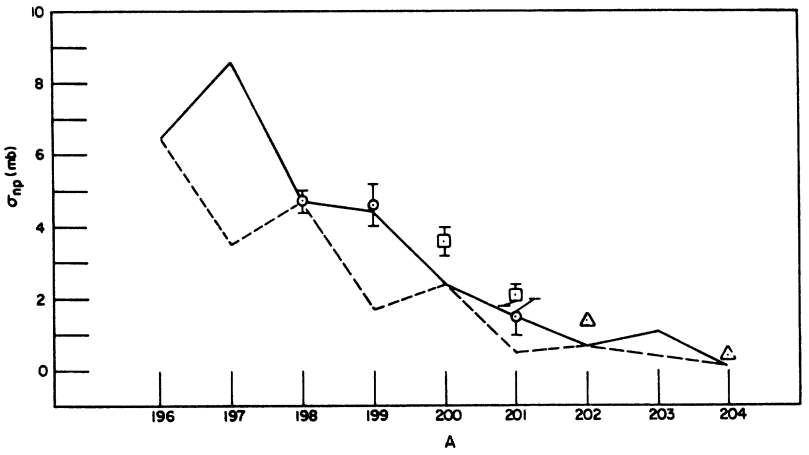

FIG. 3. Comparison of experimentally determined (n, p) cross sections with cross sections calculated from the formula of Gardner and Poularikas (Ref. 30). The solid line connects values calculated with $\delta = 1.2$ MeV; the dashed line connects values calculated with $\delta = 1.7$ MeV. Calculated values are normalized to 4.7 mb at $A = 198$. Circles: present investigation; squares: Ref. 1; triangles: Ref. 3.

spin cutoff parameter is 4 ± 1. They obtained their information about production of ^{197g}Hg from observation of the 77-keV transition. As discussed above, it is difficult to extract information concerning this transition from γ-ray spectra because of its proximity to the gold K x rays. For this reason we believe that the ratio obtained in the current investigation is indeed more accurate.

The cross section for the reaction ^{199}Hg$(n, n')^{199m}$Hg has been measured by Swann and Metzger[28] in the region from threshold to 2 MeV and by Broadhead and Shanks[29] at 2.8 MeV. The excitation function obtained by Swann and Metzger increases monotonically to a value of 150 mb at 2 MeV, and Broadhead and Shanks report a value of 95 ± 12 mb. The upper limit of 80 mb at 14.1 MeV deduced in the present investigation is consistent with these results.

The cross sections for ^{200}Hg$(n, p)^{200}$Au and for ^{201}Hg$(n, p)^{201}$Au have been measured by Coleman *et al.*,[1] who determined the activity produced by absolute β counting. The upper limit of 12 mb obtained in the present investigation for the ^{200}Hg(n, p) reaction is consistent with their value of 3.63 ± 0.36 mb. Their value of 2.12 ± 0.32 mb for the ^{201}Hg(n, p) cross section agrees to within experimental error with our value of 1.5 ± 0.7 mb.

Coleman *et al.*[1] have also measured the cross sections for the ^{200}Hg$(n, \alpha)^{197}$Pt and ^{202}Hg$(n, \alpha)^{199}$Pt reactions. We place an upper limit of 1 mb on the cross section for the (n, α) reaction on ^{202}Hg, which is not inconsistent with their measured value of 1.01 ± 0.1 mb. In the case of ^{200}Hg, however, the value of 0.2 ± 0.1 mb obtained in the present investigation is an order of magnitude lower than the value 1.77 ± 0.35 mb obtained by Coleman *et al.* As discussed in detail above, this cross section was deduced from a three-component fit to the data points shown in Fig. 2. The relatively small contribution to this curve from ^{197g}Pt is responsible for the 50% uncertainty in our value; however, it is difficult to understand how the parameter a_3 could be increased by an order of magnitude. Such an increase would have to be compensated for by a corresponding change in a_2. The ratio a_1/a_2 must, however, be the same as in the fits to the data points for the natural-abundance samples, an example of which is shown in Fig. 1. Therefore, it would appear from these data that the value of the ^{200}Hg(n, α) cross section is indeed considerably smaller than that reported by Coleman *et al.*

B. (n, p) Cross Sections

A formula has been developed by Gardner and Poularikas[30] for the ratios of (n, p) cross sections for all isotopes of any one element. The ratios are given by

$$\sigma(Z, A+1)/\sigma(Z, A) \approx \exp 2[(aE)_{A+1}^{1/2} - (aE)_A^{1/2}], \tag{6}$$

where $a = 1.15 \exp[1/(54A)]$ for elements in the range $65 \leq Z \leq 80$ and $E = E_n + Q_{np} - \delta$. Figure 3 shows the values computed from this formula, along with the experimental values. Q values were taken from the compilation of Mattauch, Thiele, and Wapstra,[31] except for ^{197}Hg, for which Q_{np} was computed from the decay energy of ^{197}Hg reported by De Wit and Wapstra,[32] and for ^{204}Hg, for which Q_{np} was computed from the decay energy of ^{204}Au reported by Ward *et al.*[3] The calculated values were normalized to a value of 4.7 mb for ^{198}Hg. The experimental points shown include the values measured in the current investigation, those measured by Coleman *et al.*,[1] and those measured by Ward *et al.*[3] The dashed line in Fig. 3 connects the points calculated with a value of 1.7 MeV for the pairing energy δ, as suggested by Gardner and Poularikas. The solid line connects the values calculated with $\delta = 1.2$ MeV, which appears to give a somewhat better fit. The

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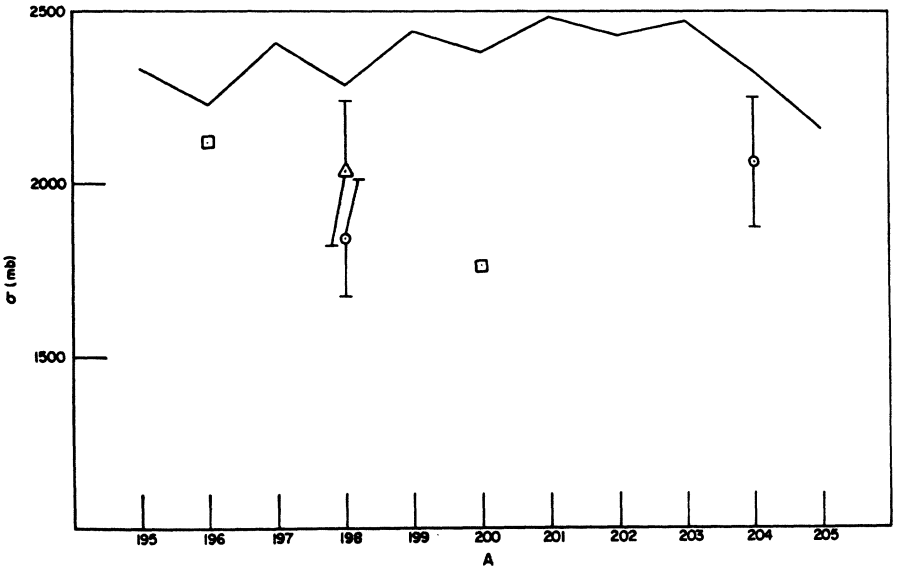

FIG. 4. Comparison of experimentally determined $(n, 2n)$ cross sections with values predicted by Pearlstein (Ref. 34). The calculated values are connected by the solid line. Circles: directly measured in this experiment; triangle: obtained from our value of σ_m and the value of σ_g/σ_m reported in Ref. 2; squares: obtained by doubling the value of σ_m measured in this experiment.

criterion suggested by Gardner and Poularikas is that, for any Z, the values of $Q_{np}-\delta$ should be a monotonic decreasing function of A. This is true for both values of δ. Unfortunately, measurements of (n, p) cross sections in the high-A region are generally scarce, and it is therefore not possible to choose between the two values by comparison with other measurements.

C. $(n, 2n)$ Cross Sections

A statistical-model approach for calculating $(n, 2n)$ cross sections has been developed by Pearlstein.[33,34] In Fig. 4 the values for the Hg$(n, 2n)$ cross sections taken from his tables[34] are compared with those experimentally determined. For ^{198}Hg we show the value obtained from our measured value of σ_g/σ_m and from that measured by Vandenbosch and Huizenga.[2] The experimental values shown for ^{196}Hg and ^{200}Hg were obtained by doubling the measured value of σ_m for these isotopes, in analogy to the ratio σ_g/σ_m determined for ^{198}Hg. The agreement between the calculated and experimental values is comparable to that obtained for other nuclides,[33] although there are cases for which the calculated and experimental values are in much better agreement[33,35] than that demonstrated here for the Hg isotopes. The largest discrepancy occurs for ^{200}Hg, which may be an indication that $\sigma_g/\sigma_m>1$ for this nuclide.

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