$^{36}S(n,\gamma)^{37}S$ reaction with thermal neutrons and decay of ^{37}S to levels in ^{37}Cl

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The $^{36}S(n,\gamma)^{37}S$ reaction with thermal neutrons has been studied utilizing a highly enriched ^{36}S target. Fifteen γ rays were observed which have been incorporated into a ^{37}S level scheme. The neutron separation energy of ^{37}S was determined to be 4303.52±0.12 keV; and the thermal neutron capture cross section of ^{36}S to be 230±20 mb. The subsequent β^- decay of ^{37}S to levels in ^{37}Cl has also been studied. Seven γ rays were observed which have led to an improved ^{37}S decay scheme.

I. INTRODUCTION

Because ^{36}S has an extremely low natural abundance (0.017% of natural S) and a small thermal neutron capture cross section (~200 mb), the $^{36}S(n,\gamma)^{37}S$ reaction has not been reported by any previous workers in the (n,γ) field. We have studied this reaction by utilizing a 100-mg target enriched to (81.1 ± 0.2)% in ^{36}S. This material originated in the Soviet Union.[1] Preliminary results of the (n,γ) study were reported previously.[2]

We have also reinvestigated the decay of 5-min ^{37}S to levels in ^{37}Cl by employing sources prepared by neutron irradiation of both natural S and the enriched ^{36}S. This investigation was prompted by the possibility that previously unknown γ rays might become observable through study of the enriched sample. Also, considerable interest exists in the level structure of ^{37}Cl because this nucleus has a magic number ($N=20$) of neutrons.

II. THE $^{36}S(n,\gamma)^{37}S$ REACTION

A. Experimental procedure and results

The (n,γ) measurements were made at the Los Alamos Omega West Reactor. The internal target position was 1.5 m from the edge of the reactor core. The target material was contained in a graphite holder. The thermal neutron flux at the target position was $\sim 6 \times 10^{11}$ neutrons/cm^2 sec. The γ rays were studied with a 26-cm^3 Ge(Li) coaxial detector with a NaI(Tl) annulus. This detector was positioned 6.3 m from the target and was operated in either a Compton-suppressed or a pair spectrometer mode. The measured spectrum in the 400-3800 keV region is shown in Fig. 1. Strong γ rays due to ^{12}C (from the graphite holder) and ^{34}S (from the target) and weak γ rays due to ^{1}H, ^{6}Li, N, Cl, Ar, and Cd (trace elements known to be present in the target channel) were expected and were observed. In addition, weak γ rays due to Na, Al, Si, and K were detected. These trace elements are apparently present in the target material, which also contained 0.12 mg of ^{10}B (Ref. 3). The $^{10}B(n,\alpha\gamma)$ cross section is however so large (~3700 b) that the resulting 478-keV, Doppler-broadened transition (see Fig. 1) dominated the low-energy part of the γ-ray spectrum. Despite the smallness of the $^{36}S(n,\gamma)$ cross section and the presence of several undesirable impurities, 15 γ rays were definitely assigned to ^{37}S (see Table I).

B. Discussion

The ^{37}S level scheme based on the current measurements is shown in Fig. 2. Construction of this scheme was relatively straightforward because a separate $^{36}S(d,p)$ study,[4] with an effective proton energy resolution of ~15 keV, yielded the level scheme also shown in Fig. 2. The $^{36}S(d,p)$ reaction has also been studied by other authors.[5–7] The energy levels at 646, 1398, 2023,

TABLE I. Energies and intensities of γ rays from the $^{36}S(n,\gamma)^{37}S$ reaction.

Energy[a] (keV)	Intensity[b]	Energy[a] (keV)	Intensity[b]
646.171 *14*	215 *23*	1665.695 *22*	52 *7*
751.32 *18*	1.5 *3*	1991.585 *36*	54 *7*
810.85 *7*	2.4 *3*	1991.9[c] *5*	≈2[c]
1041.713 *35*	8.1 *10*	2022.9 *5*	≈3[d]
1239.18 *11*	3.1 *5*	2311.65 *8*	9.4 *12*
1345.75 *5*	7.3 *8*	2615.68 *12*	6.0 *10*
1376.99 *21*	1.2 *3*	3657.28 *7*	161 *18*
1469.50 *22*	1.4 *3*		

[a]The notation is 646.171 *14* ≡ 646.171 ± 0.014, etc.
[b]γ-ray cross section in mb. Multiply by 0.435 to obtain photons per 100 neutron captures. The notation is 215 *23* ≡ 215 ± 23, etc.
[c]Inferred from the level scheme.
[d]After corrections due to a γ ray of similar energy in the $^{34}S(n,\gamma)^{35}S$ reaction.

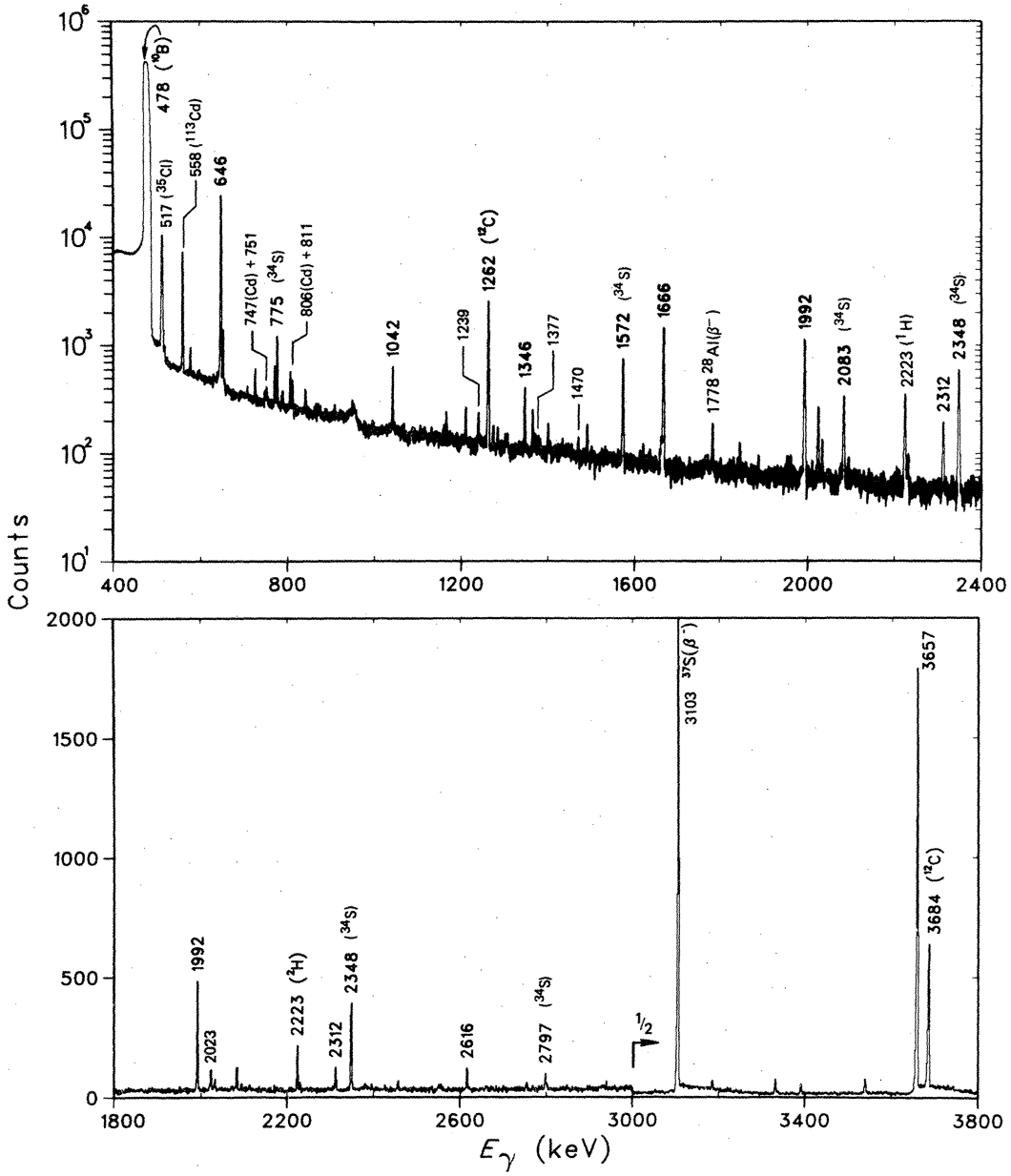

FIG. 1. Portions of the γ-ray spectra from the ^{36}S(thermal n,γ)^{37}S reaction. The top part was obtained in the Compton-suppression mode; the bottom in the pair-spectrometer mode. All energies are in keV.

and 3262 keV populated in the (n,γ) reaction have also been excited in the ^{37}Cl(t,^{3}He) reaction.[8]

The γ-ray energies (see Table I), the level energies (see Fig. 2), and the neutron separation energy $S_n(^{37}S)$ = 4303.61 ± 0.04 keV reported here from the (n,γ) reaction are all based on the energy calibrations described in detail in Ref. 9. The uncertainties quoted in the above values include only the statistical uncertainties. The final neutron separation energy of 4303.52 ± 0.12 keV includes calibration and systematic uncertainties and the conversion of the S_n value to the ^{198}Au(411.8044 ± 0.0011 keV) standard as discussed in Ref. 9.

In Table I, the intensities of γ rays (I_γ) are given in units of mb, but the conversion factor to obtain photons per 100 neutron captures is also given in footnote b of that table. Expressed in the former units, the quantities ΣI_γ (primary) = 233 ± 20 mb, $\Sigma E_\gamma I_\gamma / S_n$ = 233 ± 20 mb, and ΣI_γ (secondary to the ^{37}S ground state) = 220 ± 23 mb are all mutually consistent. These values also agree with the (n,γ) cross-section value of 230 ± 20 mb based on the subsequent β^- decay of ^{37}S represented by the strong 3103-keV γ ray (see Fig. 1). Insofar as the ^{36}S(n,γ) reaction with thermal neutrons is concerned, the ^{37}S level scheme is essentially complete except for explaining an ~1.5 mb missing feeding to the

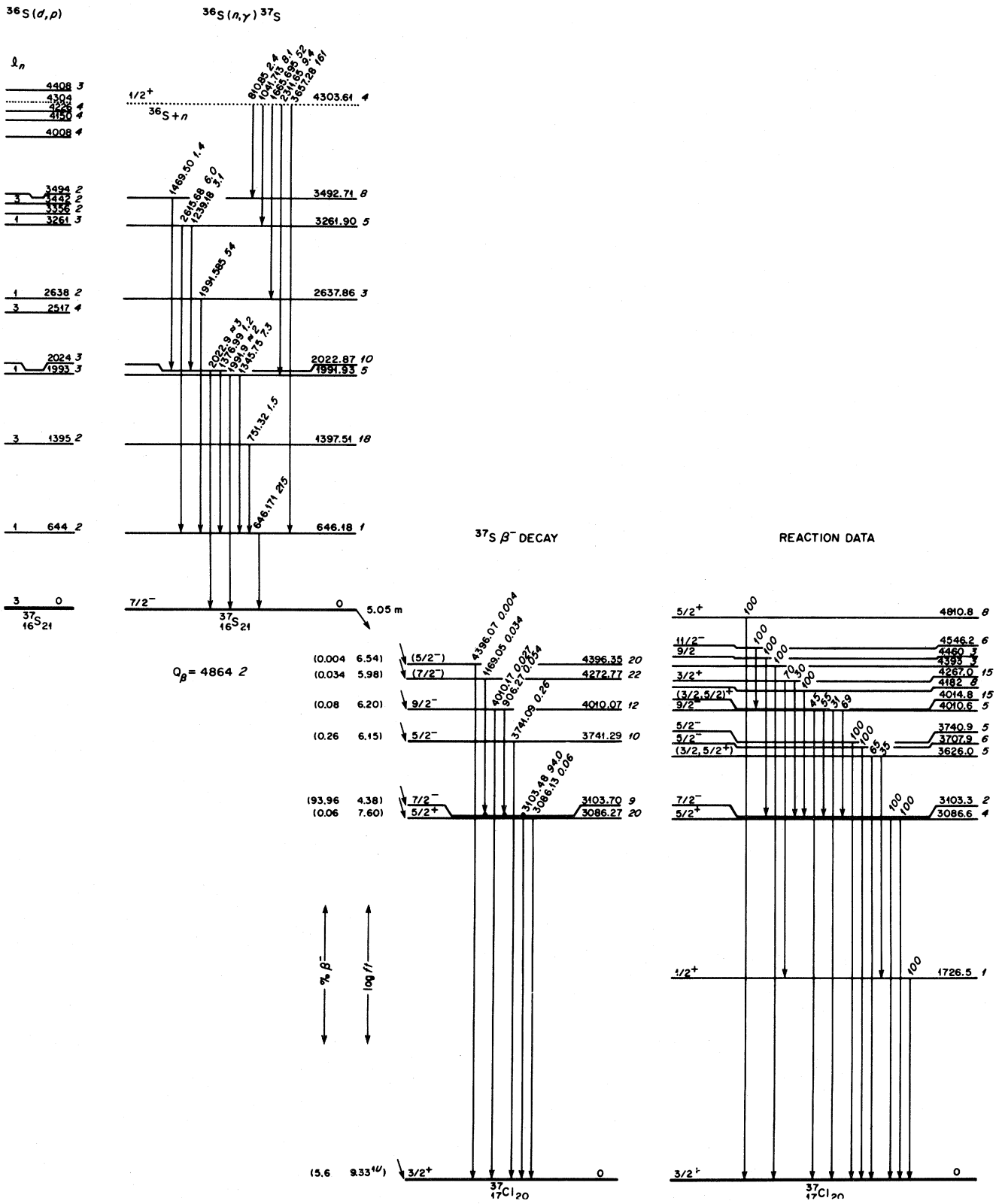

FIG. 2. Proposed schemes for ^{37}S and ^{37}Cl. All level energies are in keV with the notation 646.18 *1* ≡ 646.18 ± 0.01, etc. The intensities of γ rays from the ^{36}S(*n*,γ) reaction are in units of mb; those from ^{37}S β$^-$ decay in units of photons per 100 decays. The ^{36}S(*d*,*p*) data are from Ref. 4; the ^{37}Cl reaction data are from Ref. 14. In deducing the level energies from the current measurements, nuclear recoil has been taken into account.

1398-keV level and an ~1.0 mb intensity imbalance at the 3493-keV level (see Fig. 2).

We had earlier measured[10] the thermal neutron capture cross section of ^{32}S as 518 ± 14 mb. This value was subsequently employed to determine the thermal neutron capture cross section of ^{34}S as 294 ± 15 mb. Because the present enriched ^{36}S target contained (18.8 ± 0.1)% ^{34}S, the use of the above cross section for ^{34}S resulted in the cross section values listed in Table I. Our final value of 230 ± 20 mb for the thermal neutron capture cross section of ^{36}S is higher than the value of 137 mb obtained by Hughes *et al.*[11] This discrepancy cannot be checked further because the latter authors give no experimental details.

III. DECAY OF ^{37}S

A. Experimental procedure and results

The singles γ-ray measurements were made with a large Ge(Li) detector having a resolution of 2 keV FWHM (full width at half maximum) at 1 MeV. The energy calibration and efficiency of the detector as a function of energy were established through measurements on a number of standard sources. The detector was shielded from beta particles with 1.3 cm of Al.

The enriched S sample was irradiated and counted repeatedly. After a 10-s irradiation and a 5-min delay, the γ spectrum of the sample was recorded for 16 min. During the 16-min counting period, the source-to-detector distance was varied step-wise five times from 40 cm to 15 cm to keep the counting rate relatively constant. After an additional delay of 4 min, a second 16-min count of the source was initiated, which generated a background spectrum. During the background count, the source was cycled through the same set of position-vs-time steps as used in the first count. After numerous data acquisition runs, the spectra were summed, and the background data were subtracted from the gross data. A detailed examination of the net spectrum (see Fig. 3) revealed the γ rays listed in Table II, all of which were found to decay with a half-life of ~5 min. A similar set of runs in which 5-g samples of high-purity natural S were used revealed these same γ rays with the same relative intensities. Thus, all of the transitions given in Table II are assigned to the decay of ^{37}S. Four of these transitions were reported earlier by Hill,[12] but the 1169.0-, 3086.1-, and 4396.1-keV transitions had not been observed previously in decay studies. It is, however, possible that the 1168-keV transition observed by Harris and Perrizo[13] in their $^{36}S(p,\gamma)^{37}Cl$ reaction study is identifiable with our 1169.0-keV transition.

The 3086.1-keV γ ray is a ground-state transition from a level of this energy known from charged-particle reaction data.[14] To establish whether the newly observed 1169.0-keV γ ray feeds the 3086.3-keV level or the well-known[14] 3103.7-keV level, a γ-γ coincidence experiment was performed. The data were acquired with two large Ge(Li) detectors oriented at 180° in close geometry. Each detector was shielded from betas with 1.3 cm of Al. Between the Al plates, a γ-ray backscatter shield consisting of a 0.6-cm-thick Pb plate with a 1.3-cm-diam central hole was located. The ^{37}S sources were placed in this hole.

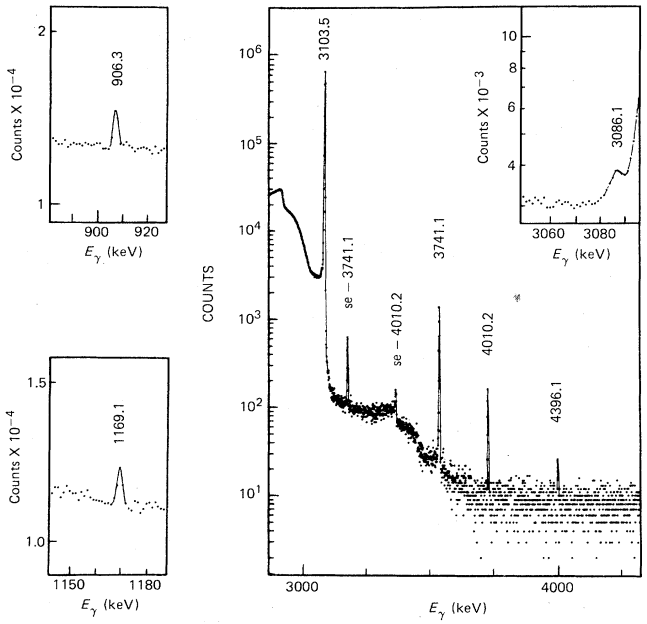

FIG. 3. Portions of the γ-ray spectra from the decay of 5-min ^{37}S.

The sources consisted of 250 mg of natural S, encased in high-purity polyethylene. Each source was irradiated for 10 s, and after a 5-min delay was counted for 10 min. After an additional 5-min delay, a 10-min background count was recorded. A total of 50 samples was counted in this manner.

Two multichannel analyzers were employed to record the coincidence spectra, one for each detector. One analyzer displayed pulses in coincidence with the spectral region between 3.0 and 3.15 MeV; the other, between 800 keV and 1.2 MeV. The coincidence resolv-

TABLE II. Energies and intensities of γ rays from ^{37}S decay.

Energy[a] (keV)	Relative intensity[b]	Energy[a] (keV)	Relative intensity[b]
906.27 *10*	0.57 *7*	3741.09 *10*	2.76 *28*
1169.05 *20*	0.36 *7*	4010.17 *20*	0.29 *11*
3086.13 *20*	0.66 *22*	4396.07 *20*	0.04 *2*
3103.48 *10*	1000		

[a]The notation is 906.27 *10* ≡ 906.27 ± 0.10, etc.
[b]Multiply by 0.0940 ± 0.0006 to obtain absolute intensity per 100 decays. This factor is based on the adopted intensity of (5.6 ± 0.6) % for the ground state β branch. The notation is 0.57 *7* ≡ 0.57 ± 0.07, etc.

ing time was 25 ns. In the coincidence spectra, peaks were observed at 906 and 1169 keV, with the same relative intensity (within statistics) as in the singles data. The coincidence data in the vicinity of 3.1 MeV revealed only a single peak at 3103 keV. These data clearly establish that both the 906.3- and 1169.0-keV γ rays feed the 3103.7-keV level. Observation of the 906-3103 keV coincidence was reported previously by Hill.[12]

B. Discussion

The decay scheme indicated by the above measurements is shown in Fig. 2. The log-ft values were calculated using a Q_{β^-} value of 4864 ± 2 keV deduced from our S_n (^{37}S) value and the known atomic masses of stable ^{36}S and stable ^{37}Cl. The (5.6 ± 0.6)% intensity of the β branch to the ^{37}Cl ground state was taken from Ref. 15.

The 3086.3-, 3103.7-, 3741.3-, and 4010.1-keV levels are identifiable with levels of these approximate energies observed in reaction experiments[13,14] (see Fig. 2). The log-ft values calculated for the β transitions feeding these levels are compatible with the spins and parities deduced from the reaction data. In the case of the 4010.1-keV, $9/2^-$ level, the rather surprising competition between the 4010-keV, $E3$ ground-state transition and the 906-keV, $M1+E2$ transition has been discussed by Nolan *et al.*[16] Their lifetime measurements indicate that the $E3$ transition has a strength of 13 ± 1 W.u. (Weisskopf units). The 724-keV γ ray reported by Alenius *et al.*[17] as depopulating the 4010-keV level has subsequently been shown[16] to depopulate a $13/2^-$ level at 5271 keV.

The 4272.8-keV level has no analog in the reaction data. Because this state depopulates only to the 3103.7-keV, $7/2^-$ state and the feeding β transition has log ft = 5.98, we conclude that the spin and parity of the 4272.8-keV state are most likely $7/2^-$ or $9/2^-$. This state may be identifiable with the $7/2^-$ state predicted at this approximate energy by the large-scale shell-model calculations of Hasper.[18]

The 4396.4-keV level is probably the same as the 4394 ± 3 keV level reported by Piiparinen *et al.*[19] Because this state decays observably only to the ground state and the feeding β transition has log ft = 6.54, the spin is most likely 5/2, with either parity allowable. However, the calculations of Hasper[18] clearly favor negative parity.

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