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Abstract

High-spin states in ^{39}Ar were populated using the ^{27}Al(^{14}C, pn) reaction at 25.6 MeV. The de-exciting γ rays were measured with the FSU γ detector array along with evaporation protons in a Si E-ΔE telescope. The known high-spin level scheme was extended up to over 11 MeV with a dozen new levels above the neutron decay threshold. The decay pattern appears somewhat atypical for heavy-ion fusion-evaporation reactions. The structure of ^{39}Ar is discussed in terms of the new FSU cross-shell *spsdpf* interaction fitted to a wide range of nuclei. This interaction has proved quite successful in accounting for the level scheme of ^{39}Ar, including the previously suggested fully aligned $\pi f_{7/2} \otimes \nu f_{7/2}$ $17/2^+$ state and previously discovered analogs of the lowest states in ^{39}Cl.

I. INTRODUCTION

Shell structure has provided the most fruitful framework for understanding the microscopic structure of many nuclei, but nuclear shell structure is not as pronounced as that of the atoms which inspired it. Another source of richness or complication in nuclei is the interaction between the filling of the shells for protons and neutrons. This has lead to the evolution of shell structure with neutron number. The nucleus ^{39}Ar with 18 protons and 21 neutrons straddles the $N = 20$ shell gap at doubly magic ^{40}Ca and provides an experimentally accessible case to further explore the usefulness of shell structure.

^{39}Ar lies in an ideal position for single-particle transfer reactions between two stable Ar isotopes. Considerable structural information on this nucleus came from several ^{38}Ar(d, p) reactions [1–4]. Neutron angular momentum transfer values ℓ and spectroscopic factors (s.f.) were measured for a number of mostly lower-spin states, but whether the neutron spin adds or subtracts from ℓ is not well determined in many of these cases, leading to a J ambiguities. ^{39}Ar was also investigated with the ^{40}Ar(p, d) pickup reaction [5]. Not surprisingly a relatively large s.f. of $C^2S = 2.4$ was measured to the $7/2^-$ ground state (g.s.) with an ℓ value of 3, indicating pickup of one of the two $0f_{7/2}$ neutrons in ^{40}Ar. The largest s.f. was to the lowest positive-parity state in ^{39}Ar at 1517 keV ($3/2^+$, $\ell = 2$, s.f. $= 3.2$). The other relatively large s.f. was to the 2358 keV $1/2^+$ state ($\ell = 0$, s.f. $= 1.1$). The latter 2 indicate neutron pickup from the $1s_{1/2}$ and $0d_{3/2}$ orbitals leaving the two $0f_{7/2}$ neutrons coupled to spin 0. Another neutron pickup experiment ^{40}Ar(^{3}He, α) [6] reported relative s.f. in general agreement with the (p, d) reaction. This reaction also identified states at 9075 and 9463 keV as the isobaric analogs of the g.s. and first excited state of ^{39}Cl.

Most light-ion transfer reactions preferentially populate relatively low-spin states. An interesting exception is the (α, d) reaction which preferentially populates higher-spin states, most strongly those in which the spins of the transferred protons and neutrons are fully aligned, as in the deuteron g.s. This is clearly seen in two ^{37}Cl(α, d) reaction studies [7, 8]. In both the highest cross section is to a state at 5.54 MeV populated with a clear $\ell = 6$ angular momentum transfer, consistent with a full aligned p-n configuration. The other selectively populated states are reached by $\ell = 4$, 6, or a mixture of 4 and 6. In contrast, the ^{37}Cl(^{3}He,p) reaction [9] shows a very different selectivity even though it transfers the same proton plus neutron combination. This reaction favors low-spin states and the most strongly populated one is the $3/2^+$ isobaric analog of the g.s. of ^{39}Cl at 9.078 MeV, confirming the identification of the analog state from the ^{40}Ar(^{3}He,α) reaction.

Heavy-ion fusion-evaporation reactions bring the most angular momentum to the compound nucleus because of the high momentum of the projectile and the higher cross section for peripheral collisions and light particle evaporation removes relatively little spin. Gamma decay strongly favors the highest energy transitions possible without changing spin by more than 2. The result is a strong preference for population of the lowest states of a given spin - the so-called yrast states. The yrast states in ^{39}Ar were preferentially populated up to the stretched $17/2^+$ state in a survey of several heavy- ion fusion-evaporation reactions [10] and lifetimes of this high-spin decay sequence were measured in similar reactions [11].

Our goal in the present project was to use a modern Compton-suppressed γ detector array to further explore the high-spin structure of ^{39}Ar experimentally and to interpret the results with a new more comprehensive cross-shell effective interaction.

II. EXPERIMENT AND RESULTS

Higher-spin states in ^{39}Ar were populated in the ^{27}Al(^{14}C, pn) reaction using a 25.6 MeV beam from the Florida State University FN tandem accelerator. The self-supporting ^{27}Al target was 100 μg/cm^2 thick. A 20 μm thick Au foil was placed after the target to prevent beam particles from reaching the Si E-ΔE telescope placed at 0° relative to the beam. The telescope which subtended about 2 sr of solid angle was used to identify the evaporated light ions. γ-rays in coincidence with protons were detected in an array of 10 high-purity Ge detectors. Three were 4-crystal "Clover" spectrometers and the remaining 7 were single crystals. All were Compton suppressed. They were distributed at angles of 35°, 90°, and 145° relative to the beam direction. The signals were digitized with an XIA Pixe-16 system with custom logic to perform Compton suppression and particle-γ coincidence logic. The proton-γ-γ and γ-γ coincidence data were sorted into two-dimensional symmetric and anti-symmetric arrays for gating to construct the level scheme and to determine Directional Correlation of Oriented nuclei (DCO) ratios to infer spin changes, respectively. The formula used is

$$R_{DCO} = \frac{I_{\gamma 2}(at\, 135^0\, gated\, by\, \gamma_1\, at\, 90^0)}{I_{\gamma 2}(at\, 90^0\, gated\, by\, \gamma_1\, at\, 135^0)}, \quad (1)$$

where, $I_{\gamma 2}$ denotes the intensity of the γ transition whose multipolarity is to be determined and γ_1 is the gating transition.

A list of these DCO ratios is given in Table I. They help to firm up spin assignments of the lower states, but, unfortunately, the statistics were not adequate to extract reliable DCO ratios for the high-lying newly-observed states.

As mentioned earlier heavy-ion fusion-evaporation reactions selectively populate higher-spin states and the present reaction is no exception. A significant number of new γ transitions have been observed to feed into the two previously known highest-spin states, $15/2^+$ and $17/2^+$. An example of the γ-γ coincidence spectrum is shown in Figure 1. The level and decay scheme of ^{39}Ar as deduced from the present and previous work is shown in Figure 2. State energies and decay information for the newly- observed structures are listed in Table II.

III. DISCUSSION

Most of the newly observed γ transitions in Figure 2 decay into the lowest $15/2^+$ and $17/2^+$ states, the highest-spin states previously known. While favoring the yrast states is expected in heavy-ion fusion-evaporation experiments observed by electromagnetic decays, the pattern is not so typical. The feeding distribution is shown in Figure 3. Eight decays have been observed into the very likely yrast $17/2^+$ state, with no single line dominating. By contrast, decay of this $17/2^+$ state to the also likely yrast keV $15/2^+$ one (992 keV) does dominate the 5 transitions feeding to the $15/2^+$ state. Below this only one feeding transition has been observed into the $13/2^+$ and $11/2^-$ states in the present experiment. This funnel-like feeding pattern will be discussed in the context of theoretical calculations later.

The simplest structures that can form in ^{39}Ar, which has an even number of protons and one neutron beyond a filled sd shell, involve the odd neutron in any of the 4 orbitals of the fp shell. Indeed, the ground state has the quantum numbers of the $0f_{7/2}$ orbital and the first excited state, that of the $1p_{3/2}$ one. However, the second excited state has positive parity, implying excitation of an additional nucleon across the $N = 20$ gap (1p1h). Further structure possibilites come from the recoupling of two $d_{3/2}$ protons from 0 to 2, which can add or subtract to that of the fp particle, giving a range of states from $3/2^-$ to $11/2^-$. An indication of the energy cost of recoupling these two protons comes from the 2^+ first excited state of ^{38}Ar, which lies at 2167 keV. This energy is comparable to the 2470 keV centroid of the $f_{7/2} \otimes 2$ multiplet in ^{39}Ar.

To understand the structure of ^{39}Ar further, one needs to know the energy cost of these different modes of excitation. Microscopic shell model calculations can provide a better answer, but ^{39}Ar is outside the model space for which the best established sd interactions (USD [12], USDA, and USDB [13]) apply. Fortunately, our group has recently performed a comprehensive fit to many known states with a few particles outside the sd shell [14]. A few of the states in ^{39}Ar were included in the 270 used in the overall fit. These are the 1267, 1517, 2093, 2358, 2433, 2481, and 5533 keV levels. As expected, the calculations show that the g.s. is very nearly a pure $\nu f_{7/2}$ one. While the structure of the first excited state is dominated by the $\nu p_{3/2}$ orbital, it is predicted not to be completely pure, with 16% $\nu f_{7/2}$ admixture, suggesting that the energy cost of recoupling 2 $d_3/2$ protons is comparable to the $1p_{3/2}$ to $0f_{7/2}$ spacing.

A comparison of the calculated energies using the FSU interaction with experimental ones below 5 MeV is shown graphically in Figure 4. For clarity the experimental levels are divided by parity and the theoretical ones, by the number of particles outside and number of holes inside the sd shell relative to the dominant configuration of the g.s. of ^{39}Ar. There is good agreement up to 3 MeV between the negative-parity experimental states and the calculated ones with 0p0h configuration. States above 3 MeV and 2p2h ones will be discussed later. As seen experimentally from the (p, d) pickup reaction [5], 1p1h $\pi = +$ states begin relatively low at 1.5 MeV in this near-closed-shell nucleus. Good agreement is also seen here up through the $15/2^+$ state. After identification of the experimental negative-parity states with theoretical ones, no 0p0h predicted states were left within 500 keV of the experimental 2524 keV level with possible J^π values of $5/2^-$, $7/2^-$, $7/2+$, or $9/2^-$. A close energy match (2672 keV, $7/2^+$) does exist in the 1p1h ones, so the experimental state is shown on the positive-parity side of the level scheme. Again, there are no possible unassigned predicted 0p0h states below 4391 keV to match the 3062 or 3160 keV (both $5/2^-$ or $7/2^-$) levels. The lowest two 2p2h states at 3036 keV ($5/2^-$) and 3058 keV ($7/2^-$) do provide close energy matches. The predicted 0p0h 3945 keV $9/2^-$ level provides a reasonable energy match for the experimental 3748 keV state. Although the predicted 2p2h $9/2^-$ level lies another 100 keV higher, its identification with the 3748 keV level cannot be ruled out because of the observed 3748 $\rightarrow$ 3160 keV γ decay and the likely correspondence of the 3160 keV state with the 2p2h 3058 keV $7/2^-$ one.

One can see clearly from Figures 2 and 4 that the 0p0h configuration is yrast (lowest energies for a given spin) up through 11/2 where the $\pi = +$ states lie an MeV or so higher. Above this, the only way to achieve higher spin in the 0p0h configuration is to promote protons from the deep $0d_{5/2}$ orbital up to $0d_{3/2}$ and recouple protons up to spin 4. This energy cost is significantly higher than that of promoting another particle into the $f_{7/2}$ orbital. The lowest calculated $13/2^-$ 0p0h state lies at 8425 keV, compared to 3991 keV for the lowest calculated $13/2^+$ 1p1h level.

Direct transfer reactions, especially the ^{38}Ar(d,p) reaction [1–4], provide an insight into the microscopic structure of ^{39}Ar. A table of (d,p) spectroscopic factors (s.f.) calculated using the FSU interaction is given in Table III. Very small s.f. are not listed because these are too sensitive to small details of the calculated wavefunctions and could never be clearly distinguished experimentally from multi-step processes. The few measured s.f. listed in the table do agree fairly well with the calculated ones. Experimental ones are generally lower, as has been seen in Ref. [14]. A number of s.f. have been reported for higher states, but their J values have not been established well and the present experiment cannot add any further information because it populated mainly yrast and near-yrast states. The FSU calculations suggest strong $1p_{1/2}$ structures at 2585 and 3973 keV (Table III), but no $1/2^-$ states are uniquely assigned in the current NNDC overall compilation. Also the relatively large s.f. predicted for the state at 6229 keV suggests a strong $0f_{5/2}$ component in the wavefunction. Intriguingly, measured $\ell = 3$ s.f. of 0.40 (assuming $J = \ell - 1/2$) are reported for each of two states at 6057 and 6278 keV, but even the sum of these s.f. does not approach the predicted value of 4.91.

Somewhat uniquely among direct reactions, the (α, d) one strongly favors higher-spin states, especially those with fully-aligned proton-neutron structures. In two ^{37}Cl(α, d) investigations [7] [8] the most strongly populated state has an $\ell = 6$ angular distribution and lies at 5.54 or 5.544 MeV with a likely spin-parity of $17/2^+$. This surely corresponds to the 5533 keV state in the yrast γ-decay sequence, as these papers already suggested by comparison to a previous fusion-evaporation measurement [10]. Both papers also reported a relatively strongly populated level at 5.23 or 5.261 MeV which is very likely the 5247 keV experimental one whose γ decay has been newly observed in the present work. Spins of $11/2^+$ or $13/2^+$ were suggested for this state. Two higher states were observed in the experiment with highest α beam energy ([7]) at 5.81 and 6.23 MeV with ℓ values of 6 and 4 + 6, respectively. A γ decay line has been newly observed from the 5812 keV level, but no decays from likely candidates for the 6.23 MeV state were seen in the present experiment.

The FSU cross-shell interaction was not fitted to any states whose configurations involved 2p2h outside the dominant g.s. configurations. Two 1p1h states in ^{38}Ar, 4^- (4480 keV) and 5^- (4586 keV), were included in the fit. Before discussing 2p2h configurations further in ^{39}Ar, it is worth testing how well such calculations work in a nearby nucleus whose experimental structure is better known. Some results for ^{38}Ar are shown in Figure 5. It can be seen that the 0p0h calculations reproduce the excitation energies of the first two 2^+ states relatively well, but the first 0^+ and 4^+ levels are predicted much too high. This reflects the same issue mentioned earlier for ^{39}Ar – namely the very high energy cost of promoting protons from $0d_{5/2}$ to $0d_{3/2}$ in nuclei near the top of the *sd* shell. The 2p2h calculations reproduce the second 0^+ and first 4^+ states much better, as well as the first 6^+ and 8^+ ones in ^{38}Ar.

An extended comparison of the excited states of ^{39}Ar with shell model calculations using the FSU interaction is shown in Figure 6. This figure focuses on the newly observed experimental states which are mainly the higher-spin ones. For clarity, the yrast states are emphasized, while the near-yrast states are displaced a little. Where spins are not known, this division is based on the intensity of the γ decays. A similar convention is used for the theoretical states where yrast states for each parity separately are emphasized. As mentioned before, the yrast sequence starts with the $7/2^-$ g.s. (not shown) and continues through the $9/2^-$ and $11/2^-$ ones. These correspond relatively well to the calculated 0p0h ones. Above this, the $13/2^+$ 1p1h state becomes yrast and lies about 4 MeV below the calculated $13/2^-$ 0p0h one (not observed). The 1p1h configuration remains yrast up through the $19/2^+$ state. The calculations predict a big jump of 4.5 MeV up to the $21/2^+$ state. The 2p2h $11/2^-$ state is over 2 MeV above the 0p0h one and does not become yrast until the $21/2^-$ state which is about 2.5 MeV below the 1p1h $21/2^+$ level.

As mentioned above, the 5247, 5533, and 5813 keV experimental states are the ones seen strongly in the (α, d) reaction. There are good matches for them among the 1p1h calculated states with spins of $13/2^+$, $17/2^+$, and $15/2^+$, respectively. These match the assigned spins for the highest two and are within the experimentally possible range for the

5247 keV state. The $17/2^+$ state is yrast in the calculations. It is clearly special in both the present reaction where the largest number of the newly observed transitions decay to it it and in the (α, d) reaction where it has the largest formation cross section. Such states have been discussed in other upper sd shell nuclei where a fully aligned $\pi f_{7/2} \otimes \nu f_{7/2}$ configuration has been proposed on varying evidence. The significance of the fully aligned or stretched configuration is that it provides the maximum spin of 7 because it is not limited by the Pauli principle as is that of a pair of like particles. Such a state can be reached in the (α, d) reaction by transfer of a deuteron in its $J = 1$ g.s. It is also unique in that promotion of an extra neutron above the $N = 20$ shell gap generally requires less energy than for a proton in nuclei with neutron excess. Therefore one signature of a fully aligned $\pi f_{7/2} \otimes \nu f_{7/2}$ state is nearly equal proton and neutron occupancies. The calculated occupancies for the $\pi f_{7/2}$ and $\nu f_{7/2}$ orbitals are 0.86 and 1.10, respectively, for the 5309 keV $17/2^+$ state. The next highest $\pi f_{7/2}$ occupancies among nearby higher spin states are 0.60 for the 5056 keV $13/2^+$ and 0.56 keV for the 5991 keV $15/2^-$ states which likely correspond to the 5247 and 5813 keV experimental ones which are also selectively populated in the (α, d) reaction, but with a lower cross section.

Above the 5533 keV $17/2^+$ state there are enough near yrast states with 1p1h or 2p2h to account for the observed ones up to about 9 MeV, but matching individual ones cannot be accomplished with any degree of certainty. Perhaps most surprising is that no experimental state stands out as a likely match for the yrast $19/2^+$ state predicted at 7622 keV. None of the decays of the possible experimental states in this region is particularly strong, suggesting that the $19/2^+$ yrast state is not strongly populated in this reaction, unlike the other yrast levels below it. The two strongest feedings into the $17/2^+$ state come from the 8706 and 9188 keV levels, two MeV above the predicted yrast $19/2^+$ state. There is a predicted $19/2^+$ non-yrast state close in energy to the 8706 keV level, but no $19/2^+$ one near the 9188 keV experimental state. There are 3 $17/2^+$ predicted states (not shown in Figure 6) between 9001 and 9342 keV which are less likely to correspond to a more selectively populated state. The 10183 and 11302 keV levels are even less likely to correspond to 1p1h states.

We can also explore the role of the predicted 2p2h states. The challenge here is that the first $19/2^-$ state lies about 900 keV above the yrast 1p1h $19/2^+$ level. This 8506 keV $19/2^-$ state is a reasonable energy match for the 8706 keV experimental one. Two more $19/2^-$ states just above it are also possible candidates for the 9024 and 9188 keV experimental levels.

These could be somewhat selectively populated if states populated in the reaction above them are 2p2h configurations. The 2p2h states are predicted to become yrast right above this at 9546 keV ($21/2^-$) and 9586 keV ($23/2^-$). The second predicted $21/2^-$ and $23/2^-$ states make good energy matches for the experimental 10183 and 11132 keV experimental states, but this leaves unexplained why there are no good observed state matches for the predicted yrast $21/2^-$ and $23/2^-$ levels. Besides the larger energy differences, it is less likely that the yrast $21/2^-$ and $23/2^-$ states correspond to the 9024 and 9188 keV experimental levels because their observed decays would be of M2 or E3 character. With the present evidence, it appears likely that states of 2p2h character account for some, or possibly all, of the observed levels above 8500 keV, but detailed correspondences cannot be made with certainty.

Another special group of states is the isobaric analogs of low-lying states in another nucleus with the same A but larger isospin T_Z and T. For example, $T_Z = 3/2$ in ^{39}Ar and the g.s. and all excited states below 9 MeV have $T = 3/2$. $T_Z = 5/2$ for ^{39}Cl and its g.s. and all its lower excited states have $T = 5/2$. The $T = 5/2$ analogs of the $3/2^+$ g.s of ^{39}Cl and of a few excited states have been assigned from the ^{37}Cl(^{3}He,p) reaction [9]. The g.s. analog (J$^\pi = 3/2^+$) was observed at 9.078(9) MeV and the lowest two J$^\pi = 1/2^+$ analogs were reported at 9.463(9) and 11.312(10) MeV. The FSU interaction was not fitted to any states with $T > T_Z$. The lowest J$^\pi = 3/2^+$ $T = 5/2$ state calculated with the FSU interaction in ^{39}Ar lies at 9.030 MeV or 48(9) keV below experiment. The lowest calculated J$^\pi = 1/2^+$ $T = 5/2$ states lie at 9.621 and 10.945 MeV or 158 and 367 keV away from observation. For comparison both the ^{35}Cl(^{3}He, p)^{37}Ar and ^{39}K(d, α)^{37}Ar reactions [15] observed a strong peak maximizing near 0° (characteristic of $\ell = 0$ transfer) at 4.733 or 4.750 MeV, respectively, which is very likely to be the analog of the $3/2^+$ g.s. of ^{37}Cl. Calculations with the FSU interaction predict the lowest $3/2^+$ $T = 3/2$ state in ^{37}Ar at 4.845 MeV, which is about 100 keV above the experimental candidate.

IV. SUMMARY

States in ^{39}Ar were populated in the ^{27}Al(^{14}C, pn) reaction using a 25.6 MeV beam. Protons were detected and identified with a Si ΔE-E telescope centered around 0°, and coincident γ radiation was detected with the Compton suppressed FSU detector array. These data were acquired using an XIA Pixe-16 digital system. Half a dozen new γ transitions were observed connecting previously known lower-lying states, but most of the newly observed decays fed into the two previously known highest spin states of $15/2^+$ and $17/2^+$. Measured DCO ratios confirmed some previously suggested spins, but statistics of the higher-lying transitions were not adequate to definitively determine those multipolarities.

A somewhat atypical γ decay pattern, compared to most heavy-ion fusion-evaporation reactions, was observed. While the 992 keV decay from the yrast $17/2^+$ level dominated the decays into the $15/2^+$ state, 5 weaker decays were newly observed to decay into the latter state. Above this, no single decay dominated feeding into the $17/2^+$ level. Eight decays were observed feeding the $17/2^+$ level with no single one dominating, although 2 lines were each about twice or more stronger than the others. It is not clear whether this is due to any unusual nuclear structure in ^{39}Ar or, perhaps more likely, this experiment has observed the entry or near entry states fed by *pn* evaporation before the electromagnetic decays funnel through the yrast states.

Calculations using the newly fitted comprehensive FSU shell model interaction in the *spsdpf* shells have been performed for ^{39}Ar. There is good agreement between the measured and calculated energies of the states below 3.5 MeV. Because of its proximity to the $N = 20$ shell gap, positive-parity experimental states start at the relatively low energy of 1.5 MeV and are accounted for well by the calculated states with 1p1h (relative to the g.s.) configurations. These become yrast with the 3991 keV $13/2^+$ state and provide good energy matches with the states with most intense γ decays up through the experimental 5533 keV $17/2^+$ level. This is the state most strongly populated in the $^{37}\mathrm{Cl}(\alpha, d)$ reaction.

States calculated with 2p2h configurations start at 3 MeV and provide the best match for the 3062 and 3161 keV experimental states, although they do not become yrast until the $21/2^-$ level predicted at 9546 keV. The 7622 keV $19/2^+$ 1p1h state is predicted to be yrast but no state in this region stands out with a relatively stronger decay intensity. There are an adequate number of relatively high spin states calculated with 1p1h and 2p2h configurations to account for all the states seen experimentally up through the highest at 11132 keV, but individual matching with the theoretical states cannot be made uniquely at present.

A further test of the FSU interaction was made by computing known states in neighboring even-even ^{38}Ar using 0p0h and 2p2h configurations. Good energy matches were found for the g.s. and first 2^+ state with 0p0h structures, while predictions for the excited 0^+ and lowest

TABLE I. Directional correlation of oriented nuclei ratios between the 3 $\Delta J = 1$ transitions and the indicated γ lines. Ratios near unity are expected if the second transition also has $\Delta J = 1$, A ratio near 2 is expected if the second transition has $\Delta J = 0$ or 2.

	Gate (keV)		
Line (keV)	551 keV	993 keV	1341 keV
308	0.97(17)	-	1.02(16)
541	0.95(28)	-	-
551	-	1.04(6)	1.02(5)
1271	2.0 (15)	-	-
1341	0.97(7)	1.01(18)	-

4^+, 6^+, and 8^+ experimental states were over 3 MeV too high. The energies of the latter group of states were reproduced relatively well with 2p2h calculations. The FSU interaction has also reproduced relatively well the energies of several $T = 5/2$ states in ^{39}Ar (analogs of low-lying states in ^{39}Cl) and some (d, p) spectroscopic factors to low-lying states in ^{39}Ar. All of these results suggest that the FSU interaction will be valuable in the interpretation of other nuclear structure in this region.

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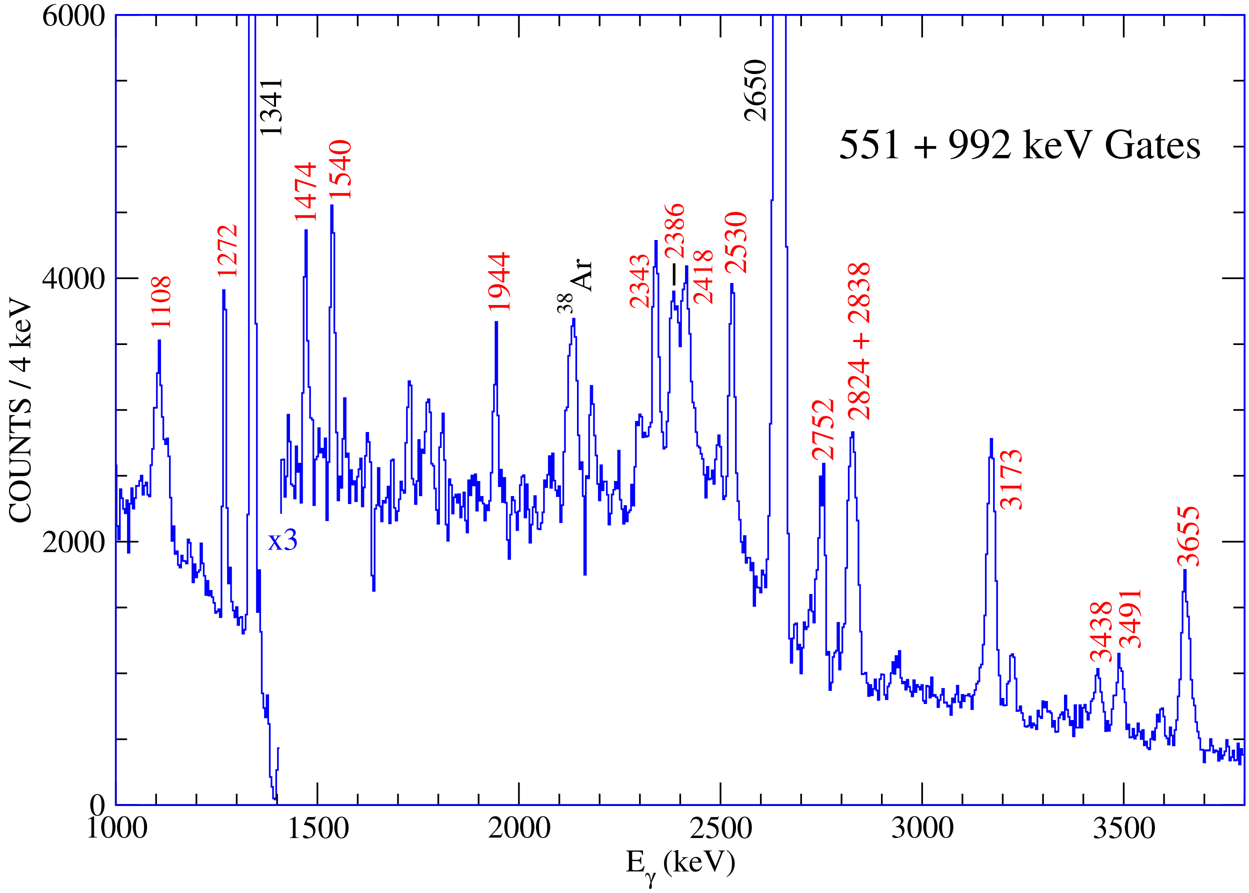

FIG. 1. A portion of the γ spectrum in coincidence with the $15/2^+ \rightarrow 13/2^+$ (551keV) and/or $17/2^+ \rightarrow 15/2^+$ (992keV) decays in ^{39}Ar. Newly observed γ lines are labeled in red while lines from contaminants are labeled by the nucleus. Energies are in keV

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TABLE II. Higher spin states in ^{39}Ar and their decay information.

E_x (keV)	J^π	E_γ (keV)	Rel. Intensity
2342.5 (17)	$9/2^-$	2342.5 (17)	26
2650.1 (12)	$11/2^-$	2649.9 (12)	100
		308.2 (5)	10
3450.7 (20)	$11/2^+$	1108.2 (10)	12
3991.0 (14)	$13/2^+$	1340.6 (8)	84
		540.5 (2)	3
4541.5 (15)	$15/2^+$	550.6 (5)	73
5031 (4)		1580 (3)	2
5247 (4)		1796 (3)	2
5533.4 (20)	$17/2^+$	992.1 (13)	26
5812.6 (21)	$15/2^+$	280.1 (3)	-
		1271.7 (15)	4
6960 (3)		2418 (3)	2
7072 (2)		2530 (4)	2
		1540.2 (19)	2
7380 (3)		2838 (4)	2
7919 (3)		2346 (3)	2
7980 (4)		3438 (4)	1
8285 (3)		2752 (3)	2
8357 (4)		2824 (3)	3
8706 (3)		3173 (2)	8
9024 (4)		3491 (3)	1
9188 (3)		3655 (3)	5
10183 (5)		1474 (3)	3
11132 (5)		1944 (3)	2

TABLE III. ^{38}Ar(d,p) spectroscopic factors $(2J+1)C^2S$ calculated using the FSU interaction are compared with some measured ones where the J value is well established.

J^π	E_{thy}(keV)	E_{exp}(keV)	$(2J+1)C^2S$ thy	$(2J+1)C^2S$ exp
$7/2^-$	0	0	6.71	5.0
$3/2^-$	1186	1267	2.85	2.0
$3/2^-$	2226	2433	0.40	0.10
$7/2^-$	2446	2481	0.97	0.67
$1/2^-$	2585		0.58	
$1/2^-$	3973		1.39	
$3/2^-$	4329		0.36	
$5/2^-$	6229		4.91	

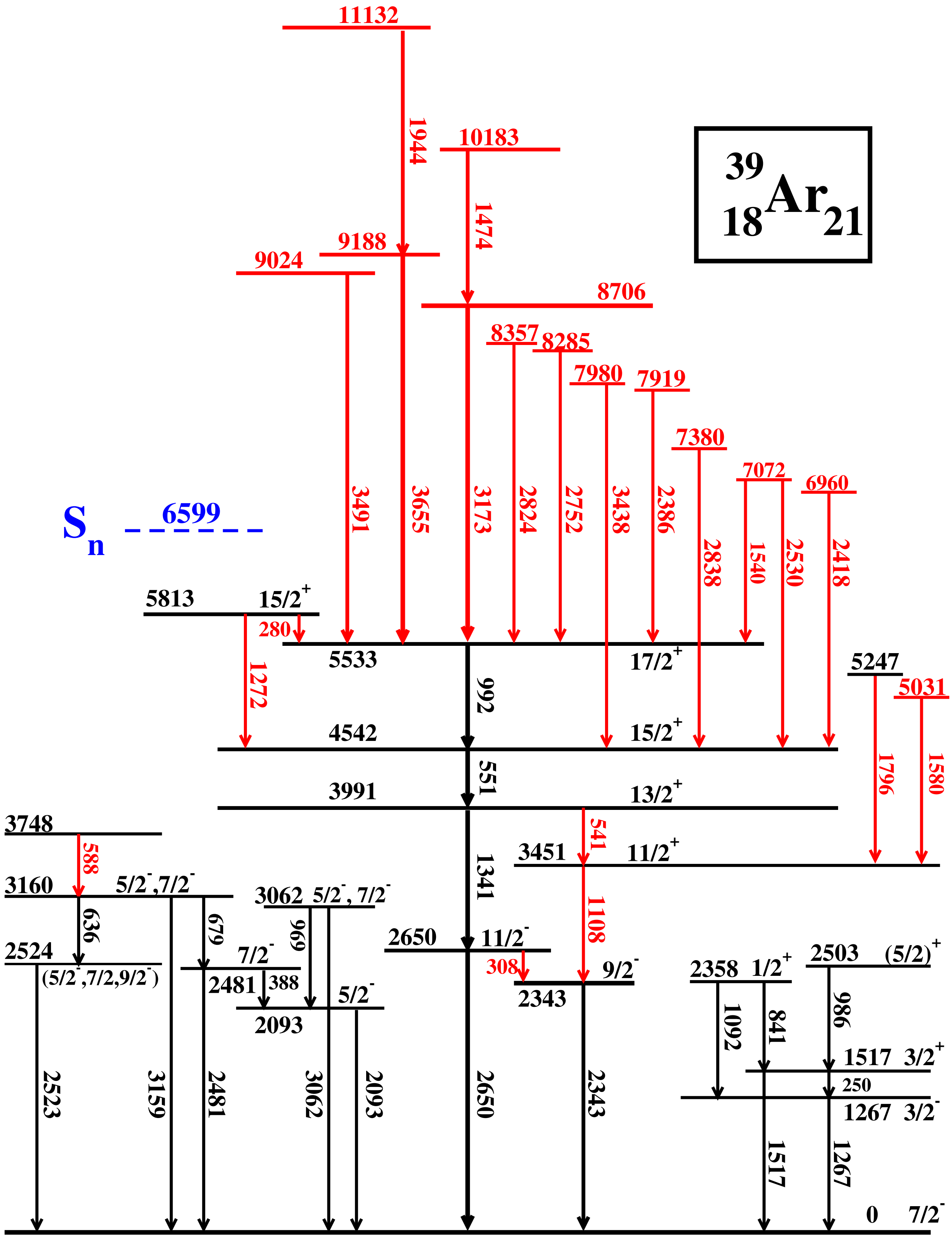

FIG. 2. The level and decay scheme of ^{39}Ar as deduced from the present and previous work. Newly observed γ transitions and excited states are shown in red. Energies are in keV.

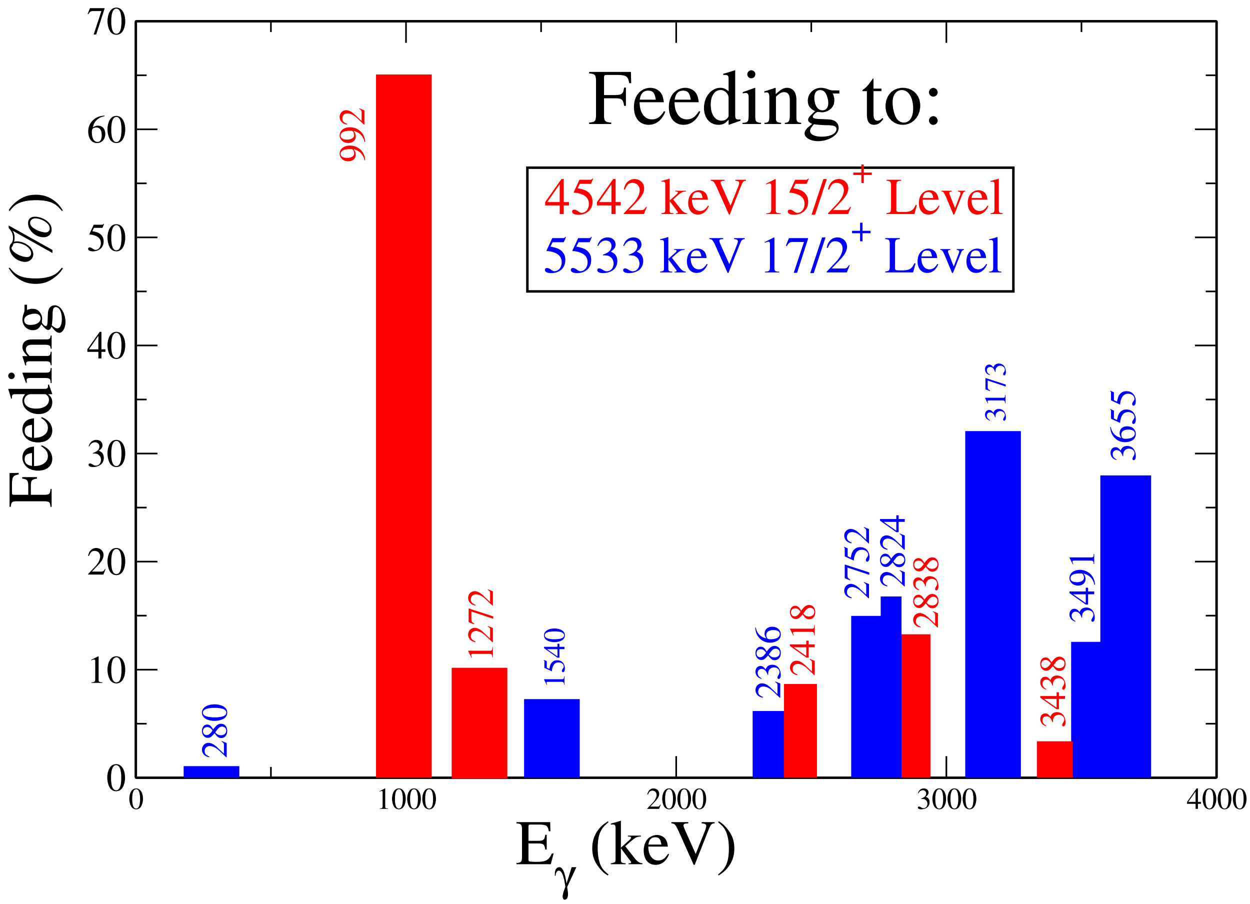

FIG. 3. The distribution of intensities of the γ lines feeding into the 4542 and 5533 keV states.

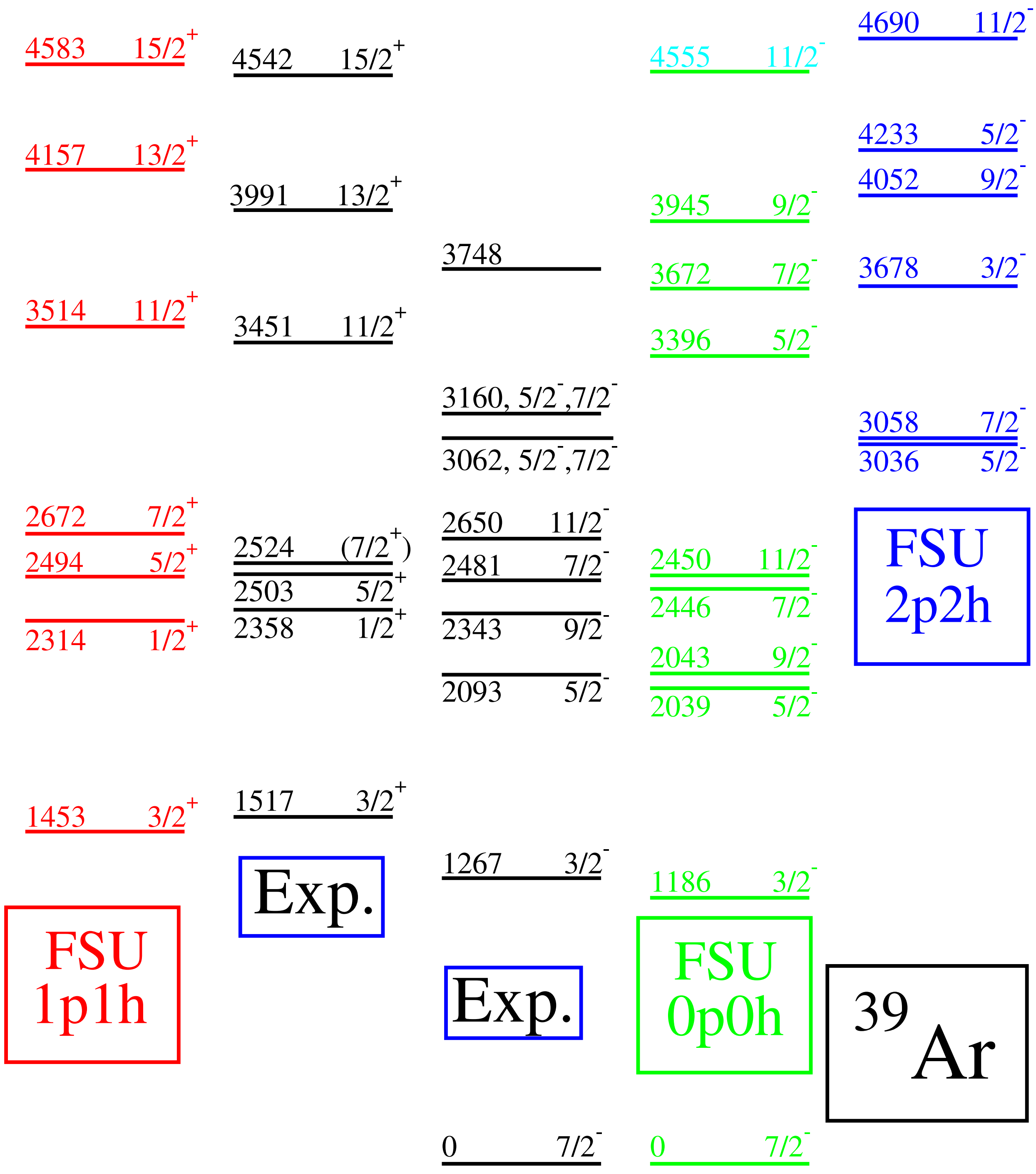

FIG. 4. A comparison of the lower experimental energy levels in ^{39}Ar with the results of shell model calculations using the FSU cross-shell interaction. The calculated levels are separated by the number of additional particles outside the *sd* shell and holes inside the *sd* shell relative to the dominant configuration of the g.s.

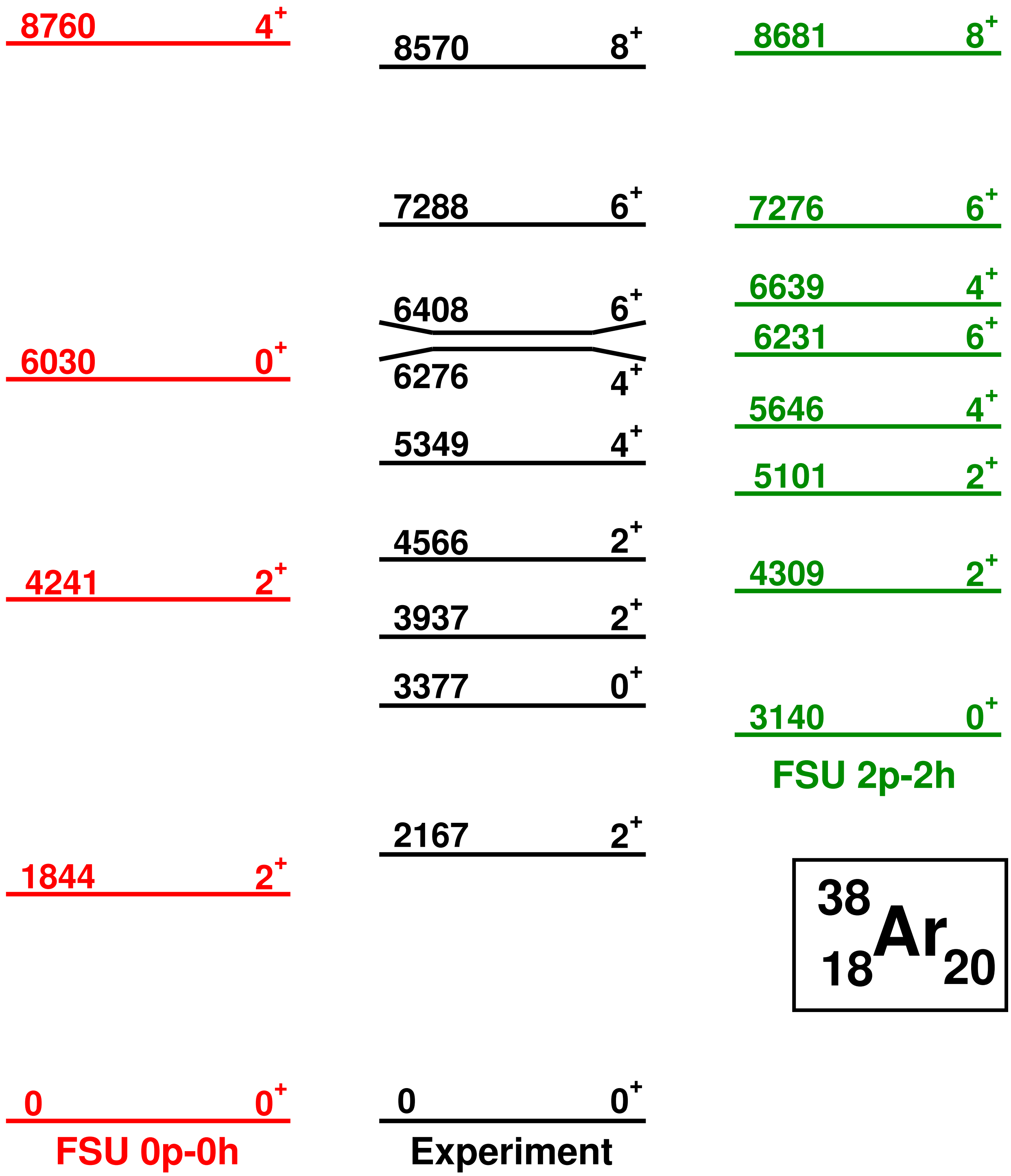

FIG. 5. Experimental positive-parity states in ^{38}Ar compared with shell model calculations using the FSU cross-shell interaction for 0p0h and 2p2h configurations.

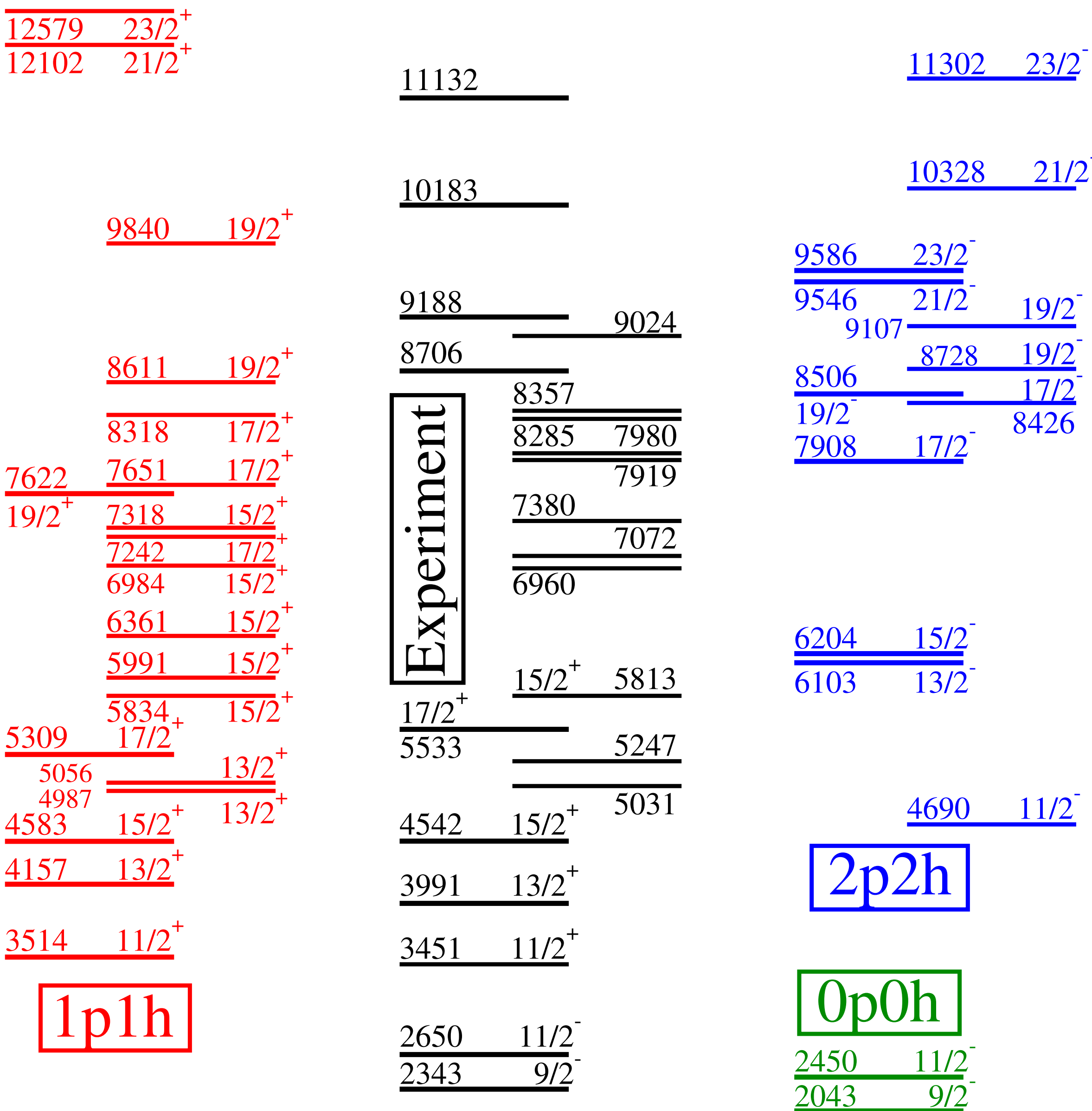

FIG. 6. A comparison of the experimental yrast and near yrast excited states in ^{39}Ar with the results of shell model calculations using the FSU cross-shell interaction. The g.s. $7/2^-$ state is not shown for space reasons. For clarity, the yrast and near yrast states have been staggered. The calculated levels are separated by the number of additional particles outside the *sd* shell and holes inside the *sd* shell relative to the dominant configuration of the g.s.