Particle-core coupling in ^{37}S

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Excited states of the neutron-rich $N = 21$ ^{37}S nucleus have been studied using binary grazing reactions produced by the interaction of a 215-MeV beam of ^{36}S ions with a thin ^{208}Pb target. The magnetic spectrometer, PRISMA, and the γ-ray array, CLARA, were used in the measurements. The level scheme of ^{37}S was established to an excitation energy of 4196 keV and a number of new transitions were observed, in particular that corresponding to the decay of the proposed $J^\pi = (11/2^-)$ level at an excitation energy of 2776 keV. The structure of the state is discussed within the context of state-of-the-art shell-model calculations using the SDPF-U effective interaction; the main component of the wave function corresponds to the coupling of the odd $1f_{7/2}$ neutron to the first 2^+ state of the ^{36}S core. The electromagnetic decay properties of the state are discussed within the context of a particle-core coupling model and the shell model. The other members of the multiplet of states are also discussed.

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I. INTRODUCTION

The present paper is concerned with the nuclear structure of $^{37}_{16}S_{21}$ studied using binary grazing reactions and forms one of a series of studies of neutron-rich nuclei lying between the $N = 20$ and 28 shell closures. Earlier related studies have been mainly concerned with the role of negative-parity intruder orbitals in the structure of neutron-rich nuclei on the periphery of the tightly circumscribed island of inversion, centered on ^{32}Mg, and on the description of such nuclei using state-of-the-art shell-model calculations. See, for example, Ref. [1] and references therein. Binary grazing and deep-inelastic reactions have been used extensively over the last few decades to study the structure of neutron-rich nuclei over a wide range of nuclear masses. The coupling of large solid-angle magnetic spectrometers to arrays of escape-suppressed Ge detectors in studies of this type (see, e.g., Refs. [2–4]) has represented a very significant experimental advance in relation to earlier techniques which exploited large arrays of Ge detectors but no particle identification, as in the pioneering work of Broda *et al.* [5]. In the present paper, the discussion is focused on the proposed $J^\pi = 11/2^-$ state of ^{37}S at an excitation energy of 2776 keV and its description in terms of the coupling of a $1f_{7/2}$ neutron to the first excited 2^+ state of the ^{36}S core.

From the simplest perspective of the nuclear shell model, the $^{37}_{16}S_{21}$ ground state has four proton holes in the sd shell and one neutron in the $1f_{7/2}$ orbital, outside the $N = 20$ shell closure, and has a J^π value of $7/2^-$. Excited states of ^{37}S correspond to promotion of the odd-neutron across the $N = 28$ shell gap to the higher-lying $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ shell-model states and to the rearrangement of protons within the *sd* shell. The coupling of the odd $1f_{7/2}$ neutron to states of the ^{36}S core will give rise to multiplets of states. The lowest-lying core state of ^{36}S, the first $J^\pi = 2^+$ state, lies at an excitation energy of 3291 keV; consequently, core-excited states of ^{37}S are expected to be observed at around this energy, with J^π values of $3/2^-$, $5/2^-$, $7/2^-$, $9/2^-$, and $11/2^-$. ^{37}S is thus a good nucleus within which to study *n-p* cross-shell interactions and single-particle states around the $N = 20$ shell closure. The structure of the low-lying states of ^{37}S will be discussed within the context of state-of-the-art shell-model calculations presented later in the paper.

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Binary grazing reactions with stable neutron-rich beams and heavy targets can be used to populate yrast and near yrast states of moderately neutron-rich projectile-like species [6–10]. In general, experiments using such reactions, although unable to reach the most neutron-rich nuclear species currently accessible to experiment, provide more detailed spectroscopy than is possible at the present time using fragmentation reactions [11] or intermediate-energy Coulomb excitation; in the latter case, the states that are populated are, in general, those that are connected directly to the ground state by $E2$ transitions [12]. Because the target nucleus here, ^{36}S, has a closed neutron shell, it is expected that both single-particle (neutron), yrast, and near-yrast states will be populated.

In the present work, the level scheme of ^{37}S, populated in binary grazing reactions, was studied. We have exploited the combination of a large acceptance magnetic spectrometer, PRISMA [13], and a high granularity and high efficiency γ-ray detection array, CLARA [14], which allows good reaction-channel selection and precise Doppler correction of γ-ray energies.

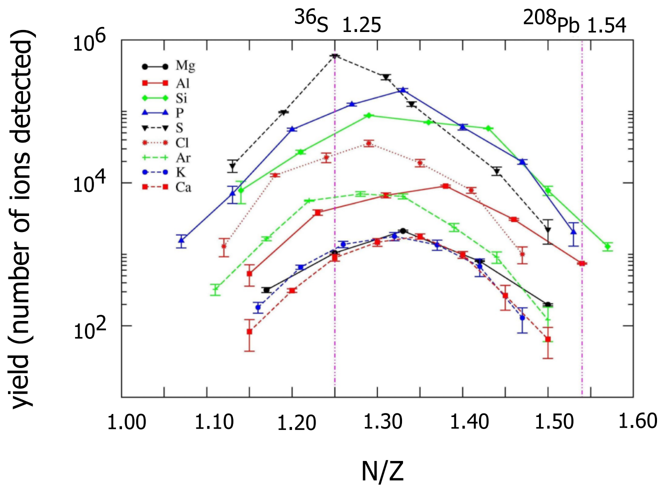

FIG. 1. Yields of ions detected at the PRISMA focal-plane detectors as a function of *N/Z* for atomic numbers in the range from 12 to 20. The *N/Z* values of projectile and target are indicated.

II. EXPERIMENT

States of ^{37}S were populated using binary grazing reactions produced in the interaction of a 215-MeV beam of $^{36}S^{9+}$ ions, delivered by the Tandem-ALPI accelerator complex at the INFN Legnaro National Laboratory, Italy, with a thin ^{208}Pb target. The target, isotopically enriched to 99.7% in ^{208}Pb, was of thickness 300 μg cm^{-2} on a 20 μg cm^{-2} carbon backing. Projectile-like fragments produced during the reaction were analyzed with PRISMA [13], a large acceptance-angle magnetic spectrometer placed at 56° to the beam axis, and covering a range of angles including the grazing angle of the reaction (58°). Gamma rays from the de-excitation of projectile- and target-like binary reaction products were detected using CLARA [14], an array of 25 escape-suppressed Ge clover detectors (22 Ge clover detectors were used during the present work). The detection of γ rays in time coincidence with projectile-like fragments, identified at the focal plane of the PRISMA spectrometer, provides an unambiguous association of γ-ray transitions with each projectile-like binary fragment of a particular A and Z. CLARA was positioned in the hemisphere opposite to the PRISMA spectrometer and covering the azimuthal angles from 98° to 180° with respect to the entrance aperture of PRISMA. The CLARA total photopeak efficiency for 1.3-MeV γ rays is around 2.8%, and the peak-to-total ratio is 45% for ^{60}Co 1.3-MeV γ rays. Doppler correction of γ-ray energies was performed on an event-by-event basis. More details of the experimental equipment used here have been given in earlier publications, e.g., [10]. Experimental data were accumulated during a six-day run with an average beam current of 7 pnA. The statistics were not sufficient to allow a γ-γ coincidence analysis to be undertaken.

III. RESULTS AND DISCUSSION

In the present experiment, a wide range of nuclear species, from Mg ($Z = 12$) to Ca ($Z = 20$) (see Fig. 1), was identified at the focal plane of PRISMA. Here, we focus on a discussion of ^{37}S, one neutron away from the ^{36}S projectile nucleus. The mass spectrum of sulfur isotopes is presented in Fig. 2.

In total, around 3.2×10^5 ^{37}S ions were detected in coincidence with at least one γ ray in the present study. The Doppler-corrected one-dimensional γ-ray spectrum of ^{37}S is shown in Fig. 3. Lead characteristic x rays are marked as "Pb-X" and photopeaks from the γ-ray decay of unobserved target-like binary reaction partners, mainly the ^{207}Pb nucleus, are labeled as "C". Direct one-neutron transfer is expected to be a significant process in the population of the ^{37}S nucleus and the associated reaction partner ^{207}Pb. In Fig. 3, there are two very broad γ-ray photopeak structures at energies of around 600 and 950 keV, which correspond to γ rays from the reaction partner (^{207}Pb) nucleus without appropriate Doppler correction. The γ-ray spectrum of Fig. 4 corresponds to an appropriate Doppler correction for target-like reaction partners, assuming two-body kinematics. The previously known γ-ray photopeaks in the

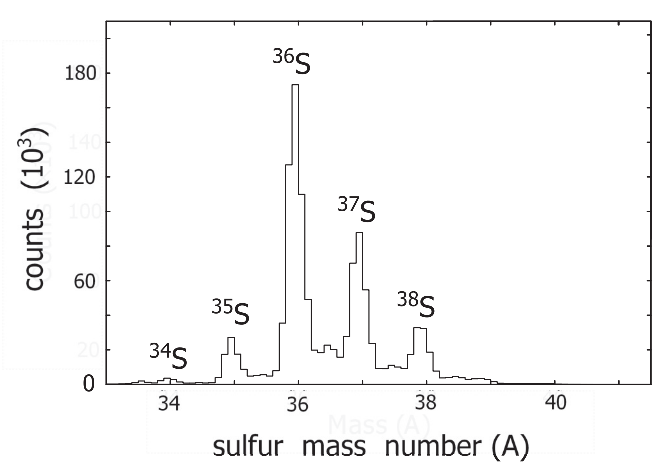

FIG. 2. Mass spectrum for sulfur ($Z = 16$) isotopes populated in the present work. See text for details.

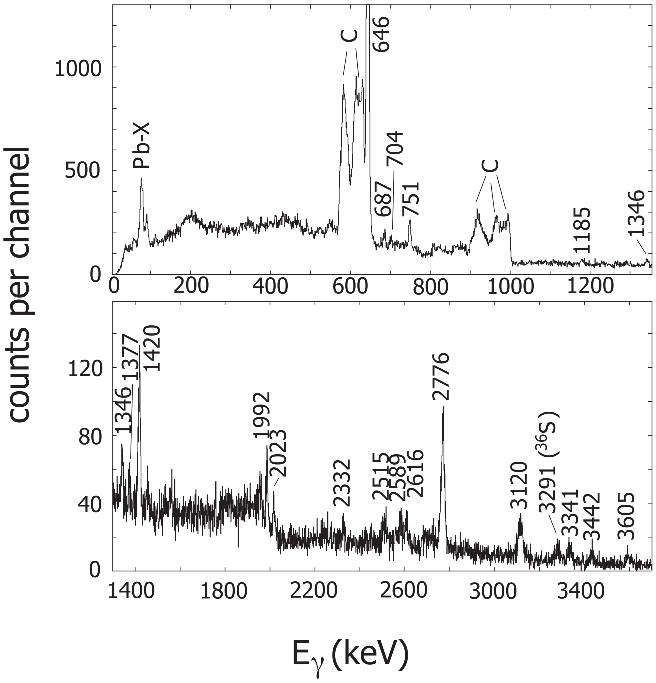

FIG. 3. One-dimensional Doppler-corrected γ-ray energy spectrum observed in association with ^{37}S nuclei detected at the focal plane of the PRISMA spectrometer. See text for details.

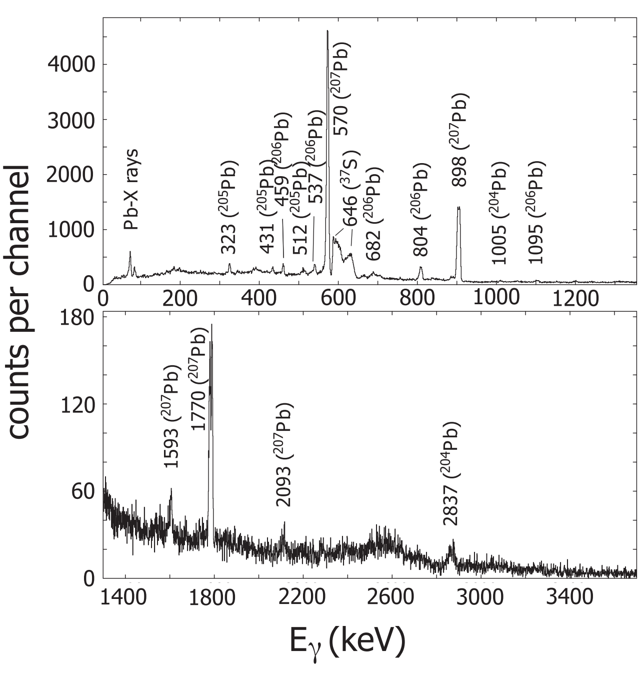

FIG. 4. One-dimensional Doppler-corrected γ-ray energy spectrum corresponding to target-like fragments observed in association with ^{37}S nuclei detected at the focal plane of the PRISMA spectrometer. Photopeaks marked with "Pb-X" correspond to characteristic lead x rays from the lead target. The most intense photopeaks correspond to γ-ray transitions de-exciting the known neutron hole states of ^{207}Pb.

TABLE I. Measured γ-ray transition energies and relative intensities observed in the present work. Level energies and the energies of the initial and final states are also given (* previously unobserved γ-ray transitions; $\dagger$ possible unresolved doublet).

E_{level} (keV)	E_γ (keV)	$E_i \rightarrow E_f$	I_γ/I_{646} (%)
646	646(1)	$646 \rightarrow 0$	100.0(0.8)
1397	751(1)	$1397 \rightarrow 646$	5.4(0.3)
1992	1992(1)†	$1992 \rightarrow 0$	3.4(0.3)
	1346(1)	$1992 \rightarrow 646$	1.9(0.2)
2023	2023(1)	$2023 \rightarrow 0$	1.5(0.2)
	1377(1)	$2023 \rightarrow 646$	0.8(0.2)
2515	2515(1)*	$2515 \rightarrow 0$	4.0(0.4)
2638	1992(1)†	$2638 \rightarrow 646$	3.4(0.3)
2776	2776(2)*	$2776 \rightarrow 0$	17.3(0.6)
2978	2332(2)*	$2978 \rightarrow 646$	2.1(0.3)
3120	3120(2)*	$3120 \rightarrow 0$	7.4(0.4)
3262	2616(2)	$3262 \rightarrow 646$	3.3(0.3)
3341	3341(2)*	$3341 \rightarrow 0$	2.6(0.3)
3442	3442(2)*	$3442 \rightarrow 0$	1.3(0.2)
3605	3605(3)*	$3605 \rightarrow 0$	2.3(0.3)
4196	1420(1)*	$4196 \rightarrow 2776$	7.5(0.3)

spectrum of Fig. 3 at energies of 646, 751, 1346, 1377, 1992, 2023, and 2616 keV are clearly observed. In addition, hitherto unobserved γ-ray photopeaks are clearly identified at energies of 687, 704, 1185, 1420, 2332, 2515, 2589, 2776, 3120, 3341, 3442, and 3605 keV. The measured γ-ray energies and relative intensities are presented in Table I.

The excited states of ^{207}Pb at energies of 570, 898, 1633, and 2340 keV are strongly populated in the ^{208}Pb$(p, d)^{207}$Pb direct single neutron pickup reaction [15], and they correspond to fairly pure neutron hole states, $2f_{5/2}^{-1}$, $3p_{3/2}^{-1}$, $1i_{13/2}^{-1}$, and $2f_{7/2}^{-1}$, respectively. The principal decay γ rays from these states have energies of 570, 898, 1064, and 1770 keV, respectively, and, other than the 1064-keV line, these transitions dominate the γ-ray spectrum of Fig. 4. The absence of the 1064-keV transition is explained by the isomeric decay (0.8 s; $M4 + E5$) of the $J^\pi = 13/2^+$ state. The 2093-keV transition corresponds to the decay of the $J^\pi = 7/2^+$ state at 2662 keV, which is a member of the $3^-(^{208}\mathrm{Pb}) \otimes \nu\,(3p_{1/2})^{-1}$doublet. An inspection of Fig. 4 also shows that the complementary undetected fragment is not only ^{207}Pb; the Pb isotopes ^{206}Pb, ^{205}Pb, and ^{204}Pb are also populated, albeit weakly. Neutron evaporation from the initially formed target-like and projectile-like fragments occurs; this was noted in previous work, e.g., [16].

Most of the levels populated here in ^{37}S were established in previous studies [17–20]. An evaluation of nuclear data for $A = 37$ nuclides was also recently published by Cameron *et al.* [21]. We follow the established assignments for previously known γ-ray transitions. The previously unobserved γ-ray transitions at energies of 2332, 2515, 2776, 3120, 3341, 3442, and 3605 keV match the energy difference between previously known levels and the ground state or the first excited state at 646 keV and they have been assigned to the level scheme on this basis. Within experimental error, the energy difference between the excited states at 3442 and 2023 keV would suggest that the 1420-keV transition observed here connects these two states.

However, if the 1420-keV photopeak corresponds to a single transition, intensity arguments rule out such an assignment. Based on intensity considerations, but later supported by nuclear structure arguments, it is tentatively proposed that the 1420-keV transition populates the 2776-keV level. The observation of a high-spin state (a tentative J^π value of $13/2^+$ will be proposed later) at 4196 keV is consistent with the population of yrast states in the present work. The possible structure of this state will be discussed later. However, it cannot be totally dismissed that the 1420-keV transition feeds the ground state or the 646-keV level. The latter assignment can probably be more easily excluded, because this would require a low spin state at 2066 keV, and such a state was not observed in any of the previous published works, to which reference was made earlier. Gamma-gamma coincidence measurements, not possible in the present work because of the poor statistics, are required to confirm the proposed placement of the 1420-keV transition within the level scheme. The 687-, 704-, 1185-, and 2589-keV γ rays were not assigned to the ^{37}S level scheme because of the lack of supporting evidence. Within experimental error, the weak 1185-keV transition matches the energy difference between the previously identified states at 3962 and 2776 keV; such an assignment is inconsistent with the previously established J^π value of the state and, on this basis, the 1185-keV transition is not included in the level scheme based on the present work. Here, the previously known 1991.9- and 1991.6-keV γ-ray transitions cannot be resolved. The 1992-keV γ ray observed here may contribute to the decay from the 1992-keV state in addition to deexciting the 2638-keV state. From the branching ratio of the 3262-keV state [21], the intensity of the 1239-keV transition from the 3262-keV level to the 2023-keV level is expected, in the present work, to be about 1.6 units $[I_\gamma/I_{646}]$ (%); however, the corresponding photopeak was not identified here. The excitation energy of the current level scheme extends up to 4196 keV, close to the one-neutron separation energy of 4304 keV [18].

Figure 5 presents the proposed level scheme from the present work together with those from earlier work [17–19]. The results of an $0\hbar\omega$ sd-pf shell-model calculation which uses the SDPF-U effective interaction [22] are also presented in the figure. The full $sd(pf)$ valence space was used for protons (neutrons) above an ^{16}O core. Within the configuration space of the calculation, only negative parity states can be calculated. The low-lying negative parity states mainly correspond to one neutron occupation of the fp shell, coupled to the ground state of the ^{36}S core. Core-excited states have also been identified and we shall return to this later. Shell-model calculations were performed with the NATHAN [23,24] and NUSHELLX [25] codes; the latter code was used in a more detailed examination of wave functions, as discussed later in the paper.

The first excited state of ^{37}S at 646 keV was identified by Ajzenberg-Selove and Igo [17] using the ^{37}Cl$(t,\,^3$He$)^{37}$S charge-exchange reaction. This state was assigned a J^π value of $3/2^-$ by Thorn *et al.* [19] from proton angular distribution measurements in the ^{36}S$(d,\,p)^{37}$S one-neutron transfer reaction, in which states with excitation energy up to 5.72 MeV ($J^\pi = 5/2^-$) were observed; spectroscopic factors were measured for most states. A ^{36}S$(n,\gamma)^{37}$S thermal neutron-capture study [18] populated states up to the one-neutron separation energy [4303.58(9) keV]; all observed states were assigned J^π values. The 646- and 1397-keV excited states were observed in the ^{37}P β-decay study of Dufour *et al.* [20].

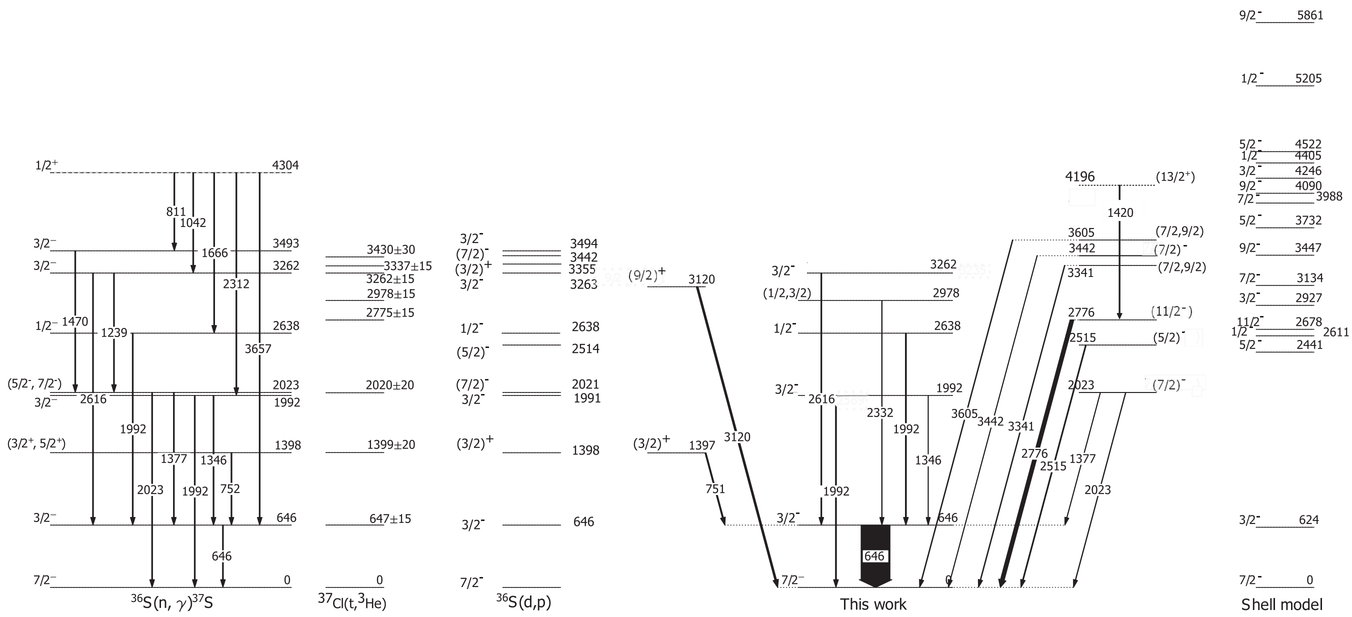

FIG. 5. A comparison of the level schemes from the ^{36}S$(n,\gamma)^{37}$S thermal neutron capture study [18], the ^{37}Cl$(t,\,^3$He$)^{37}$S reaction [17], the ^{36}S$(d,\,p)^{37}$S nucleon-transfer study of Thorn *et al.* [19], and the proposed level scheme from the present work. The states identified by Thorn *et al.* are shown with energies and J^π values taken from the evaluation of Cameron *et al.* [21]. The results of sd-pf $0\hbar\omega$ shell-model calculations are also included. J^π values of the levels based on the present work, where previously established, have been taken from the evaluation of Cameron *et al.* [21]. Other proposed spins and parities are based on the present work. Energies are in units of keV. See text for details.

In the ^{36}S(d, p)^{37}S one-neutron transfer reaction [19], the ground state is populated in $l = 3$ neutron transfer with a spectroscopic strength of $(2j+1)\mathrm{S} = 6.2$ and this is consistent, within the normal uncertainties associated with a distorted wave Born approximation (DWBA) analysis, with a description of the ^{37}S ground state in terms of a ^{36}S ground-state core with a neutron occupying the $1f_{7/2}$ orbital outside the core. Similarly, most of the $2p_{3/2}$ neutron-transfer strength, $(2j+1)\mathrm{S} = 2.6$, is located in the 646-keV $J^\pi = 3/2^-$ first excited state while, for $2p_{1/2}$ neutron transfer, most of the strength, $(2j+1)\mathrm{S} = 1.5$, lies in a single state at an excitation energy of 2638 keV. As will be seen later, the results of shell-model calculations indicate that about 20% of the wave function of the first excited $J^\pi = 3/2^-$ state corresponds to the coupling of a $1f_{7/2}$ neutron to the first excited $J^\pi = 2^+$ state of the ^{36}S core, and this component cannot, of course, be populated in a direct one-neutron transfer process. The relatively strong population of the non-yrast 646-keV $J^\pi = 3/2^-$ first excited state in the present work is consistent with single-neutron transfer playing an important role. However, the 2638-keV ($J^\pi = 1/2^-$) state is not particularly strongly populated here, contrary to the observed strength in the (d, p) reaction. Of course, the reaction process is undoubtedly much more complex than direct single-neutron transfer. Thus, the relatively strong direct population of the yrast $11/2^-$ state at an excitation energy of 2776 keV cannot be explained in terms of such a process; the structure of the state, as we shall see later, is inconsistent with its population in this simple way.

The thick-target data from a previous ^{36}S + ^{176}Yb γ-γ experiment [26] was revisited. However, there are no coincidences observed between the 646-keV transition and the relatively strong transitions observed here. It is interesting to note here that a similar lack of coincidences was also observed in the same data for transitions in the $N = 21$ isotones, ^{36}P [1] and ^{38}Cl [27]; this may be related to the lifetimes of the populated states. In thick target deep-inelastic and binary-grazing-reaction experimental studies with arrays of Ge detectors, γ-ray transitions are normally observed only for states with lifetimes longer than the slowing-down time of the decaying nucleus in the target material (*circa* 1 ps).

The strong 2776-keV transition was assigned to the decay of the previously identified 2776-keV excited state to the ground state. The structure of the state will now be discussed. There is no previous credible evidence for its population in a direct single-neutron transfer reaction and its strong population here suggests that it is yrast; a tentative J^π value of $11/2^-$ is assigned here, based on the population characteristics of binary grazing reactions and on comparison with the results of shell-model calculations, also presented here. With this proposed assignment, decay to the ground state takes place through an $E2$ transition. The shell-model $11/2^-$ yrast state lies at an excitation energy of 2678 keV. The wave function of the state is dominated (76%) by the configuration,

$$\nu(1d_{5/2})^6(2s_{1/2})^2(1d_{3/2})^4(1f_{7/2})^1 \otimes \pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1.$$

In this configuration, protons, coupled to a J^π value of 2^+, are aligned with the total angular momentum of the odd $1f_{7/2}$ neutron. Of course, there is more than one core configuration with an angular momentum of 2^+. For example, the first 2^+ state of ^{36}S has, as the dominant configuration (90%),

$$\nu(1d_{5/2})^6(2s_{1/2})^2(1d_{3/2})^4 \otimes \pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1,$$

while the dominant configuration (93%) of the second 2^+ state, at a measured excitation energy of 4575 keV, is

$$\nu(1d_{5/2})^6(2s_{1/2})^2(1d_{3/2})^4 \otimes \pi(1d_{5/2})^6(2s_{1/2})^0(1d_{3/2})^2.$$

The state at 2776 keV was previously populated in the ^{37}Cl(t, ^{3}He)^{37}S charge-exchange reaction [17]; here we propose that population occurs through the pickup of a $2s_{1/2}$ proton from the ^{37}Cl ground state and the transfer of a neutron to the empty $1f_{7/2}$ shell. The observed population in the (t, ^{3}He) reaction provides additional evidence in support of the proposed assignment. The state was, somewhat surprisingly, observed in one of the three published (d,p) neutron transfer studies [28]. If the state has the suggested configuration, it would appear that a compound nucleus process, rather than a direct one-step reaction, might be responsible for population of the state. The ^{36}S target used in the (d,p) experiment was enriched only to 62% and contained relatively large admixtures of other elements. No yield information or proton angular distributions were given for the state. Thus, the evidence for population and, in particular, population in a direct reaction process, is very weak.

Following on from the above discussion of the $11/2^-$ state, it is instructive to identify the component of the wave functions of other states which corresponds to a $1f_{7/2}$ neutron coupled to the first $J^\pi = 2^+$ state of the ^{36}S core at 3290 keV. Figure 6 shows the percentage of the wave function which corresponds to this coupling for the $J^\pi = 3/2^-, 5/2^-, 7/2^-, 9/2^-$, and $11/2^-$ states of ^{37}S. More exactly, the figure shows the contribution of the component

$$\nu(1d_{5/2})^6(2s_{1/2})^2(1d_{3/2})^4(1f_{7/2})^1 \otimes \pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1$$

to the total wave function of the state, with the two unpaired protons coupled to a J^π value of 2^+. The shell-model calculation here was performed using the NUSHELLX code [25] with the SDPF-U effective interaction. As expected, there is a larger distribution in energy of strength for the lower-spin members of the multiplet, which reflects the higher density of these states. It may be seen from Fig. 6, that the $11/2^-$ state corresponds, to a good approximation (76% of the total wave function), to the coupling of a $1f_{7/2}$ neutron to the first 2^+ state of the ^{36}S core. Figure 6 also shows the excitation energies of the multiplet of shell-model states with the largest component corresponding to the coupling of a $1f_{7/2}$ neutron to the first 2^+ state of the ^{36}S core together with the proposed experimental counterparts. For the $J^\pi = 7/2^-$ state, most of the predicted strength lies in a state at an excitation energy of 3988 keV, for which there appears to be no nearby experimental counterpart and this state is not included in the figure. The agreement between the experimental and shell-model excitation energies is reasonably good.

The decay characteristics of the $11/2^-$ state of ^{37}S and that of the first 2^+ state of the ^{36}S core will now be compared within

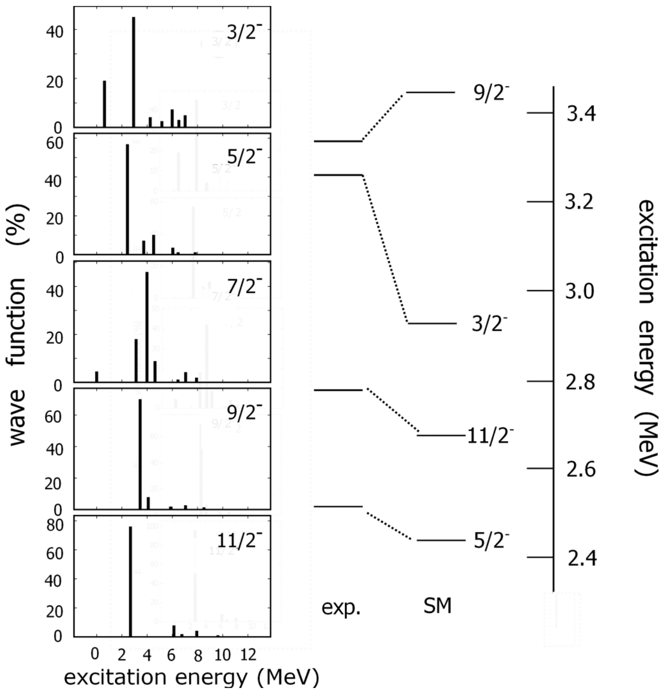

FIG. 6. Percentage of the wave function of the $J^\pi = 3/2^-, 5/2^-, 7/2^-, 9/2^-$, and $11/2^-$ states of ^{37}S which corresponds to the coupling of the odd $1f_{7/2}$ neutron to the first 2^+ state of the ^{36}S core. The excitation energies of the states (excluding the $J^\pi = 7/2^-$ state) with the largest such component in the wave function are shown, together with the proposed experimental counterparts. See text for details.

the context of a simple particle-core coupling model and the shell model. Using the formalism of Rose and Brink [29] [Eq. (4.7)], it can be shown that, in a pure particle-core configuration, the ratio of $B(E2)$ values in ^{37}S and in ^{36}S is given by

$$B(E2; 11/2^- \rightarrow 7/2^-)/B(E2; 2^+ \rightarrow 0^+) = [E_\gamma(2^+ \rightarrow 0^+)/E_\gamma(11/2^- \rightarrow 7/2^-)]^4.$$

The $B(E2)$ ratio, based on the measured transition energies, is 1.98. The ratio, based on the results of shell-model calculations of $B(E2)$ values, is 1.49, in reasonable agreement with that calculated from a simple particle-core model. Here, it is worth commenting that the results of shell-model calculations show that the 2678-keV state is not a pure "particle-core" coupled state; the component in the wave function corresponding to an unpaired $1f_{7/2}$ neutron coupled to the first $J^\pi = 2^+$ state of the ^{36}S core accounts for 76% of the total wave function.

The other states populated in the present work will now be discussed. For each of the states, Table II presents the measured excitation energies based on the present work, the accepted J^π values based on the evaluation of Cameron et al. [21], and proposed J^π values (where these have not previously been established or where there is disagreement with the accepted value) based on the observed γ-ray decay characteristics of states in the present work. In addition, the excitation energy of the corresponding shell-model states, the shell-model J^π value, the main components of the shell-model wave function, and the percentage contributions of the main components are given. The final two columns of the table present the shell-model values of the single-neutron spectroscopic factor, based on calculations using the NUSHELLX code [25], and the experimental value from the ^{36}S(d, p)^{37}S one-neutron transfer reaction studied by Thorn et al. [19]. For the 3442-keV state, the experimental spectroscopic factor was not determined by Thorn et al. and the quoted value comes from the work of Eckle et al. [30]. J^π values based on the present work are made on the assumption that γ-ray decay preferentially takes place by $E1$, $M1$ or $E2$ transitions.

The 646-keV state has a firmly established J^π value of $3/2^-$. The measured (d,p) spectroscopic factor for the state and the shell-model wave function both support the description of the state as having a large component in its wave function corresponding to a $2p_{3/2}$ neutron outside the ^{36}S core. Warburton and Becker [31] have identified levels at 1992, 2023, and 2517 keV as candidates for intruder states. All three states are observed in the present work. The state, observed here at 2515 keV, was populated in $\ell = 3$ neutron transfer in the (d,p) studies of Thorn et al. [19], Piskor et al. [28], and Eckle et al. [30] and was assigned a tentative J^π value of $5/2^-$. The corresponding shell-model state is that at 2441 keV ($J^\pi = 5/2^-$). The component in the wave function of the state, corresponding to a $1f_{5/2}$ neutron outside an inert $Z = 16$, $N = 20$ core, namely,

$$\nu(1d_{3/2})^4(1f_{5/2})^1 \otimes \pi(1d_{5/2})^6(2s_{1/2})^2.$$

corresponds to about 1% of the total wave function, and this is not incompatible with the measured spectroscopic strength of $(2J+1)S = 0.14$ [19]. Consequently, this state is not an intruder state. The main component of the wave function is given in Table II. The positive-parity 1397-keV state with $J^\pi = (3/2)^+$ is also an intruder state, as are those at 3120 keV with $J^\pi = (9/2)^+$ and at 4196 keV with $J^\pi = (13/2^+)$.

The 2638-keV state was previously populated in the (n,γ) reaction [18] and in a number of (d,p) studies [19,28,30]. On the basis of population in $\ell = 1$ transfer in all three (d,p) works and polarization measurements [30], a J^π value of $1/2^-$ was assigned. The state carries most of the $2p_{1/2}$ strength, $(2J+1)S = 1.56$ [19], and the corresponding shell-model state at 2611 keV has a wave function (Table II) consistent with this observation. The 2978-keV level was previously identified in the ^{37}Cl$(t, {}^3$He$)^{37}$S reaction [17]. Here, the gamma-ray decay of the state was observed for the first time and a tentative spin assignment of (1/2, 3/2) is proposed on the basis of the observed decay to the 646-keV $J^\pi = 3/2^-$ state. It was not possible to identify the shell-model counterpart of the state.

While most of the $2p_{3/2}$ neutron strength was identified in (d,p) studies [19,28,30] to reside in the 646-keV state, the state at 3262 keV carries about 10% of the sum-rule limit. A J^π value of $3/2^-$ was previously assigned. The corresponding shell-model state is that at 2927 keV. The main component of the wave function is given in Table II. A significant component of the wave function (45%) corresponds to the coupling of the odd neutron in the $1f_{7/2}$ shell to the first 2^+ state of the ^{36}S core (see Fig. 6).

TABLE II. The main components of the wave functions of the states of ^{37}S populated in the present work calculated using the SDPF-U effective interaction. The listed J^π values (column 2) are those from the Nuclear Data Sheets compilation of Cameron *et al.* [21]. Energy levels not listed by Cameron *et al.* are indicated by the symbol $\star$. Proposed J^π values (column 3) are based on the observed γ-ray decay characteristics of the state. Spectroscopic factors, based on experimental measurement and from the results of shell-model calculations using the NUSHELLX code [25], are also presented. See text for details.

E (keV)	J^π (NDS)	J^π	E(SM) (keV)	J^π (SM)	SM main component of wave function	%	S(SM)	S(exp)
0	$7/2^-$		0	$7/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$		0.86	0.77
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^2$	70		
646	$3/2^-$		624	$3/2^-$	$\nu(1d_{3/2})^4(2p_{3/2})^1$		0.75	0.65
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^2$	63		
1397	$(3/2)^+$				Intruder state			
1992	$3/2^-$				Intruder state			
2023	$(7/2)^-$				Intruder state			
2515	$(5/2)^-$		2441	$5/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$		0.015	0.02
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1$	70		
2638	$1/2^-$		2611	$1/2^-$	$\nu(1d_{3/2})^4(2p_{1/2})^1$		0.88	0.77
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^2$	75		
2776		$(11/2^-)$	2678	$11/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$			
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1$	76		
2978		$(1/2, 3/2)$			Shell-model counterpart uncertain			
3120	$(9/2)^+$				Intruder state			
3262	$3/2^-$		2927	$3/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$		0.20	0.15
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1$	45		
3341*		$(7/2, 9/2)$	3447	$9/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$			
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^1(1d_{3/2})^1$	78		
3442	$(7/2)^-$	$(7/2, 9/2)$	3134	$7/2^-$	$\nu(1d_{3/2})^4(1f_{7/2})^1$		0.07	0.02
					$\otimes\pi(1d_{5/2})^6(2s_{1/2})^0(1d_{3/2})^2$	34		
3605	$(1/2^-, 3/2^+)$	$(7/2, 9/2)$						
4196*		$(13/2^+)$			Potential yrast intruder			

The 3341-keV state was previously observed in the ^{37}Cl(t, ^{3}He)^{37}S charge-exchange reaction [17], but it was not included in the evaluation of Cameron *et al.* [21]. It decays directly to the ground state and this suggests J values of (7/2, 9/2). The proposed shell-model counterpart is that at 3447 keV, with $J^\pi = 9/2^-$. This state is a member of the multiplet of states corresponding to the coupling of a $1f_{7/2}$ neutron to the first excited $J^\pi = 2^+$ state of the ^{36}S core (see Fig. 6). The shell-model wave function would suggest population in the ^{37}Cl(t, ^{3}He)^{37}S reaction through the pickup of a $2s_{1/2}$ proton and the transfer of a $1f_{7/2}$ neutron.

The 3442-keV state was previously assigned a J^π value of ($7/2^-$) based on the results of two (d,p) experiments. Both Piskor *et al.* [28] and Eckle *et al.* [30] have assigned an orbital angular momentum quantum number of $\ell = 3$ to neutron transfer to the state and the polarization measurements of Eckle *et al.* favor a J^π value of $7/2^-$, rather than $5/2^-$. The proposed corresponding shell-model state is that at 3134 keV with $J^\pi = 7/2^-$. The measured spectroscopic strength $(2J+1)S = 0.16$ [30] is in reasonable agreement with the predictions of the shell model; the component of the wave function of the state corresponding to a single $1f_{7/2}$ neutron outside a closed neutron and proton core corresponds to 16% of the total wave function.

The 3605-keV state, previously assigned a J^π value of ($1/2^-$, $3/2^+$), based on population in the (d,p) reaction with transfer orbital angular momentum quantum number of $\ell = 1$ or 2, is observed in the present work to decay to the ground state and this is not consistent with the earlier possible spin assignments. The electromagnetic decay characteristics would suggest a spin value of (7/2, 9/2). The closest lying shell-model $1/2^-$ state is at 4405 keV, which is unlikely to be the corresponding state and, of course, positive parity intruder states are not within the model space of the calculations. It would therefore appear that either there is a disagreement in relation to the spin assignment of this state or that the state observed here is not that populated in the (d,p) study.

The state tentatively proposed at an excitation energy of 4196 keV is a possible candidate corresponding to the coupling of the odd neutron in the $1f_{7/2}$ orbital to the $J^\pi = 3^-$ state of the ^{36}S core at an excitation energy of 4193 keV [32]. On this basis, a tentative J^π value of $13/2^+$ is proposed. The apparent success of this simple description of the state adds confidence to its inclusion in the level scheme. However, it is again emphasized that γ-γ coincidence measurements are required to confirm the inclusion of the 4196-keV state in the level scheme of ^{37}S.

For the seven excited states of ^{37}S for which a direct comparison was proposed here between shell-model predictions and experiment, the root-mean-square deviation between experimental and shell-model excitation energies is about 180 keV. The most significant deviations are those corresponding to the 2927-keV ($J^\pi = 3/2_2^-$) and 3134-keV ($J^\pi = 7/2_2^-$) shell-model states for which the differences in excitation energies are about 300 keV. Such differences between experiment and theory for states with excitation energy in excess of about 2.5 MeV are not unusual and are generally considered as reflecting reasonable agreement.

IV. SUMMARY

Binary grazing reactions have been used to populate states of ^{37}S. The level scheme which was constructed was compared with the results of large-scale state-of-the-art shell-model calculations using the NATHAN code [23,24] with the SDPF-U effective interaction [22] and good agreement was obtained. The strongly excited state at 2776 keV was tentatively assigned a J^π value of $11/2^-$. The structure and electromagnetic decay properties of the state have been discussed in terms of the coupling of an odd neutron in the $1f_{7/2}$ shell to the first 2^+ state of the ^{36}S core. The other members of the multiplet of states corresponding to the same coupling have been discussed and their experimental counterparts identified. A hitherto unobserved excited state at 4196 keV with a structure corresponding to the coupling of the first $J^\pi = 3^-$ state of the ^{36}S core to the odd $1f_{7/2}$ neutron is tentatively proposed.

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