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Slow Neutron Capture Gamma Rays in Hg^{200} †

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Coincidence measurements on the gamma rays following slow neutron capture by Hg^{200} have been made with thermal neutrons and at the 34-, 129-, and 175-eV resonances. The two new low-lying levels found at 1.05 and 1.27 MeV constitute the third and fourth excited states of Hg^{200}. These new states, together with the previously known second excited state, are shown to be consistent with a two-phonon vibrational triplet. Transitions to several other states were also observed. The transitions from the four capturing states to various low-lying states are summarized.

INTRODUCTION

THE low-lying levels of Hg^{200} are reached through the decay of the neighboring isobars Tl^{200} and Au^{200} as well as through the gamma rays that follow the capture of a neutron by Hg^{199}. The β decay of[1–3] Tl^{200} and[4,5] Au^{200}, as well as the radiations following thermal-neutron capture[6–11] by Hg^{199} have been extensively studied, but the results are divergent on several points. Specifically, in several cases what appears to be the same level decays differently depending on whether it follows β decay or neutron capture. While at first one might have been tempted to ascribe these discrepancies to experimental error, each reaction has been investigated by several independent groups. These experiments suggest that the apparent discrepancies arise because the two reactions often proceed through different but closely spaced levels. We have therefore undertaken to study the level scheme of Hg^{200} by examining the γ-ray cascades following resonant neutron capture in Hg^{199}.

All of the work to date agrees that the first excited state of Hg^{200} is at 0.368 MeV. This state has been shown[1] to be 2^+. The β-decay studies place the second excited state[1–3] at 0.947 ± 0.001 MeV and then find no more levels below about 1.6 MeV; above this are several levels spaced on the average about 50 keV apart throughout the energetically accessible region. Studies of the gamma rays from thermal-neutron capture[6–8] find two levels near 1 MeV and, again, a number of levels above 1.6 MeV, but most of the latter do not appear to correspond to the levels reached by the cascades following β decay.

One particularly interesting issue for investigation by resonant neutron capture is the nature of the second, third, and fourth excited states. For an even-even nucleus in this mass region, theory would have these states be the 0^+-2^+-4^+ triplet of a vibrational spectrum. The energy sequence of these states is not definitely predicted and, in fact, the phonon model (harmonic oscillator approximation[12]) has them degenerate. The expected differences between this simple model and an actual nucleus could readily remove this degeneracy.[12–16] The state[1,2] at 0.947 MeV, which the β-decay work takes to be the second excited state, has been determined[2] to be 4^+. The β-decay studies report no other levels in this energy region. No strong transitions following thermal-neutron capture go to levels at this energy,[6] though the thermal-capture work does show[7,8] some evidence for other levels close to, but distinct from, the 4^+ 0.95-MeV state. The absence of strong direct transitions from the capturing state to any of the members of the 0-2-4 triplet is to be expected because thermal-neutron capture on Hg^{199} is known[17] to be dominated by a spin-0 state. On the other hand, some of the slow-neutron resonances are known[18] to form 1^- states (Hg^{199} is $\frac{1}{2}^-$) and these states could decay to the 0^+ and 2^+ members of the triplet by $E1$ transitions. Special effort was made in the present work to identify a possible vibrational triplet, particularly by studying the gamma-ray cascades from two prominent 1^- levels which are formed by resonance-neutron capture. In addition, the decay

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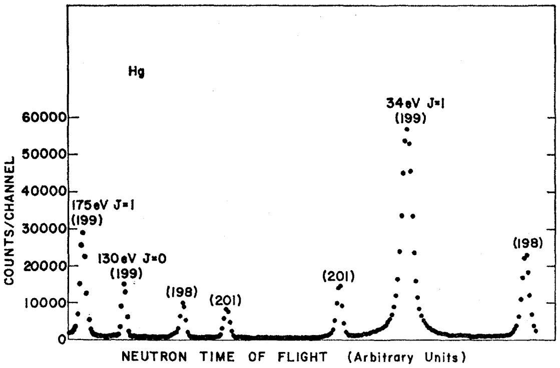

FIG. 1. Time-of-flight spectrum of neutrons in coincidence with all recorded gamma-ray cascades. The isotopic assignments (in parentheses) and spin assignments are from Ref. 17.

from a resonance known[18] to be 0^- has been examined, and the thermal capture has been restudied.

RESONANCE CAPTURE

An HgO sample was irradiated by a mechanically chopped neutron beam from the Argonne CP-5 reactor. The sample was viewed by two NaI(Tl) crystals 8 in. in diameter×6 in. thick placed on opposite sides of the sample. The face of each crystal was 4 in. from the center of the sample. The data were recorded in a 3-parameter[19] multichannel pulse-height analyzer. When a coincidence occurred between the two crystals, the pulse height in each crystal and the time required for the captured neutron to traverse the 25-m flight path were recorded. The amplifier gains and discriminator biases were set so that one (high-energy) crystal recorded events corresponding to gamma rays with energies between about 2.5 and 10.0 MeV while the other (low-energy) crystal covered the range between 0.22 and 2.70 MeV. The neutron energy range covered was from about 20 to 200 eV.

The three runs taken differed only in the lead absorbers that were placed between the sample and the crystals. The purpose of the absorbers was to reduce and evaluate the summing of gamma rays since, with the large solid angles used, summing could easily lead to erroneous results unless allowances were made. In all of the runs there was $1\frac{1}{2}$ in. of paraffin and $\frac{1}{4}$ in. of lead in front of the high-energy crystal and 1 in. of paraffin in front of the low-energy crystal. The absorbers used in the three runs were (1) only these absorbers, (2) these plus $\frac{1}{8}$ in. of lead in front of the low-energy crystal only, and (3) similar to run 2 plus an additional $\frac{1}{4}$ in. of lead in front of the high-energy crystal.

A total of some 1.4 million events were recorded. A time-of-flight spectrum of neutrons in coincidence with all of the gamma-ray cascades recorded in one run is shown in Fig. 1. The neutron spectra were virtually identical for the three runs. Only the three $\text{Hg}^{199}+n$ resonances below 200 eV were investigated. In a preliminary[20] report, we reported transitions from the capture state associated with the 34-eV resonance to a state at 1.27 MeV and from that of the 175-eV resonance to a state at 1.05 MeV. The present work confirms and amplifies our previous work.

Figure 2 shows one of the spectra of low-energy gamma rays resulting from neutron capture in the 175-eV resonance. It is the spectrum obtained when pulses from the low-energy crystal were gated by gamma rays feeding levels at excitations between 0.95 and 1.22 MeV in Hg^{200}. That is, the gating pulses from the high-energy crystal were required to fall in a window corresponding to gamma-ray energies between 6.81 and 7.08 MeV if the neutron binding energy is taken to be 8.03 MeV.[6] These data represent a sum of all three runs. The spectrum contains two peaks which represent gamma rays of energy 0.37 and 0.68 MeV. The spectrum of Fig. 2 is distorted at the low-energy end by the lead absorbers that were present during two of the three runs. In the run taken without a lead absorber in front of the low-energy crystal, the 0.37- and 0.68-MeV gamma rays had approximately equal intensity after allowance was made for the variation of peak efficiency with gamma-ray energy.

Figure 3 shows the spectrum in the high-energy crystal in coincidence with the 0.68-MeV line when the 3-parameter analyzer selected gamma-ray cascades resulting from capture in the 175-eV resonance. The peak at about 6.98 MeV represents a gamma ray feeding a level at 1.05 MeV in Hg^{200}. The combined evidence from Figs. 2 and 3 definitely establishes a level at 1.05±0.02 MeV, the determination of the energy being derived from the spectrum in the low-energy crystal. The energy definition is sufficient to justify a positive statement

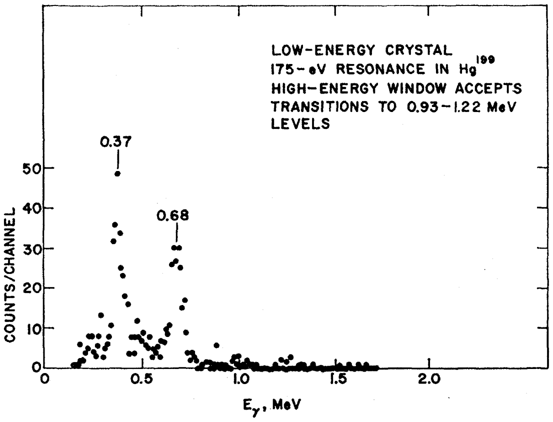

FIG. 2. Gamma-ray spectrum from neutron capture in the 175-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 0.93 and 1.22 MeV in Hg^{200}.

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that the new level is distinct from the previously known[1,2] state at 0.947 MeV.

It can be seen from Fig. 2 that no ground-state transition was observed from the 1.05-MeV level. There is a slight bump or background fluctuation at 1.0 MeV, in Fig. 2, just below the correct energy (1.05 MeV). Although this bump is suggestive, it does not appear to be statistically significant. From an examination of all the data, we conclude that the crossover from the 1.05-MeV state to the ground state is less than 7% as intense as the stopover to the 0.37-MeV first excited state.

The most important evidence establishing the new level at 1.27 MeV is presented in Fig. 4, which shows the spectrum resulting from capture in the 34-eV resonance and in coincidence with gamma rays feeding the appropriate energy region. In addition to the omnipresent 0.37-MeV peak, the main features of the spectrum are peaks corresponding to gamma-ray energies of about 0.90 and 1.27 MeV. The high-energy spectra in coincidence with these peaks showed a transition from the capturing state to a level in Hg^{200} at about 1.27 MeV and thus confirmed the new level, placed at 1.27 ±0.02 MeV.

Before the 1.27-MeV peak could be certified as being the ground-state transition from the new state, it was necessary to make sure that summing effects were properly allowed for. The intensity of the 1.27-MeV peak relative to that of the 0.90-MeV stop-over appears to be much too large to be caused by summing in the low-energy crystal. This supposition was confirmed by comparing the data taken with and without an absorber in front of the low-energy crystal; the absorber reduced summing by more than a factor of three yet no attenuation of the 1.27-MeV peak was observed. An extraneous peak at about the right energy could also be caused by summing in the high-energy crystal. This occurs because a strong transition, some ten times as strong as the transition to the 1.27-MeV state, terminates on a state at about 1.60 MeV (Fig. 5). This 1.60-MeV state decays primarily via a 1.23-MeV gamma ray to the first excited state. Thus summing of the 0.37-MeV gamma ray and the (6.43-MeV) gamma ray feeding the 1.60-MeV state could be mistakenly identified as a 6.80–1.23-MeV cascade which in turn could be interpreted as a two-step cascade through the 1.27-MeV state. While the "1.23-MeV" gamma ray in the spectrum in coincidence with the line feeding the 1.60-MeV state (Fig. 5) was shifted down in energy relative to that in the spectrum in coincidence with the line feeding the 1.27-MeV state (Fig. 4), the statistics of the latter spectrum were poor enough that the validity of the crossover from the 1.27-MeV state could not be certified on these grounds alone. However, the possibility that summing was responsible for the crossover appearing in the spectrum was eliminated when the spectra taken with and without an absorber in front of the high-energy crystal were compared; the absorber was sufficiently opaque to 370-keV radiation to virtually eliminate summing, yet, within statistics, the 1.27-MeV peak remained undiminished. Thus the crossover transition from the 1.27-MeV state to the ground state was established and found to depopulate the level about 40% of the time.

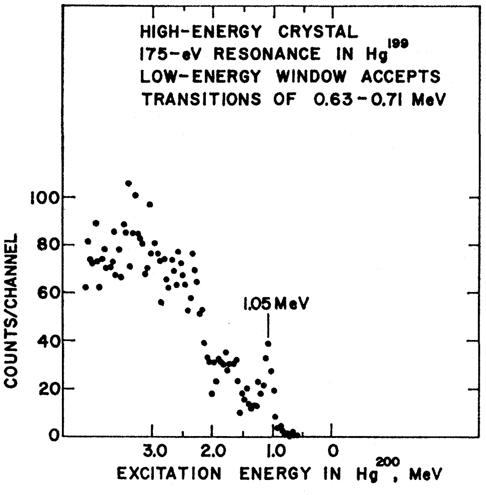

FIG. 3. Gamma-ray spectrum from neutron capture in the 175-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 0.63 and 0.71 MeV in Hg^{200}. The abscissa is the excitation energy in Hg^{200}, approximately (8.03 MeV-E_γ). Since the high-energy crystal was calibrated mainly by observing cascades proceeding through known low-lying states, our energy scale is given in terms of the level fed rather than in terms of the gamma-ray energy. This avoids introducing the additional uncertainty associated with the neutron binding energy in Hg^{200} which is irrelevant for our purpose.

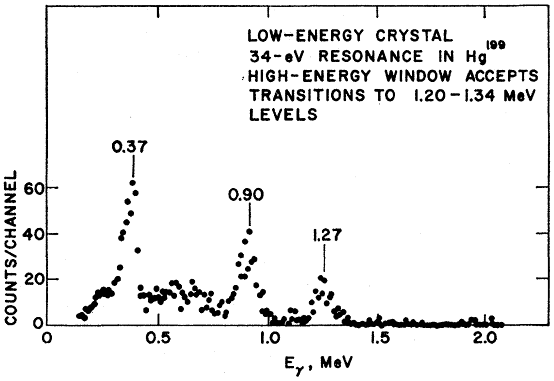

FIG. 4. Gamma-ray spectrum from neutron capture in the 34-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.20 and 1.34 MeV in Hg^{200}.

The spectrum shown in Fig. 5 demonstrates that there is a strong transition from the 34-eV resonance to a level at about 1.60 MeV. This level decays primarily to the first excited state, but there is a weaker but significant branch to the ground state. The run with an absorber in front of the low-energy crystal confirmed that summing was not a major contributor to the

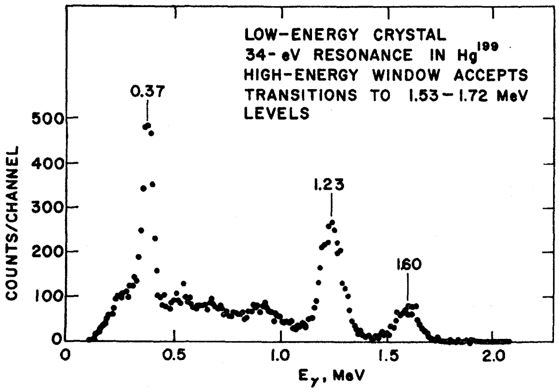

FIG. 5. Gamma-ray spectrum from neutron capture in the 34-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.53 and 1.72 MeV in Hg^{200}.

ground-state transition. It will be shown below that this cascade proceeds through at least two closely spaced levels at about 1.60 MeV. Our data on these and other cascades proceeding through low-lying states are summarized in Table I. Here "low-lying" is taken to mean excitations up to about 2 MeV; the spectrum of gamma rays feeding higher levels is so complex and problems associated with the response function and limited statistics become so troublesome that only overwhelmingly intense transitions through these higher states would stand out.

TABLE I. Strength, in photons per capture, of transitions from various capturing resonances to certain low-lying states in Hg^{200}. The errors are uncertain, but probably range up to ±50%.

Final energy (MeV)	Resonance (J^π)			
	Thermal (0^-)	34-eV (1^-)	129-eV (0^-)	175-eV (1^-)
0	3×10^{-4}[b]	2.9×10^{-2}[d]		1.3×10^{-3}[d]
0.37	7×10^{-4}[b]	1.7×10^{-3}[d]	$<1.7\times10^{-3}$	1.1×10^{-2}[d]
1.05	$<12.5\times10^{-4}$	$<5.2\times10^{-3}$	$<1.5\times10^{-3}$	1.0×10^{-2}
1.27	$<7.6\times10^{-4}$	1.0×10^{-2}	$<6\times10^{-4}$	$<6.5\times10^{-4}$
1.57 I[a]	4.9×10^{-2}	4.9×10^{-2}	2.4×10^{-2}	1.6×10^{-2}
1.57 II[a]	...[a]	5.7×10^{-2}	$\lesssim5\times10^{-3}$	1.1×10^{-2}
2.06	10×10^{-2}[c]	$<4\times10^{-3}$	3.8×10^{-2}	$\approx1.0\times10^{-2}$

[a] It is assumed that two states at about 1.57 MeV are fed by capture gamma rays; one state decays mainly to the ground state and another decays almost exclusively to the first excited state. It is further assumed that the thermal capture is exclusively to the 1.57-MeV state that has a ground-state transition; i.e., we are implying one, and only one, spin-1 level in the 1.57-MeV region. This conjecture is strengthened by the fact that the 129-eV ($J=0$) resonance appears to have a transition to the same state.

[b] See Ref. 6. The ground-state transition following thermal capture would be strictly forbidden if the thermal capture were solely due to a spin 0 resonance. However, there will be a finite contribution from the tails of spin 1 resonances at 34 eV, 175 eV, etc. The main contribution to a ground-state transition is believed to be associated with the spin-1 resonance at 34 eV. From the known (Ref. 17) parameters of this resonance and the branching ratio for this transition it can be calculated that about $1\text{–}3\times10^{-4}$ photons per hundred capture will be from this source. This can account for the measured strength of the ground-state transition at thermal capture.

[c] The intensities were normalized to those of Ref. 6 for this transition because the intensity measurements of Ref. 6 appear to be more accurate than those of the present work.

[d] Taken from the recent work reported in Ref. 21.

The transition to the 1.05-MeV state was too weak to be observed at the 34-eV resonance.

In addition to the transition to the 1.05-MeV state, the 175-eV resonance showed transitions to the 0.37-MeV first excited state and to a state at about 1.60 MeV. The spectrum at the 175-eV resonance in coincidence with gamma rays feeding the 1.60-MeV region is shown in Fig. 6. As with the 34-eV resonance, a state is indicated at about 1.60 MeV which decays to both the ground state and first excited state. While the stopover again is the stronger, comparison of Fig. 5 with Fig. 6 demonstrates that the ratio of crossover to stopover for the 175-eV resonance is about twice the ratio for the 34-eV resonance. This point will be discussed further after the results of the thermal-capture measurements have been described. The peak at 0.68 MeV in Fig. 6 reflects the fact that the first escape peak and part of the Compton tail of the transition to the 1.05-MeV state lie in the high-energy window.

The decay scheme associated with capture in the $J=0$, 129-eV resonance was also examined. Here the strongest transition to a low-lying level is to a state at about 2.09 MeV which decays chiefly to the first excited state. The relevant spectrum is shown in Fig. 7 where it can be seen that if there is any transition to the ground state, its intensity must be less than 10% of the cascade gamma (1.72 MeV). The high-energy spectrum in coincidence with the 1.72-MeV peak showed a strong peak corresponding to a gamma ray feeding a state at about 2.09 MeV plus some weak evidence for a two-step transition through a state at 1.72 MeV.

A transition from the 129-eV resonance to a state at about 1.60 MeV was also seen. Again, both a crossover and a stopover from this 1.60-MeV state was observed, the crossover being the stronger in this case. The ratio of crossover to stopover is the same as for the 1.60-MeV state that results from thermal capture (see below). Thus we feel that the same level near 1.60 MeV is

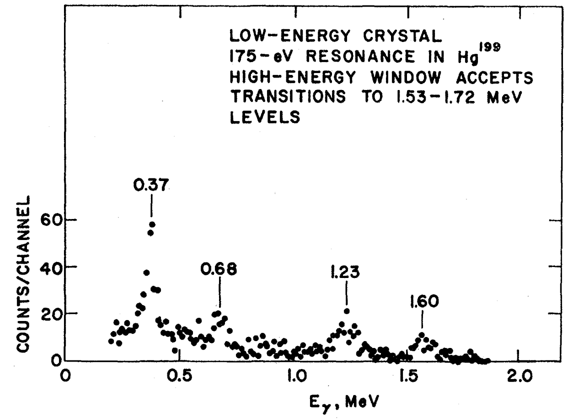

FIG. 6. Gamma-ray spectrum from neutron capture in the 175-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.53 and 1.72 MeV in Hg^{200}.

reached by neutron capture at thermal energies and at the 129-eV resonance.

THERMAL CAPTURE

The experimental setup used to study resonance capture was also used for coincidence measurements of gamma rays following the capture of thermal neutrons by mercury. The placement of sample and crystals was similar but not identical to that used for the resonance work, and again absorbers were inserted between the source and the detectors in order to ascertain the effects of summing.

We observed no transitions to the four lowest excited states (those at 0.37, 0.95, 1.05, and 1.27 MeV). The sensitivity for detecting two-step cascades through the 0.37-, 1.05-, and 1.27-MeV states was limited by summing in the high-energy crystal. Because of the high spin difference between the 0.95-MeV (4^+) state[2] and the (0^-) capturing state, the probability for direct transitions to the 0.95-MeV state is expected to be unmeasurably small. Also, it is unlikely that the 0.95-MeV state would be populated significantly by two-step cascades. As a matter of fact, no statistically significant indication of this state was encountered in any of the present work.

Although Segel[8] has reported two-step cascades through two states at about 1 MeV, it is now felt that summing in the high-energy crystal was not properly allowed for in this earlier work. Groshev *et al.*[6] report a weak transition to the first excited state with a strength consistent with the upper limit reported here. Groshev *et al.*[6] also report very weak (about 3×10^{-4} photons/capture) lines feeding a doublet at about 1 MeV. The energy best fits the 0.95- and 1.05-MeV states; but, as noted above, a transition from the capturing state to a 4^+ state would be truly remarkable. While none of the work to date rules out the existence of more levels near 1 MeV, the weakness of the transitions observed by Groshev *et al.*,[6] and the fact that the errors in their energies are larger than for the stronger transitions to other low-lying states, lead the present authors to conclude that the evidence for states in this energy region is inadequate except for those states discussed here.[21]

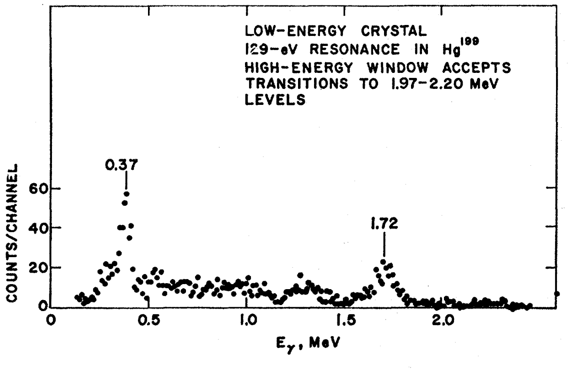

FIG. 7. Gamma-ray spectrum from neutron capture in the 129-eV resonance. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.97 and 2.20 MeV in Hg^{200}.

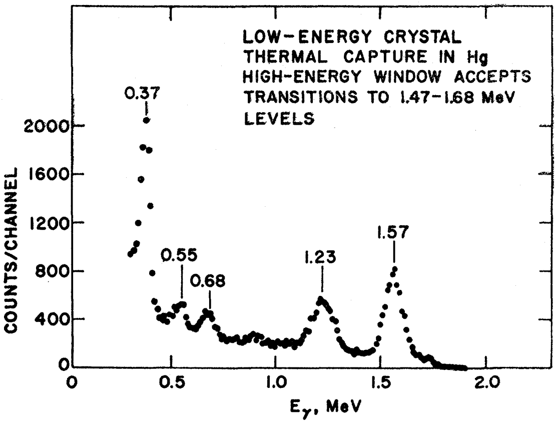

FIG. 8. Gamma-ray spectrum from neutron capture at thermal energies. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.47 and 1.68 MeV in Hg^{200}.

Although there is no strong transition from the thermal capturing state to the 1.05-MeV level, the 0.68-MeV gamma ray which emanates from this state was seen in coincidence with transitions to higher excited states in Hg^{200}. Similarly, the 0.90-MeV gamma ray from the 1.27-MeV state was seen in coincidence with transitions to states in the 2–3-MeV region; but the complexity of the decay scheme prevented identification of any single cascade to the 1.27- or 1.05-MeV levels. The fact that both the 0.68- and the 0.90-MeV lines were persistently present in the low-energy spectra tends to confirm that they originate from low-lying levels. It is noteworthy that two of the strongest low-energy lines in the singles spectrum[6,7] are at 0.68 and 0.90 MeV. This again is consistent with these lines emanating from low-lying levels. These levels apparently are fed through many different cascades.

Figure 8 shows the gamma-ray spectrum that results from thermal-neutron capture in Hg and is in coincidence with radiation feeding the 1.60-MeV region. It can be seen that the crossover transition from the state (or states) at about 1.60 MeV is stronger than the stopover to the first excited state. In contrast, when the state or states at about 1.60 MeV are fed by capture in the 34- and 175-eV resonances, the stopover is stronger than the crossover although the stopover/crossover ratio is different for the two resonances. Thus there must be at least two levels with energies close to 1.60 MeV: one that decays predominantly to the ground state and one that decays predominantly to the first excited state.

The noticeable broadening of the peak corresponding to the transition to the first excited state indicates the presence of more than one gamma ray. Furthermore,

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[21] The unpublished paper of Ref. 7, written by the authors of Ref. 6, does not list transitions from the capturing state to the states near 1 MeV.

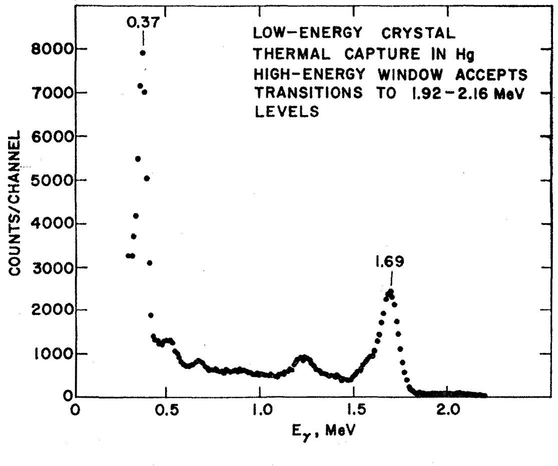

FIG. 9. Gamma-ray spectrum from neutron capture at thermal energies. This coincidence spectrum was gated by gamma rays feeding energy levels between 1.92 and 2.16 MeV in Hg^{200}.

the energy separation between the "stopover" and "crossover" is somewhat less than the energy of the first excited state. We can attribute this apparent discrepancy to a 1.29-MeV gamma ray from the previously reported[8] three-step cascade through a 1.66-MeV level. The 1.29-MeV gamma ray was allowed for in estimating the intensity of the transition to the 1.60-MeV level (Table I). The ground-state gamma ray in Fig. 8 appears to be at somewhat less than 1.60 MeV but the thermal and resonance data were taken at different times so that energy differences of about 2% between the two experiments cannot be taken as significant. Somewhat arbitrarily, we adopt 1.57 MeV as the energy of the level fed at thermal capture (and at the 129-eV resonance). The weak peaks at 0.55 and 0.68 MeV in Fig. 8 indicate a weak branch through the 1.05-MeV state. The 0.55-MeV peak appears distinct from annihilation radiation and the 0.68-MeV peak appears to be in coincidence with the same high-energy line as the 1.57-MeV ground-state transition, but the uncertainties require that this branch be regarded as tentative.

We note that the β-decay work[1,3] requires two levels near 1.60 MeV, neither of which has a strong ground-state transition. The combined evidence from all sources demands at least three states within 30 keV of 1.59 MeV.

The strongest transition from the capturing state to a low-lying state is to a level at about 2.06 MeV. The low-energy spectrum of this cascade, shown in Fig. 9, has strong peaks at 1.69 and 0.37 MeV. This indicates that the state depopulates chiefly by a transition to the first excited state. After allowance is made for a little summing, Fig. 9 shows no trace of a ground-state transition, the upper limit for the crossover intensity being 2%. While other weak peaks appear in the spectrum of Fig. 9, the situation is too complex to ascertain whether or not these are due to other decay modes from this 2.06-MeV level.

In addition to the cascades discussed above, prominent two-step cascades were observed through levels at 1.75, 2.64, and 3.25 MeV (all ±0.03 MeV) as well as a strong cascade through a level at 2.37±0.03 MeV which decays chiefly to the first excited state.

DISCUSSION

The capture-gamma-ray and β-decay data were combined in Fig. 10 to construct an energy-level diagram and decay scheme for the lowest seven excited levels in Hg^{200}. Why the set of levels populated in the capture-gamma-ray reaction should be almost completely different from the set in the β-decay reaction has not been satisfactorily explained, but neither are there any discrepancies between the two types of investigation.

It was stated earlier that a major objective of the present work was to ascertain whether or not the levels in the neighborhood of 1 MeV form a vibrational triplet. We have indeed verified that there are three levels in this energy region and have determined some of their properties.

0.95-MeV level. The β-decay work, which includes angular correlations involving this state, requires a 4^+ assignment for the state. The capture-gamma-ray work is consistent with this high spin assignment, because of the absence of a direct transition from any capturing state to this state.

1.05-MeV level. The fact that this state is not directly fed from either of the $J=0$ capturing states but does have a transition from a $J=1^-$ state favors 0 or 2 for the spin. The absence of a ground-state transition argues against a 2^+ assignment, and, if we accept the weak theoretical argument that a negative-parity state is unlikely at such a low excitation, 0^+ becomes the favored assignment.[22]

1.27-MeV level. Here again the transitions feeding the state favor 0 or 2, but an intense ground-state transition eliminates $0^\pm$ and 2^-. Therefore 2^+ is the most likely assignment.[23]

The three states near 1 MeV appear to be grouped in that they lie within a 330-keV band with there being level-free gaps extending 580 keV below and 300 keV above the populated region. This grouping, combined with the probable (4^+, 0^+, 2^+) spin assignments supports the contention that these three states constitute the two-phonon vibrational triplet that was sought. However, a simple vibrational picture is clearly inadequate in that: (1) The ratios of the energies of the "two phonon" states (0.95, 1.05, and 1.27 MeV) to the "one-phonon" state at 0.37 MeV range from 2.5 to 3.4

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[22] L. M. Bollinger, R. E. Cote, R. T. Carpenter, and J. P. Marion (to be published).

[23] The measured conversion coefficient given in Ref. 7 require $E2$ for the 0.68- and 0.89-MeV lines. These findings strengthen the spin and parity assignments given here.

while the simple vibrational model would predict 2 for this ratio. (2) The splitting between the 1.27-MeV state and the two states at 0.95 and 1.05 MeV is rather large for states that are supposed to be degenerate, and (3) the crossover transition from the 2^+ 1.27-MeV state to the ground state represents a two-phonon transition which the simple vibrational model would forbid. No attempt was made to fit the observed level scheme with a sophisticated model. As words of caution we note that it is still not certain that all of the levels below 1.60 MeV have been identified and that the spin assignments of the 1.27- and 1.05-MeV levels must be considered tentative.

The transitions seen in the present work are summarized in Table I. Some results of other capture-gamma-ray experiments are also included and are duly referenced in the footnotes. Neutron resonance studies[21] have shown that transitions from different capturing states (of the same spin) to the same final state show a large spread in width and thus our small sample (four capturing states—two for each spin) permit only limited conclusions about transition strengths. Nevertheless, in addition to the fact that the partial radiation widths to the same final state do indeed vary widely from resonance to resonance the following trends are noteworthy:

(1) A particular state at about 1.57 MeV is rather strongly excited at all of the resonances. In every case the transition to this state is one of the strongest to a low-lying level.

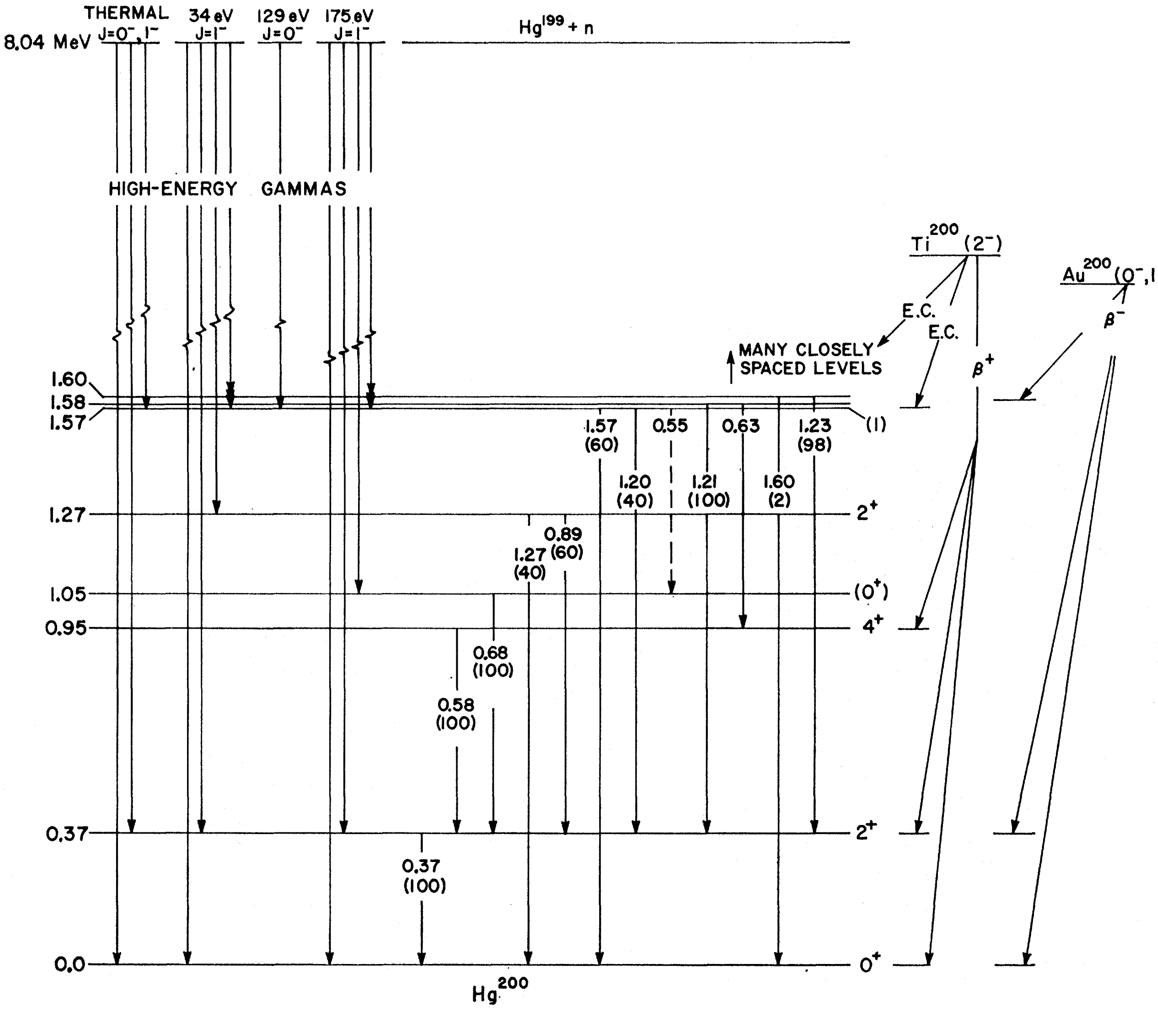

FIG. 10. Energy-level diagram showing the lowest seven excited levels in Hg^{200}. The properties of the levels at 0.95, 1.58, and 1.60 MeV come from β-decay work. The position of the 1.57-MeV level is nominal since the energy definition of the present work is not sufficient to place it relative to the 1.58- and 1.60-MeV levels. The 1.57-MeV state corresponds to 1.57 I of Table I, while either the 1.58- or the 1.60-MeV level or both, could correspond to 1.57 II. The ground-state gamma ray following thermal capture can be explained as capture in the tail of the 1^- resonance at 34-eV. (See footnote in Table I.)

(2) A transition to a state at about 2.06 MeV is the strongest radiation from the two $J=0$ capturing states, but is much weaker from the two $J=1$ states.

(3) There are four "allowed" (i.e., $E1$) transitions from capturing states to the possible "two-phonon" levels at 1.27, 1.05, and 0.95 MeV. Two of these transitions are of moderate strength and two are very weak—in fact, too weak to be detected. Thus, these results indicate some, but not complete, inhibition of transitions from the capturing state to the possible "two-phonon" states, as compared with transitions to frequently populated states at higher excitation energies (say, the 1.57-MeV state mentioned above).

(4) The two allowed transitions to the "one-phonon" 0.37-MeV state have about the same strength as the transitions to the "two-phonon" states.

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States in Si^{28} with $12.7<E_x<13.7$ MeV by (α,γ) and (α,α) Reactions on Mg^{24}†

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The radiative capture and elastic scattering of alpha particles by Mg^{24} have been studied for alpha-particle energies between 3.2 and 4.5 MeV. The yield and angular distributions of the gamma radiation in combination with a dispersion analysis of the $Mg^{24}(\alpha,\alpha)Mg^{24}$ data gave information on the resonance energies, angular momenta, parities, and some partial widths of states in Si^{28}. The excitation energies and the corresponding spins and parities of the Si^{28} levels considered were: 12.74 MeV, 2^+; 12.82 MeV, [0^+ or 3^-]; 12.83 MeV, 1^-; 12.87 MeV, 4^+; 12.92 MeV, 2^+; 12.99 MeV, 1^- and 0^+ (two levels); 13.06 MeV, 0^+; 13.12 MeV, 2^+; 13.19 MeV, [?]; 13.25 MeV, 0^+; 13.27 MeV, [1^-]; 13.38 MeV, [?]; and 13.71 MeV, 2^+.

I. INTRODUCTION

THE simple features of alpha-particle capture by a zero-spin nucleus often warrant a unique assignment of spins and parities to the energy levels of the compound nucleus. In cases in which the assignment is not unambiguous, measurements of elastic α-particle scattering can help to determine the parameters of excited states. The (α,γ) and (α,α) processes in Mg^{24} are therefore promising for investigating the Si^{28} nucleus.

Theoretical descriptions of the states of Si^{28} are quite difficult and unreliable for all but the lowest excited states.[1] However, the levels of Si^{28} at excitation energies above 11 MeV have been extensively studied by experiment, chiefly by the reactions $Al^{27}(p,\gamma)Si^{28}$,[2] $Al^{27}(p,\alpha)Mg^{24}$,[3] $Mg^{24}(\alpha,p)Al^{27}$, and $Mg^{24}(\alpha,\alpha)Mg^{24}$.[4] Recently, Smulders and Endt[5] have reported measurements on $Mg^{24}(\alpha,\gamma)Si^{28}$ with alphas incident at energies up to 3.22 MeV; the Si^{28} was excited to states between 11.30 and 12.74 MeV. This paper reports results extending the study of this reaction to 13.7-MeV excitation in Si^{28}.

II. EQUIPMENT

In the early stages of the experiment the capture gamma radiation was detected by a 4×4-in. NaI crystal. For later studies of all the weaker resonances, the detection was considerably improved through the use of a NaI crystal 10 in. in diameter and 8 in. long. Both crystals were mounted on an arm which could easily be rotated about the target spot and on which the detector-target distance could easily be adjusted. The initial optical alignment was checked by the necessary symmetries of the capture gamma rays.

Enriched Mg^{24} targets[6] evaporated *in situ* on tantalum backings were bombarded with an α-particle beam from the Argonne 4.5-MeV Van de Graaff generator. The special arrangement used to minimize carbon contamination on the target and to permit intense beams is described elsewhere.[7] Whenever a high-energy resolution (an energy spread of less than 1 keV in the beam) was required, the α particles passed through a 90° electrostatic analyzer with a radius of 1 m. Although

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