From our γ measurements, a β branching to the 7.03(4$^-$)-MeV level could be as high as 2%. This would give a logft of 5.0 which is about three orders of magnitude too small. It is reasonable to infer, from consideration of logft systematics, that such a transition has a probable branching ratio $<3\times10^{-5}$. Similar arguments could be used to estimate a possible β feeding of the α unstable states at 7.17(3$^-$), 8.90(1$^-$), and 9.16(3$^-$) MeV. Assuming a log$ft>6.0$, the corresponding branching ratios would be <0.25, <0.06, and <0.04%, respectively. These estimates are realistic and agree with the fact that those transitions were not observed in delayed-α measurements. Along the same lines, branching to 0^+ and 4^+ states by second-forbidden transitions ought to be $<10^{-7}$. This is well below the limit of 1–2% placed upon them by our γ measurements and the estimate of <0.05% obtained for a possible β transition to the 0^+ ground state of Ne^{20}.

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Beta Decay of ^{37}S†

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Radioactive ^{37}S has been prepared by the ^{37}Cl(n,p) ^{37}S reaction and its decay products have been observed with a magnetic β-ray spectrometer and with NaI(Tl) crystal and Ge(Li) crystal γ-ray spectrometers. The β-ray groups have endpoint energies, relative intensities, and comparative half-lives of 4.75±0.04 MeV (5.6±0.6)%, log $f_1t=8.01$; 1.64±0.04 MeV, 94.0%, log $f_0t=4.38$; and 1.04±0.04 MeV, ~0.4%, log f_0t $=5.65$. The γ rays have energies and relative intensities of 3.107±0.002 MeV (99.6%) and 3.708±0.004 MeV (~0.4%). No other γ rays were observed; an upper limit of 0.5% is placed on their relative intensity. Coincidence counting places an upper limit of 1% on the possibility of a cascade transition from the 3.107-MeV state of ^{37}Cl. Spin-parity assignments for ^{37}Cl are $\frac{7}{2}^-$ for the 3.107-MeV state and $\frac{5}{2}^-$ for the 3.708-MeV state. The ground state of ^{37}S has odd parity and probable spin $\frac{7}{2}$.

INTRODUCTION

In this investigation, NaI(Tl) scintillation crystals, a Ge(Li) crystal detector, and a magnetic β-ray spectrometer have been used in determining the energies and relative intensities of the β rays and the γ rays which are emitted in the β decay of ^{37}S. A primary purpose was to locate negative-parity excited states of the daughter $d_{3/2}$ subshell nucleus ^{37}Cl.

Previous Studies

Before this study was initiated, there had been reported[1,2] β-ray transitions to the ground state of ^{37}Cl (4.7 MeV, ~10%) and to a 3.1-MeV excited state (1.6 MeV, ~90%). Only a 3.1-MeV γ ray had been observed; cascading transitions or another β-ray transition which would produce γ rays of energy of less than 2 MeV had been reported[2] to be of less than 1% of the intensity of the 3.1-MeV γ ray. The logft value of 7.3 for the ground-state transition was recognized as being consistent with a unique first-forbidden transition; similarly, the logft value of 4.2 for the transition to the 3.1-MeV state was consistent with an allowed transition. In ^{37}Cl, the ground-state spin-parity was well-established[3] as $\frac{3}{2}^+$. Magnetic analysis of the charged particles from the ^{37}Cl$(p,p')^{37}$Cl* reaction had made possible the identification of states[4,5] at 0.835 (conflicting reports), 1.72, 3.087, and 3.105 MeV. The doubtful 0.835-MeV state was not observed in the ^{37}Cl(p,p') reaction[5] with the use of separated isotopes of Cl, it was not observed in the ^{37}Cl$(n,n'\gamma)$ reaction,[6] and it was not observed in the ^{40}Ar$(p,\alpha'\gamma)$ reaction.[7]

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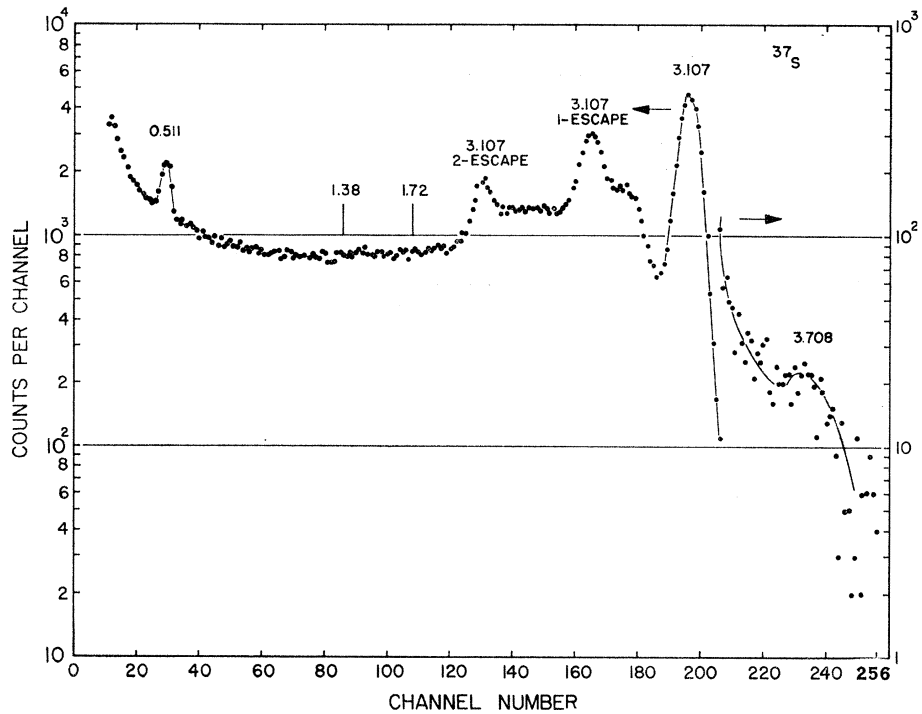

FIG. 1. Spectrum of pulses due to the β decay of ^{37}S to ^{37}Cl obtained with NaI(Tl) crystal spectrometer. The energy of the prominent γ ray has been determined to be 3.107 ± 0.002 MeV by the use of a Ge(Li) crystal spectrometer. The full-energy peak positions of other energetically possible (but not observed) γ rays are marked. There is at channel 235 a poorly resolved peak which is produced by a 3.708-MeV γ ray.

The energy of the 1.72-MeV state has been more recently determined[6] as 1.726 ± 0.004 MeV. Stribel[8] had reported the γ-ray energy to be 3.09 ± 0.03 MeV; from this value, it was not possible to decide which of the two known states near 3.1 MeV was involved in the β decay. The half-life had been reported as 5.04 ± 0.02 min[1] and as 5.07 ± 0.01 min.[9]

PRODUCTION OF ^{37}S

Radioactive ^{37}S was produced by the ^{37}Cl$(n,p)^{37}$S reaction, with the neutrons coming from the ^{3}H$(d,n)^4$He reaction. In a typical preparation, the University of Kentucky neutron generator accelerated a beam of 1 mA of 165-keV deuterons onto a thick ZrT target. Samples of 20 to 40 g of NaCl were irradiated for 10 min; then, during a period of about 4 min, the ^{37}S was extracted by chemical procedures as barium sulfate. The separation was necessary in order to reduce the bulk of the sample and because of the production of 32.0-min ^{34}Cl. Also, a 5.756-g pellet of sodium chloride enriched[10] in ^{37}Cl to 98.4% was similarly irradiated many times and used without chemical separation. During the course of a study by other workers of this laboratory of the β decay of 1.4-min ^{40}Cl, strong sources of ^{37}S were made available by the bombardment of liquid argon with fast neutrons through the ^{40}Ar$(n,\alpha)^{37}$S reaction.

The ^{37}S was identified through observation of the 3.1-MeV γ ray and through measurement of the half-life, for which was determined the value of 5.05 ± 0.10 min, in good agreement with others.[1,9]

GAMMA RAYS

In Fig. 1 is displayed the spectrum due to ^{37}S as obtained with a 7.62-$\times$7.62-cm-diam NaI(Tl) scintillation crystal. The previously observed 3.1-MeV γ ray is apparently the only radiation, although there is a very low-intensity peak at channel number 235 which will be discussed in the following paragraph. The radiations which would correspond to a possible cascade ($3.107\rightarrow1.726\rightarrow0$), or to a γ ray following a β-decay transition to the 1.726-MeV level, were not observed. The upper limit 0.005:1 was deduced for the intensity of 1.38- or 1.73-MeV γ rays relative to the intensity of the 3.1-MeV γ ray.

A Raboy-Trail total-energy spectrometer[11] was used in a further search for possible low-intensity γ rays. An annular NaI(Tl) crystal, 30.48-$\times$20.32-cm diam, served as an anticoincidence shield around a 15.24-$\times$6.03-cm diam NaI(Tl) crystal and provided very significant rejection of pair peaks, Compton distribution, and cosmic-ray background. In Fig. 2 is shown the high-energy portion of a spectrum in which a peak for a previously unobserved γ ray with energy 3.71 MeV is to be seen. Its intensity is 0.004:1 relative to that of the 3.1-MeV γ ray. That this 3.71-MeV γ ray is emitted

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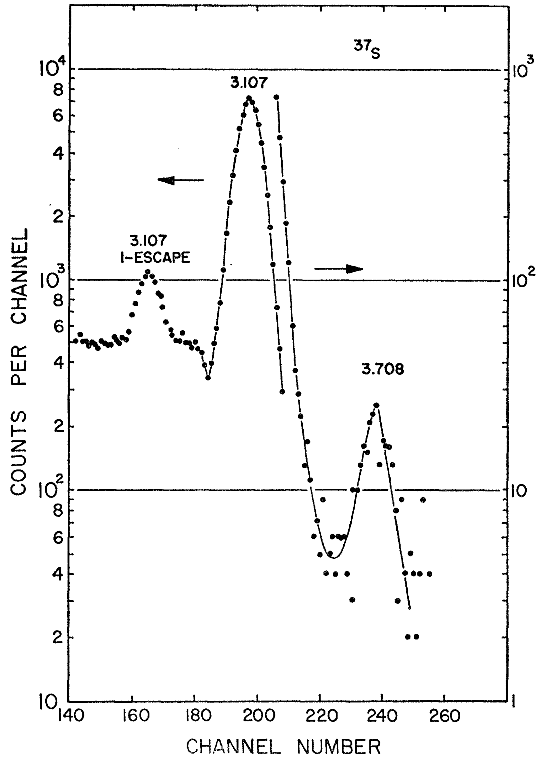

FIG. 2. Spectrum of pulses from a total-absorption spectrometer, with the full-energy peaks of the two γ rays which are emitted from ^{37}Cl following the β decay of ^{37}S. Their energies are 3.107 $\pm$0.002 MeV and 3.708$\pm$0.004 MeV, as determined with a Ge(Li) crystal spectrometer.

in the β decay of ^{37}S was verified by (a) the observation that this radiation came from the barium sulfate precipitate after the chemical separation; (b) the measurement of the half-life, which was determined to be the same as that of the 3.1-MeV γ ray; and (c) the relative intensity, which gives a reasonable $\log ft$ value for an allowed β decay (calculated as described under β rays). Also, here at this laboratory, an excited level of ^{37}Cl at 3.71$\pm$0.02 MeV was observed to be populated by the ^{37}Cl$(n,n'\gamma)$ reaction[6] and was assumed to be this same level, and elsewhere, a γ ray of energy 3.73 MeV was observed[12] in the ^{36}S$(p,\gamma)^{37}$Cl reaction.

A search was made for possible coincident γ rays of energy 1.381 and 1.726 MeV, using two 7.62-$\times$7.62-cm diam NaI(Tl) crystals and a fast-slow time-coincidence circuit. The coincidence spectrum was gated by pulses in the region appropriate to a 1.381-MeV total energy peak. The spectrum did not contain an identifiable 1.726-MeV peak, but only the expected number of chance coincidence counts. The upper limit on the intensity of this cascade was 0.01:1 relative to the 3.1-MeV transition.

A Ge(Li) crystal spectrometer was employed to determine the energy of the high-intensity radiation to be 3.107$\pm$0.002 MeV, and of the low-intensity radiation to be 3.708$\pm$0.004 MeV. Again, no evidence was found for the existence of 1.381- or 1.726-MeV radiation.

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BETA RAYS

Radioactive sources for a magnetic shaped-field spectrometer were prepared by neutron irradiation as described above. The ^{37}S was precipitated as barium sulfate; the glass-fiber filter paper was washed with alcohol, dried by ignition, mounted in a source holder and inserted into the spectrometer, within a period of 5 min. The circular sources were 2.2 cm in diameter; the average source surface density was 19.2 mg/cm^2, and the glass-fiber-backing surface density was 5.2 mg/cm^2. Due to the low intensity of the sources, the spectrometer was operated at high transmission and low resolution. Many sources were used and were normalized through the counting of the yield of 3.107-MeV γ rays with a magnetically shielded NaI(Tl) scintillation crystal detector.

Two β-ray groups were observed to be present. The endpoint energies were found to be 1.64$\pm$0.04 and and 4.75$\pm$0.04 MeV. Their relative intensities are in the ratio 94.4 to 5.6($\pm$0.6), as determined by a Fermi-Kurie plot separation. An unresolved third group with end-point energy of (4.75$-$3.71$=$1.04) MeV is assumed to produce the 3.708-MeV excited state: its relative intensity is estimated as $\sim$0.4% from the 3.708-MeV γ-ray intensity. The highest end-point energy, 4.75 MeV, was determined with best accuracy by adding the γ-ray energy, 3.107 MeV, to the 1.64 MeV energy of the intermediate β-ray group. The uncertainty of the points on the Fermi-Kurie plot, for the 4.75-MeV β-ray group, made it impossible to state whether there is or is not a "unique spectrum, $\Delta J=\pm 2$" curvature. For the 4.75-MeV group, the comparative half-life is $\log f_1 t=8.01$. For the 1.64-MeV and the 1.04-MeV groups they are evidently in the allowed range, being $\log f_0 t$ equal to 4.38 and 5.65, respectively.

DISCUSSION

The diagram of Fig. 3 summarizes the results of these measurements. The present observation of $\log f_1 t=8.01$ for the ground-state β transition confirms the earlier interpretation[2] that it is a first-forbidden transition; the value 8.01 permits the possibility that it is a "unique," $\Delta J=\pm 2$(yes), transition. Unfortunately, 8.01 lies midway between the mean values for first-forbidden $\Delta J=0$, ± 1 and $\Delta J=\pm 2$ types. However, the parity of the ground state of ^{37}S is definitely odd, and the allowed β-decay transitions to the levels of known spin at 3.107- and 3.708-MeV limit its spin to either $\frac{7}{2}$ or $\frac{5}{2}$. The fact that the shell-model expectation is that the 21st neutron in ^{37}S will determine its spin parity as $\frac{7}{2}^-$ makes reasonable the *assuming* of $\frac{7}{2}^-$ for the ground state of ^{37}S. That this is a very good assump-

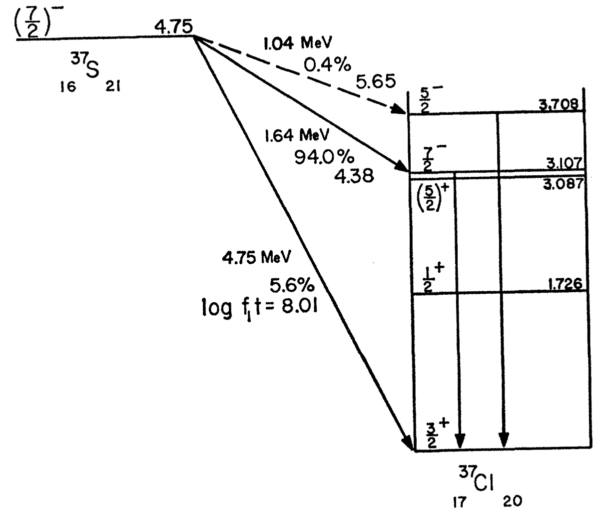

FIG. 3. β decay of ^{37}S to ^{37}Cl. Tentative spin assignments are in parentheses.

tion is indicated by Hyder and Harris's[13] discovery and identification of a spin-parity $\frac{7}{2}^-$ level, at 10.24 MeV in ^{37}Cl, as the $T=\frac{5}{2}$ isobaric analog of the ground state of ^{37}S.

3.708-*MeV Level.* The spin parity is $\frac{5}{2}^-$. The odd parity is determined by the observation of the allowed β decay, and the spin of $\frac{5}{2}$ by the ^{37}Cl$(n,n'\gamma)$ study.[6] Because of the extremely low relative population of the 3.708-MeV level, it was not possible in the present study to investigate possible branching to the lower-energy levels.

3.107-*MeV Level.* The spin parity is $\frac{7}{2}^-$. The odd parity is determined by the observation of the allowed β decay, and both spin and parity as $\frac{7}{2}^-$ by the triple angular-correlation studies of the ^{36}S$(p,\gamma\gamma)^{37}$Cl reaction by Hyder and Harris.[13] A branching transition to the 1.726-MeV state was not observed, with an upper limit of 1% relative to the transition to the ground state.

3.087-*MeV Level.* A theoretical calculation[14] places a $\frac{5}{2}^+$ state at this energy. Coincidence measurements with the ^{36}S$(p,\gamma\gamma)^{37}$Cl reaction[12] show a cascade from a $J=\frac{3}{2}$ state, which does not contradict an assumed $\frac{5}{2}^+$ assignment. Positive parity seems highly probable, for with positive parity the β-decay transition probability would be vanishingly small, as was observed, for all choices of the spin.

1.726-*MeV Level.* Spin parity of $\frac{1}{2}^+$ has been assigned previously, [6,15] with the parity uncertain. Spin $\frac{1}{2}$, with even parity, is consistent with the absence of the 1.726-MeV γ ray in the β-decay data, since the transition would be third-forbidden. Spin parity $\frac{3}{2}^+$ would permit a first-forbidden β-decay transition probability which would give the 1.726-MeV γ-ray relative intensity to be approximately at the minimum level of detectability, so $\frac{3}{2}^+$ is not excluded. However, $\frac{5}{2}^+$ or $\frac{7}{2}^+$ would permit a relative intensity of the 1.726-MeV γ ray of approximately 1–3% (assuming an average logft value) which would permit detection; hence $\frac{5}{2}^+$ and $\frac{7}{2}^+$ have low probability of being the correct assignments. Also, if $\frac{5}{2}^+$ or $\frac{7}{2}^+$, the Weisskopf single-particle transition probability[16] for a cascade from the 3.107-MeV state is large enough so that the $(3.107 \rightarrow 1.726 \rightarrow 0)$ cascade would have been observed, unless the transition were inhibited.

Theoretical predictions are consistent with the spin-parity assignments of Fig. 3. Glaudemans *et al.*[14] place the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states at slightly lower energies than observed, using a shell model with an inert ^{28}Si core and two-particle interactions of the outer nucleons. The shell-model calculation of Erne,[17] with an inert ^{32}S core and residual two-body interaction and with one nucleon in the $f_{7/2}$ shell, gives negative parity states as $\frac{7}{2}^-$ at 2.94 MeV, $\frac{3}{2}^-$ at 3.24 MeV, $\frac{5}{2}^-$ at 3.40 MeV, $\frac{1}{2}^-$ at 3.76 MeV, and $\frac{9}{2}^-$ at 3.84 MeV; the predicted energies are low but the order is correct for the $\frac{7}{2}^-$ and the $\frac{5}{2}^-$ states.

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