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^{36}S(t,pγ)^{38}S reaction

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The ^{36}S(t,pγ)^{38}S reaction was used to populate levels in ^{38}S up to 3-MeV excitation. A definite 2^+ assignment to the 1292-keV first-excited state was obtained from a (t,pγ) angular correlation. Doppler shift information provided lower limits of 0.45 and 0.2 ps for the mean lifetimes of the $1291 \rightarrow 0$ and $2825 \rightarrow 1291$ transitions. Evidence for a possible new level at 2805 keV was obtained from p-γ coincidence data. The known level spectrum of ^{38}S is compared to predictions of a shell-model interaction utilizing the full *sdpf* model space. The $E2$ and $M1$ transition rates predicted by this calculation are also presented.

I. INTRODUCTION

Neutron-rich $^{38}_{16}$S$_{22}$ has four proton holes in the *sd* shell and two neutrons in the *fp* shell. It is thus a good candidate for testing cross-shell shell-model interactions in the model space including some or all of the $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$ orbits. There have been several recent calculations of properties of ^{38}S via interactions including some of these orbits.[1,2] In this study we shall predict some properties of ^{38}S using an interaction[3]—called *SDPF*—which utilizes the full *sdpf* model space.

Previous experimental information on ^{38}S has been provided by two-nucleon heavy-ion transfer reactions[4,5] and by the ^{36}S(t,p)^{38}S reaction.[1] Some J^π values were obtained from the angular momentum L of the two neutrons transferred in the (t,p) reaction. Two-neutron spectroscopic factors were also obtained and were compared to shell-model predictions with fair success.[1]

In this paper we present information obtained from the ^{36}S(t,pγ)^{38}S reaction with the beam energy of < 3.4 MeV available from the Brookhaven National Laboratory (BNL) Van de Graaff accelerator. Some preliminary results were also obtained at the Los Alamos National Laboratory (LANL) 9-MeV Tandem Van de Graaff accelerator. The only information previously reported for ^{38}S γ rays was concerning energies.[5] We were interested in obtaining multipolarity and lifetime information as well. In Sec. II we describe the ^{36}S(t,pγ)^{38}S experiments and the analysis and results. In Sec. III shell-model calculations of energy spectra and electromagnetic transition rates are presented and compared to experiment.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The target[6] was a silver foil, 12.7 μm thick, sulfided on one side with 300 μg/cm^2 of enriched sulfur (81.1% ^{36}S, 18.8% ^{34}S). It was assumed that the sulfur is confined to that surface depth necessary to combine 300 μg/cm^2 of sulfur with silver in the stoichiometric proportion of the stable compound Ag$_2$S. This gives an Ag$_2$S target thickness of 2.12 mg/cm^2. Because of the ^{34}S in the target, some measurements were also made with a similar Ag$_2$S target fabricated from ^{34}S alone. The Q values for the (t,p) reactions on ^{36}S, ^{107}Ag, and ^{109}Ag are 3857(9), 7974, and 8163 keV, respectively.[1,5,7] The Coulomb barriers in the laboratory system for tritons incident on sulfur and silver are markedly different. These are 3.65 MeV for t+^{36}S, and 7.79 MeV for t+$^{108.7}$Ag, as calculated from

$$E_{\text{Coul}}(\text{c.m.}) = 1.44 Z_1 Z_2 / [r_0 (A_1^{1/3} + A_2^{1/3})] ,$$

with $r_0 = 1.44$ fm. It is thus possible to study the ^{36}S(t,pγ)^{38}S reaction within the range $3 < E_t(\text{MeV}) < 8$, without appreciable background from reactions with the Ag backing.

The initial measurements at LANL utilized a triton beam from the tandem accelerator, with the target placed perpendicular to the beam such that tritons passed through the backing before reaching the Ag$_2$S target layer. Protons from the (t,p) reaction emitted in the forward direction were detected by an annular plastic scintillator, with an acceptance solid angle of $\sim \pi$ sr, corresponding to an angular range $20° < \theta_p < 60°$. Elastically scattered tritons, as well as alpha particles, were stopped by an aluminum absorber foil of ~ 45 mg/cm^2 areal density which was sufficient to stop 7-MeV tritons, and correspondingly, ~ 4.6-MeV protons. Scintillator pulses were detected by a photomultiplier coupled via a light pipe to the scintillator. The energy resolution of this system is poor, but it has the ability to provide a clean yes/no signal for the detection of protons from the (t,p) reaction.

Gamma rays were detected by two gamma-x detectors (12% efficiency) placed at 90° to the beam direction (+90° and −90°) at distances of ~ 3 cm from the target. A single 12-h run was made at a bombarding energy of $E_t = 6$ MeV and a beam current of 2.5 nA. Time-coincident γ-ray spectra (i.e., gated by light charged particles) were displayed at a dispersion of 1.3 keV/channel. Gamma rays of 1291.5(5) and 1532(1) keV were observed and tentatively identified with the ^{38}S $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions (Ref. 1). Other γ-ray transitions were observed which possibly belong to ^{38}S. This preliminary experiment showed that it was feasible to study the ^{36}S(t,pγ)^{38}S reaction up to $E_t \sim 7$ MeV with the available Ag$_2$S targets. It also demonstrated that better energy resolution in the proton channel would be very advantageous. Therefore it was decided to pursue the experiment using a silicon proton detector.

The measurements at BNL were done at the 3.5-MV Van de Graaff accelerator. The triton energy was 2.9 MeV. The triton energy loss in the Ag$_2$S target was 230 keV and in the target plus Ag foil the energy loss was 1.65 MeV. The target was backed by a 25×10^{-3} cm thick Au foil. Protons were detected in an annular silicon counter (1 mm thickness $\times 200$ mm^2 area) centered at 180° to the beam and subtending an angular range of 175°—160°. A 13.7-mg/cm^2 Al foil was placed over the Si detector to preferentially degrade other charged particles. Gamma rays were observed with a 120-cm^3 coaxial Ge(Li) detector [efficiency relative to a 7.6×7.6-cm NaI(Tl) detector of 16%] with its front face 12 cm from the target and mounted to swing between 0° and 90° to the beam. The Ge(Li) detector was shielded from beam-induced room background by placing it in a cylindrical lead shield of 3-cm wall thickness. The front face was shielded against low-energy γ rays and x rays from the target by a sandwich of 3-mm Pb plus 1-cm Lucite.

Proton-gamma coincidences were recorded at $\theta_\gamma = 0°$, 30°, 45°, 60°, and 90°. Time-to-amplitude (TAC), proton, and γ-ray spectra were recorded with 512, 1024, and 4096 channels, respectively. Coincidences were event-mode-recorded on tape for subsequent playback of true-coincidence proton and γ-ray coincidence spectra. An average of 10 h of data at a beam intensity of 50 nA was collected at each angle. Examples of the results obtained from these coincidence data are shown in Figs. 1 and 2, which display true-coincidence proton and γ-ray spectra, respectively.

Gamma-ray transitions were observed corresponding to the decay of the 1292- and 2825-keV levels of ^{38}S which had been assigned J^π values of 2^+ and 4^+, respectively, in the previous ^{36}S(t,p)^{38}S angular distribution study.[1] We measured transition energies of 1291.9(2) and 1533.2(10) keV for the 1292→0 and 2825→1292 transitions, respectively. These energies are in excellent agreement with the measurements at LANL described above and with those of Mayer *et al.*[5] which are 1292(1) and 1532(2) keV after correction for Doppler effects (Ref. 1). Another γ-ray transition, with $E_\gamma = 1513(2)$ keV, was observed in coincidence with a charged particle energy window encompassing energies ±5% about that expected for the 2805-keV level. No source could be found for this transition. It is quite possible that this arises from a ^{38}S 2805→1292 transition and the 2805-keV level was overlooked in previous studies.

The 2825- and possible 2805-keV levels were formed with cross sections ~20% of the 1292-keV level. A (t,pγ) angular correlation was extracted for the 1292-keV level. For the 1533- and 1513-keV transitions the statistics and peak/background ratio were too poor to give reliable angular correlation information. Results for the 1292-keV level are shown in Fig. 3. The analysis follows method II of Litherland and Ferguson.[8] It is clear that a definite $J=2$ assignment can be given to the 1292-keV level (with the ground state taken to have $J^\pi = 0^+$). That is, $J=1,3$ are excluded by the angular correlation since both give χ^2 values which are well above the 0.1% probability limit, and spins higher than 3 are excluded by the very coarse lifetime limit, $\tau < 10^{-6}$ s, inferred from the observation of proton-gamma coincidences.

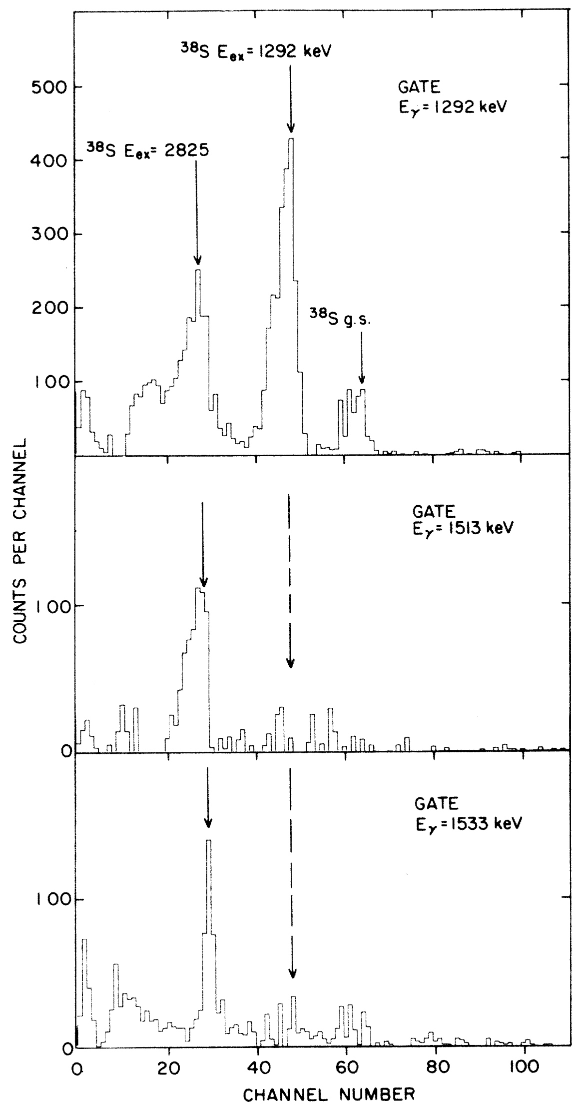

FIG. 1. Particle spectra observed in coincidence with selected γ-ray peaks. Randoms and the contributions of the background under the γ-ray peaks have been subtracted. The calculated positions of the proton peaks due to the ground state (g.s.) and first two excited states of ^{38}S are indicated. The ^{38}S g.s. peak is due to random coincidences. The γ-ray detector was at 90° to the beam.

In the previous (t,p) angular distribution study[1] an $L=2$ pattern was observed for the transition to the 1292-

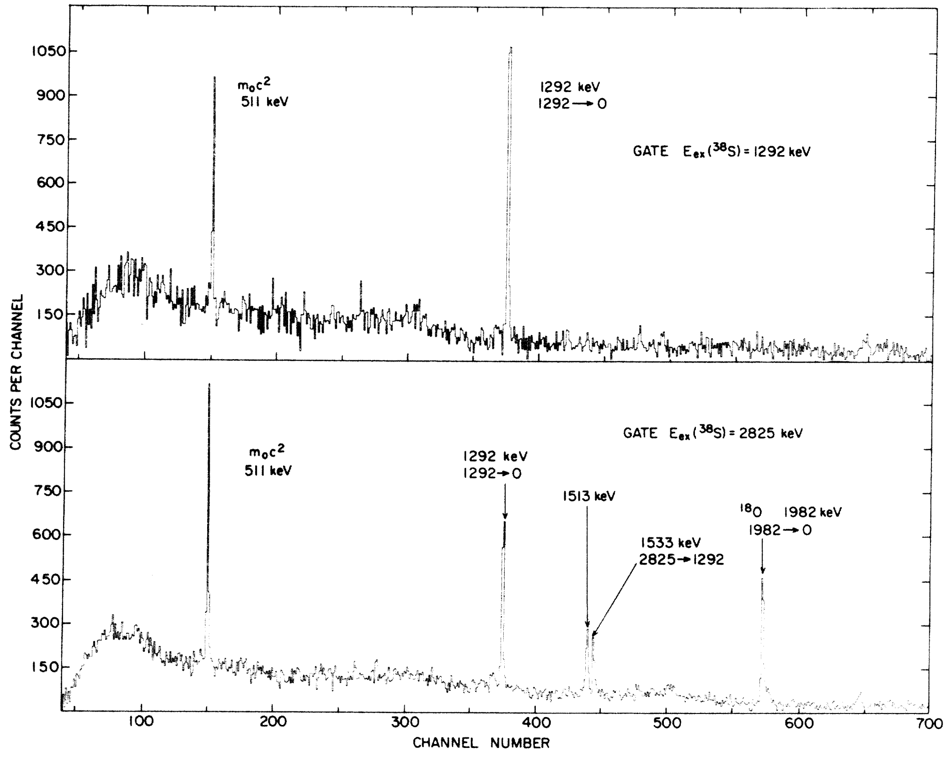

FIG. 2. Gamma-ray spectra in coincidence with proton peaks due to formation of the first two excited states of ^{38}S via $^{36}S(t,p)^{38}S$. The ^{18}O 1982→0 transition arises from the $^{16}O(t,p)^{18}O$ reaction on ^{16}O contamination of the target.

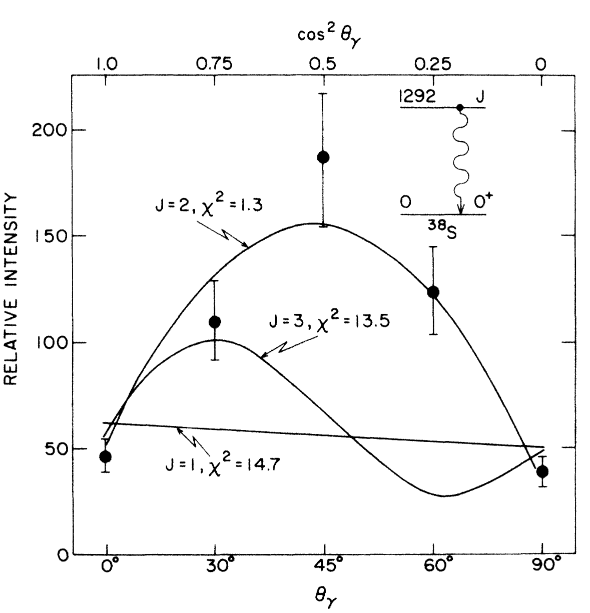

FIG. 3. $^{36}S(t,p\gamma)^{38}S$ angular correlation. Fits are shown for three assumed J values for the 1292-keV level and a J-pole multipolarity for the γ transition. The substate population of the initial state was assumed to be limited by the colinear geometry to $m=0,1$ with at most 5% admixture of $m=2$. Chi-squared (χ^2) for the 0.1% probability limit is 4.5.

keV level so that a $J^\pi=2^+$ assignment was made to that level. The present result strengthens this assignment not only because a definite $J=2$ assignment is made but because of the relatively large cross section with which the state was formed at $E_t=18$ MeV. The evidence from this large cross section that the state has parity $(-)^J$ is quite strong; i.e., $\pi=+$ if $J=2$ is considerably more sure than the assignment of $L=2$ to the angular distribution.

Doppler shift information was extracted for the 1292-, (1513-), and 1533-keV transitions by least squares fits of the peak centroid vs $\cos\theta_\gamma$, i.e., the Doppler shift attenuation factor, $F(\tau)$, was extracted from the relation

$$E_\gamma = E_{\gamma 0}[1+F(\tau)\cos\theta_\gamma] \ . \qquad (1)$$

The least squares fits yielded limits on $F(\tau)$ values of <0.25 and <0.4 for the 1292- and 1533-keV transitions, respectively. If the 1513-keV transition is due to a ^{38}S 2805→1292 transition, it has an $F(\tau)$ value of 0.6(2). We analyze these results by using the Blaugrund[9] relationship between $F(\tau)$ and τ and find limits on τ of >0.45 and >0.2 ps for the 1291- and 2825-keV levels, respectively, both being 90% confidence limits. For the possible 2805-keV level, $F(\tau)=0.6(2)$ corresponds to $\tau=0.12^{+0.13}_{-0.07}$ ps. If this transition were $E2$ in character it would have a strength >54 W.u. (1 standard deviation); this is large enough to suggest $J=1-3$ for the speculated 2805-keV level.

III. SHELL MODEL CALCULATIONS

To better understand the present results and to provide guidance for future experiments on ^{38}S, shell-model calculations were carried out with two different interactions. Two interactions were used because each was designed to represent different aspects of the ^{38}S level structure.

We first consider a simple $d_{3/2}f_{7/2}$ model (designated WDF) with ^{32}S assumed a closed core of $^{16}\mathrm{O}(0d_{5/2}1s_{1/2})^{16}$. We use an interaction by Wildenthal[10] specifically designed to estimate the relative binding energies of $n\hbar\omega$ excitations. Results of this interaction for nuclei in the range $A=35$–48 have recently been presented.[3,11] In any model we expect $(d_{3/2})^4(f_{7/2})^2$ to be the dominant component in the lowest $0^+,2^+,4^+,6^+$ states of ^{38}S and we are interested in predicting the relative binding energies of all the low-lying states of ^{38}S which are predominantly $(d_{3/2}f_{7/2})^6$. These we calculate with the shell-model program OXBASH (Ref. 12). The results are compared to experiment in Fig. 4. In this figure the odd-parity levels from $d_{3/2}^3f_{7/2}^3+d_{3/2}^1f_{7/2}^5$ are shown to the far left with the even-parity states from $d_{3/2}^4f_{7/2}^2+d_{3/2}^2f_{7/2}^4+d_{3/2}^0f_{7/2}^6$ next to them. The odd-parity states are all predicted to be $>84\%$ $d_{3/2}^3f_{7/2}^3$. The percentage of the three $d_{3/2}^{(4-n)}(f_{7/2})^{(2+n)}$ configurations are given in parentheses in the order $n=0,2,4$ and shall be referred to as $n\hbar\omega$ excitations. States predominantly of $d_{3/2}^2f_{7/2}^4$ composition are labeled with an asterisk. These $(d_{3/2}f_{7/2})^6$ calculations serve the same purpose as the weak coupling calculations described by Davis *et al.*[1] but are considerably more quantitative.

The experimental spectrum of Fig. 4 is taken from Davis *et al.*[1] as are the spin-parity assignments of that study. Our excitation energies are given for the 1292- and 2825-keV levels, and the possible 2805-keV level is indicated as such. We see that there are good candidates for the lower-lying $0\hbar\omega$ states and some of the $1\hbar\omega$ states of the $(d_{3/2}f_{7/2})^6$ calculations, but no evidence for the formation of any $2\hbar\omega$ states. As discussed by Davis *et al.*[1] this is as expected since the ^{36}S(t,p)^{38}S reaction should readily populate most $0\hbar\omega$ and $1\hbar\omega$ states, but not $2\hbar\omega$ states.

A less truncated space than $(d_{3/2}f_{7/2})^6$ is necessary in order to predict all low-lying ($\lesssim 5$-MeV excitation) states expected in ^{38}S. The $(d_{3/2}f_{7/2})^6$ space should be adequate

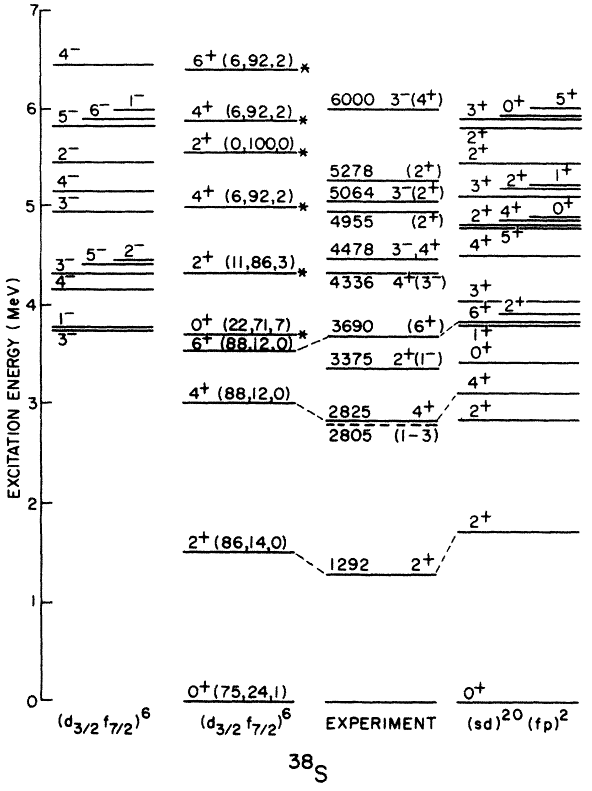

FIG. 4. Comparison of the experimental ^{38}S level spectrum (from Ref. 1 and the present work) to shell-model predictions. The $(d_{3/2}f_{7/2})^6$ results are from the WDF interaction of Wildenthal with unrestricted occupation of the $(d_{3/2}f_{7/2})^6$ model space. For the even-parity states the percentage occupation of $(d_{3/2})^{(4-n)}(f_{7/2})^{(2+n)}$ is shown in the order $n=0,2,4$. The states which are predominantly $(d_{3/2})^2(f_{7/2})^4$ are indicated by an asterisk. The spectrum to the far right is the *SDPF* calculation in the $d_{5/2}d_{3/2}s_{1/2}f_{7/2}f_{5/2}p_{3/2}p_{1/2}$ space with the fp occupation fixed at two neutrons.

TABLE I. ^{38}S transition strengths calculated with the *SDPF* interaction. The numbers in parentheses are powers of 10.

J_n^π Initial	Final	$B(M1)$ (μ_N^2)	$B(E2)$ (e^2 fm^4)
2_1^+	0_1^+		4.175(+1)
2_2^+	0_1^+		9.959(+0)
2_2^+	2_1^+	2.053(−2)	9.452(+0)
4_1^+	2_1^+		3.498(+1)
4_1^+	2_1^+		1.725(+0)
0_2^+	2_1^+		2.945(+1)
	2_2^+		3.636(+1)
1_1^+	0_1^+	1.644(−2)	
	2_1^+	3.737(−1)	6.636(−1)
	2_2^+	9.034(−1)	1.768(+1)
	0_2^+	9.807(−2)	
6_1^+	4_1^+		2.945(+1)
2_3^+	0_1^+		1.521(+0)
	2_1^+	3.380(−2)	1.741(+1)
	2_2^+	2.150(−1)	1.894(+1)
2_3^+	0_2^+		2.559(+0)
	1_1^+	2.001(−2)	9.798(+0)
3_1^+	2_1^+	4.165(−2)	8.956(+0)
	2_2^+	1.227(−1)	5.577(+1)
	4_1^+	1.210(−1)	2.886(+1)
	1_1^+		8.690(−3)
	2_3^+	2.410(−1)	3.060(+0)
4_2^+	2_1^+		1.988(−1)
	2_2^+		2.246(+0)
	6_1^+		1.373(+1)
	2_3^+		4.398(+0)
	3_1^+	7.283(−2)	7.887(−1)
5_1^+	4_1^+	5.644(−2)	2.971(+0)
	6_1^+	2.144(−2)	1.747(+1)
	3_1^+		4.217(+0)
	4_2^+	2.360(−1)	1.273(+0)

for the $1\hbar\omega$ and $2\hbar\omega$ states in this energy range, but for $0\hbar\omega$ states a full *sdpf* model space is desirable, especially if electromagnetic or beta-decay observables are to be calculated. Thus, a calculation was made with the *SDPF* interaction described by Warburton *et al.*[3] This interaction assumes an s^4p^{12} ^{16}O core and uses the "universal" $2s,1d$ interaction—denoted *USD*—of Wildenthal.[13] A modified Millener-Kurath interaction (Ref. 14) is used for the cross-shell *sd* to *fp* interaction and a modified van Hees-Glaudemans interaction (Ref. 15) was used for the *fp* shell. As usual, the interaction is designed to incorporate in an effective way the effects of omitted configurations such as the $2\hbar\omega$ and $4\hbar\omega$ terms indicated in the second column of Fig. 4. For ^{38}S, 20 particles (four proton holes) were allowed in the three *sd* subshells and two neutrons in the four *fp* subshell orbits with no further restriction on the subshell occupancies. The maximum J dimension in this space is 1800 for $J=3$. The level spectrum resulting from this calculation is shown to the right in Fig. 4. All states other than the first $0^+,2^+,4^+,6^+$ arise from terms other than $d_{3/2}^{-4}f_{7/2}^{2}$. The ^{38}S spectrum obtained from the *SDPF* interaction is in good agreement with the spectrum presented in Ref. 1 and obtained using the van der Poel interaction[16] acting in the model space consisting of active $d_{3/2}$, $s_{1/2}$, $f_{7/2}$, and $p_{3/2}$ orbitals.[17]

$M1$ and $E2$ transition strengths calculated with the *SPDF* interaction are listed in Table I. The $M1$ rates use the free-nucleon g factors. The $E2$ rates use effective charges of $e_p=1.5e$, $e_n=0.5e$. Using the $B(M1)$ and $B(E2)$ values of Table I and the experimental energies, we calculate mean lifetimes of 2.75 ps and 5.43 ps for the $4_1^+\rightarrow2_1^+$ and $2_1^+\rightarrow0_1^+$ transitions. These are in agreement with, but far removed from the experimental lower limits of >0.45 ps and >0.2 ps, respectively.

We now turn to the evidence bearing on the existence and properties of the 2805-keV level. As can be seen in Fig. 4, there are two good candidates for the spin-parity of the 2805-keV level if, in fact, it does exist; $J^\pi=0^+$ or 2^+. If 0^+ then the decay to the 2^+ state would have an $E2$ strength >54 W.u. (1 standard deviation). This appears very unlikely; e.g., our calculation gives 3.9 W.u. for this $0^+\rightarrow2^+$ transition. A 2^+ assignment is much more palatable. In our *SDPF* calculation the 2_1^+ and 2_2^+ states are approximately orthogonal mixtures of $\pi(d_{3/2}^{4}s_{1/2}^{4})_{0^+}\nu(f_{7/2})_{2^+}$ and $\pi(d_{3/2}^{5}s_{1/2}^{3})_{2^+}\nu(f_{7/2}^{2})_{0^+}$ with $\sim43\%$ and 15%, and 19% and 47% of each for 2_1^+ and 2_2^+, respectively. If the 2_2^+ states were at 2805 keV we predict a lifetime of 0.48 ps and branching ratios of 36% to the ground state and 64% to the 1292-keV level, in reasonable agreement with the experimental facts. What do we expect for the ^{36}S(t,p)^{38}S cross section to the 2_2^+ level? From the calculation of two-particle amplitudes described in Ref. 1, we predict comparable (within a factor of ~2) cross sections for the 2_1^+ and 2_2^+ levels of ^{38}S at $E_t=18$ MeV as used in Ref. 1. However, the proton energy resolution (~55 keV) in the ^{36}S(t,p)^{38}S study of Ref. 1 was clearly inadequate to separate possible doublet states at 2805 and 2825 keV. On this point, however, the $E_t=6$ MeV measurements performed at LANL are very useful. In this latter study a γ-ray peak is evident at 1513(2) keV with an intensity $\sim25\%$ of that for the 1533-keV peak. This then is quite consistent with the experimental $E_t=2.9$ MeV results. We conclude that all available experimental and theoretical evidence is consistent with the 2805-keV level postulated from the $E_t=2.9$ MeV study. However, we feel further corroboration is necessary before it is considered definite.

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[1] N. J. Davis, J. A. Kuehner, A. A. Pilt, A. J. Trudel, M. C. Vetterli, C. Bamber, E. K. Warburton, J. W. Olness, and S. Raman, Phys. Rev. C **32**, 713 (1985).

[2] C. L. Woods, Nucl. Phys. **A451**, 413 (1986).

[3] E. K. Warburton, D. E. Alburger, J. A. Becker, B. A. Brown, and S. Raman, Phys. Rev. C **34**, 1031 (1986).

[4] L. K. Fifield, M. A. C. Hotchkis, P. V. Drumm, T. R. Ophel, G. D. Putt, and D. C. Weisser, Nucl. Phys. **A417**, 534 (1984).

[5] W. A. Mayer, W. Henning, R. Holzworth, H. J. Körner, A. Korschinek, W. U. Mayer, G. Rosner, and H. J. Scheerer, Z. Phys. A **319**, 287 (1984).

[6] C. E. Thorn, J. W. Olness, E. K. Warburton, and S. Raman, Phys. Rev. C **30**, 1442 (1984).

[7] A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).

[8] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961); **30**, 1442 (1984).

[9] A. E. Blaugrund, Nucl. Phys. **88**, 501 (1967).

[10] B. H. Wildenthal, private communication.

[11] E. K. Warburton, C. W. Beausang, D. B. Fossan, L. Hildingsson, W. F. Piel, Jr., and J. A. Becker, Phys. Rev. C **34**, 136 (1986).

[12] B. A. Brown, A. Etchegoyen, W. D. M. Rae, and N. S. Godwin, OXBASH, the Oxford—Buenos Aires Shell Model Code, Cyclotron Laboratory, Michigan State University, Internal Report, 1984.

[13] B. H. Wildenthal, Prog. Part. Nucl. Phys. **11**, 5 (1984); B. H. Wildenthal, M. S. Curtin, and B. A. Brown, Phys. Rev. C **28**, 1343 (1983).

[14] D. J. Millener and D. Kurath, Nucl. Phys. **A255**, 315 (1975).

[15] A. G. M. van Hees and P. W. M. Glaudemans, Z. Phys. A **303**, 267 (1980).

[16] G. J. L. Nooren and G. van der Leun, Nucl. Phys. **A423**, 197 (1984); G. J. L. Nooren, H. P. L. de Esch, and C. van der Leun, *ibid*. **A423**, 228 (1984); C. J. van der Poel, Ph.D. dissertation, Utrecht University, The Netherlands, 1982.

[17] The lowest-lying states of $J^{\pi}=1^{+},3^{+},5^{+}$ were not included in the shell model results presented in Ref. 1. Use of the van der Poel interaction results in excitation energies of 3060, 4036, and 4320 keV for $J_{n}^{\pi}=1_{1}^{+}$, 3_{1}^{+}, and 5_{1}^{+}, respectively.