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States in odd-odd ^{116}Sb excited by the decay of ^{116}Te

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Gamma-ray spectroscopic experiments have been performed on the β^+/ϵ decay of 2.50-h ^{116}Te. Results from these experiments and from complementary in-beam γ-ray angular distributions were used to construct a decay scheme. Twenty-one γ rays were identified and placed in the decay scheme containing states in ^{116}Sb at 0 ($J^\pi = 3^+$), 93.7 (1^+), 103.0 (2^+), 446.0 (3), 550.9 (2), 574.4 (2), 731.7 (1^+), 917.7 (1^+), and 1158.3 (1^+) keV. The structures of the odd-odd Sb states are analyzed and discussed in simple shell-model terms.

[RADIOACTIVITY ^{116}Te [from ^{116}Sn(^{3}He,3n)^{116}Te]; measured E_γ, I_γ, deduced α_K, α_{tot}; deduced logft; ^{116}Sb deduced levels, J, π; Ge(Li) singles and γ-γ coinc.; shell-model considerations.]

I. INTRODUCTION

Odd-odd nuclei can provide a convenient and useful means of examining the p-n residual interaction. Because of the general complexity of odd-odd states, it is the odd-odd nuclei close to closed shells, where the single-nucleon components of the wave functions are amenable to shell-model analysis, that are the most practicable for study. Because of the relatively low amounts of energy available for populating odd-odd states by the β decay of their even-even neighbors, the best sources of information supplement radioactivity studies with in-beam experiments.

We have embarked upon a series of in-beam experiments using the ($p,n\gamma$) reaction on nuclei near the $Z=50$ shell,[1] including populating and examining states in the odd-odd nucleus $^{116}_{51}$Sb$_{65}$. Since we discovered that the results of previous experiments on the β decay of ^{116}Te conflicted with the in-beam results and because of the complementary nature of the decay studies, we undertook a reinvestigation of ^{116}Te decay, which we report in this paper.

The identification and study of 2.50 ± 0.02-h ^{116}Te has a fairly spotty history[2-6]—for a summary of the early results, cf., Ref. 2. The basic previous work on the decay of ^{116}Te to states in ^{116}Sb remains that of Fink, Andersson, and Kantele[2] [magnetic conversion-electron and β^+ studies plus NaI(Tl) γ-ray studies, including γ-γ coincidences]. Subsequent Ge(Li) γ-ray studies[7,8] and magnetic conversion-electron studies[9] have proven less reliable. In this paper we present what we believe to be the first complete and comprehensive ^{116}Te decay scheme, based primarily on Ge(Li) γ-ray singles and γ-γ coincidence data, but also making free and extensive use of our in-beam angular correlation data[1] to facilitate making J^π assignments and to determine the more detailed structures of the states. We conclude with an examination of the structures of the lower-lying states in simple shell-model terms.

II. DESCRIPTIONS OF EXPERIMENTS

A. Source preparation

Samples of 95% enriched ^{116}Sn (obtained from Oak Ridge National Laboratory) in the form of powdered SnO_2 were contained in Al foil envelopes and bombarded with a 32-MeV ^{3}He beam from the Michigan State University Sector-Focused Cyclotron. The 32-MeV beam was chosen on the basis of excitation function calculations with the computer code CS8N,[10] which predicted that the cross section for the ^{116}Sn(^{3}He,3n)^{116}Te reaction would peak at that energy. [Q values for the (^{3}He,3n) and (^{3}He,4n) reactions are −15.66 and −26.80 MeV, respectively.]

Following 30-60-min bombardments, the ^{116}Te sources were aged for ≈ 30 min to allow the shorter-lived contaminants to decay away. The sources were then transferred to fresh Al foil envelopes for counting. Typically, three of four such sources were used to accumulate spectra having adequate statistics.

B. γ-ray singles experiments

The γ-ray singles spectra were obtained with an 18% efficient [relative to a 7.6 × 7.6-cm^2 NaI

(Tl) scintillator for the 1333-keV peak from ^{60}Co, with a source-to-detector distance of 25 cm] true-coaxial Ge(Li) detector. For the 1333-keV ^{60}Co peak it had a resolution of 2.0 keV full width at half maximum (FWHM) and a peak-to-Compton ratio of 45:1. For a more complete description of the approaches, standards, methods of data reduction, and errors, see, e.g., Ref. 11.

The singles spectra were collected in time intervals of 2.0 h over a period of 10.0 h for each ^{116}Te source, and the spectra from several sources were summed in their appropriate time intervals to obtain valid statistics. Figure 1 shows a singles γ-ray spectrum. Because the ^{116}Sb daughter itself has a half-life of 16 min, γ rays from its decay are in equilibrium with those from ^{116}Te decay. Consequently, those γ rays having a 2.50-h $t_{1/2}$ and not belonging to ^{116}Sb decay[12] were assumed to be candidates for placement in the decay of ^{116}Te. (The intense, unlabeled peaks in Fig. 1 are the transitions from ^{116}Sb decay.) Sixteen such γ rays were observed in the singles spectra, and these are listed in Table I. Five additional γ rays were shown by the γ-γ coincidence and $(p, n\gamma)$ experiments to belong to ^{116}Te decay, and these are also included in Table I.

C. γ-γ coincidence experiments

The γ-γ coincidence experiments were conducted with the previously described 18% Ge(Li) detector and an 8% Ge(Li) detector which had a resolution of 1.95 keV FWHM and a peak-to-Compton ratio of 33:1. The detectors were placed in 180° geometry, but a 1.3-cm-thick Pb block was placed between them to reduce Compton scattering from one detector to the other. Also, the source was placed outside the edges of the Pb block at a small angle to the detectors in order to reduce 511-511-keV annihilation coincidences.

By periodically replenishing the source, the coincidence counting rate was maintained at ≈ 300 counts/sec, with the singles rate in the 18% detector being $\approx 2\times10^4$ counts/sec. The resolving time was ≈ 50 nsec. A total of $\approx 7\times10^6$ events was stored on magnetic tape using an on-line PDP-9 computer. The data for the various coincidence gates were recovered using weighted background subtraction with the MSU Xerox Sigma-7 computer. (For more details, see Refs. 1 or 11.) In Fig. 2 we show the integral and some representative coincidence spectra, and the coincidence results are summarized in Table II. (It should be noted that the 93.7-keV level has a half-life of ≈ 1 μsec; thus, the 93.7-keV gate in general did not yield coincidence information in these "prompt" gates. We were able to obtain only this approximate half-life because of the weak γ rays feeding the 93.7-keV level, the large background under the 93.7-keV peak, and, of course, the rather long resolving times necessary for the measurements.)

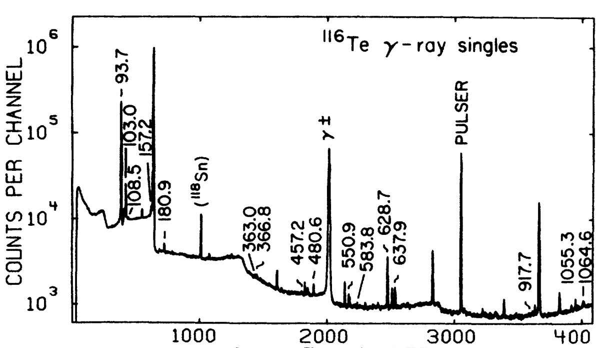

FIG. 1. ^{116}Te γ-ray singles spectrum obtained with an 18%-efficient Ge(Li) detector. This spectrum was accumulated in 10 h.

TABLE I. γ rays from the decay of ^{116}Te.

E_γ (keV)	I (per 1000 decays)
93.7 ± 0.0	958 [a] ± 42
103.0 ± 0.1	29.5 [b] ± 1.5
108.5 ± 0.1	0.47 ± 0.06
157.2 ± 0.1	4.1 [c]
180.9 ± 0.1	2.2 ± 0.1
363.0 ± 0.1	0.59 ± 0.08
366.8 ± 0.1	1.3 ± 0.1
447.8 ± 0.1 [d]	0.5 ± 0.1
457.2 ± 0.1	1.0 ± 0.1
466.0 ± 0.1	0.06 [e]
471.4 ± 0.1 [d]	0.42 ± 0.04
480.6 ± 0.1	3.7 ± 0.1
550.9 ± 0.1	2.9 ± 0.1
574.5 ± 0.1 [d]	0.36 ± 0.05
583.5 ± 0.1	0.87 ± 0.11
628.7 ± 0.1	30.3 ± 0.2
637.9 ± 0.2	7.1 ± 0.2
824.0 ± 0.2 [d]	1.1 ± 0.2
917.7 ± 0.2	1.4 ± 0.2
1055.3 ± 0.2	6.5 [f]
1064.6 ± 0.2	2.3 [f]

[a] Intensity corrected for conversion, assuming $E2$ multipolarity; see text for details.

[b] Similarly, corrected for conversion, assuming $M1$ multipolarity.

[c] Computed from the sum of γ rays depopulating the 575.4-keV level.

[d] Not observed in singles spectra; observed only in γ-γ experiments.

[e] Not observed at all in ^{116}Te decay but known to account for 11% of the deexcitation of the 466.0-keV level (cf., Ref. 1).

[f] Computed using the branching ratios obtained from in-beam experiments.

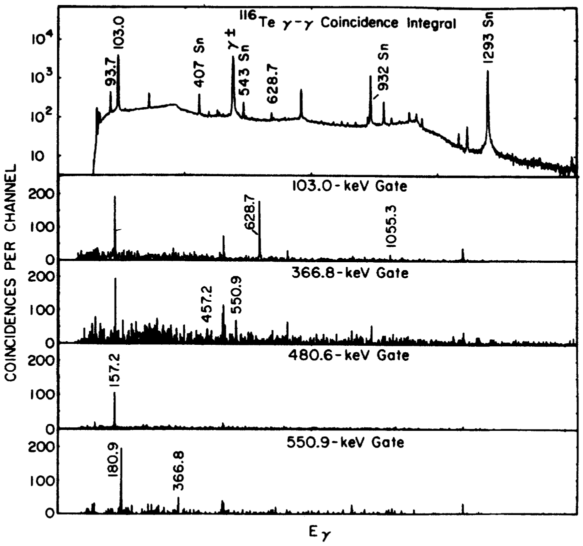

FIG. 2. Sample ^{116}Te γ-ray spectra obtained from a γ-γ "megachannel" coincidence experiment using 18%- and 8%- efficient Ge(Li) detectors. The "integral" or total coincidence spectrum in the 18%-efficient detector is shown at the top, and four selected gated spectra are shown below it. Note that the energy scales on the gated slices are expanded for optimum display.

III. DECAY SCHEME

The decay scheme constructed from our data is shown in Fig. 3. It consists of the ground state plus eight excited states in ^{116}Sb, four (possibly five, cf., below) of which are populated directly by the β decay of ^{116}Te. (We also indicate the 8^- metastable state[13] at ≈ 610 keV, although, of course, it is not populated at all by ^{116}Te decay.) All intensities are given in percent of the total ^{116}Te decay. The energies of the excited states are weighted averages of the energies of the γ rays depopulating them.

TABLE II. Results of two parameter γ-γ coincidence experiments for ^{116}Te β decay.

Gated γ ray (keV)	Coincident γ rays (keV)
103.0	628.7, 1055.3
180.3	550.9
363.0	103.0, 108.5
366.8	457.2, 550.9
447.8	180.9
457.2	180.9, 366.8
480.6	93.7, 157.2
550.9	180.9, 366.8
574.4	157.2
628.7	103.0
1055.3	103.0

The 93.7- and 103.0-keV γ transition intensities have been corrected for internal conversion, since they have been demonstrated (see three paragraphs below) to be $E2$ (calculated[14] $\alpha_K+\alpha_L+\alpha_M=2.25$) and $M1$ ($\alpha_K+\alpha_L+\alpha_M=0.61$), respectively. This was important, inasmuch as the 93.7-keV intensity, in particular, has an important effect on the relative β feedings. The other γ-ray intensities are those for the photons alone, since their multipolarities have not been determined experimentally (although many can be deduced). These other transitions are all quite weak, so their not being corrected for conversion, although having in a few cases small effects on the balance of transitions into and out of a level, does not cause significant changes in the remainder of the decay scheme.

The log*ft* values were calculated[15] on the basis of the measured Q_ϵ value[2] of 1.56 MeV. This measured value is not too precise, but it compares well with 1.56 ± 0.10 MeV, calculated from systematics.[16]

The ground state of ^{116}Sb has had its spin measured[17] by the atomic beam method to be 3. It can be accpeted as 3^+ with reasonable assurance because of the lack of shell-model states in this region which could produce odd parity. (The $h_{11/2}$ state, in fact, is the only reasonably low-lying odd-parity state available, and its first contribution would appear to be to the ≈ 610-keV 8^- metastable state.) This assignment is, of course, consistent with a total lack of direct β feeding from 0^+ ^{116}Te.

Multipolarities have been deduced for only two of the γ transitions. Fink, Andersson, and Kantele[2] found the 93.7-keV transition to be $E2$ on the basis of K/L conversion coefficient ratios, and Rahmouni's data[9] were consistent with this assignment. From consistency arguments, Fink, Andersson, and Kantele also deduced $M1$ or $E2$ for the 103.0-keV transition, which, incidentally, they mistakenly placed in ^{116}Sn rather than in ^{116}Sb. However, Rahmouni assigned this transition as $E1$, based on α_K. Now, from the coincidence data and from our in-beam reactions data, we can securely place the 103.0-keV transition as depopulating a state of the same energy directly to the ground state. An odd-parity assignment for the 103.0-keV state is highly unlikely, making the $E1$ assignment for the 103.0-keV transition also suspect. (Kiselev and Burmistov[8] assigned $M1$ to this transition, but it is difficult to determine exactly how their calculations were done.) We thus used our relative photon intensities for the 93.7- and 103.0-keV transitions and recalculated α_K for the 103.0-keV transition, assuming the calculated value[14] α_K (= 1.53) for

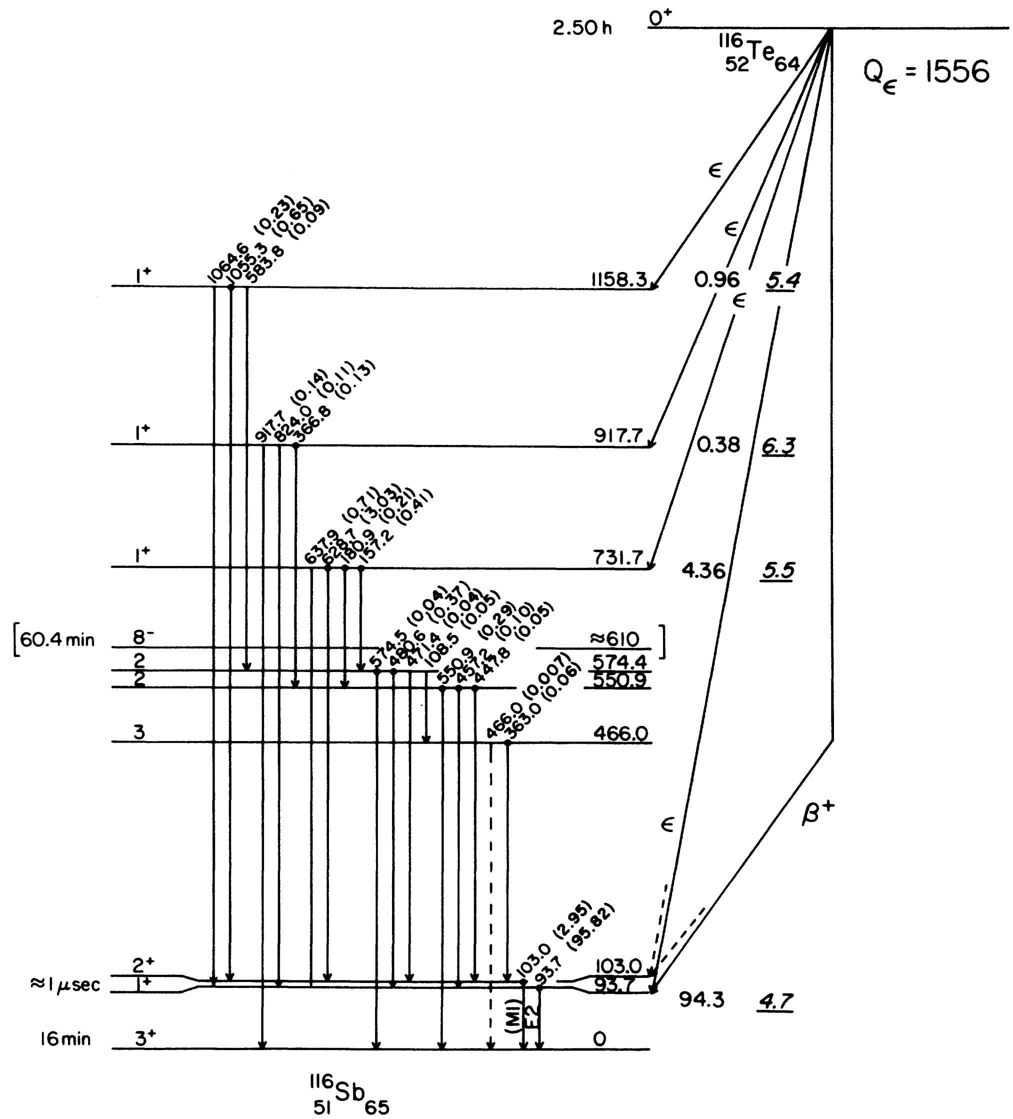

FIG. 3. ^{116}Te decay scheme. All energies are given in keV, and (total) intensities are given in percent of the ^{116}Te decays. The log*ft* values are given to the right.

the 93.7-keV transition in order to normalize the photon and electron data. With the electron intensities ($K+\Sigma L$) of Fink, Andersson, and Kantele, we obtained an α_K of 0.47 for the 103.0-keV transition. When compared with the calculated values for $E1$ (0.153), $E2$ (1.09), and $M1$ (0.503), the transition clearly appears to be $M1$. (Using Rahmouni's electron data, we obtain an even higher value for α_K.) Thus, this multipolarity assignment is consistent with the various other considerations that favor positive parity for the 103.0-keV state.

For the four states populated directly by ^{116}Te β decay, at 93.7, 731.7, 917.7, and 1158.3 keV, the respective log*ft* values are 4.7, 5.5, 6.3, and 5.4. Since these values are low enough so that the β decay is probably allowed, J^π assignments of 1^+ or 0^+ are consistent with the β decays to these states. The log*ft* of 6.3 for ϵ to the 917.7-keV state is high enough to include first-forbidden transitions, but such a transition would be extremely unlikely: It would almost certainly require a large $h_{11/2}$ component in the wave function for the 917.7-keV state (no other odd-parity components are likely at this excitation energy), so even if a first-forbidden transition were J allowed from 0^+ ^{116}Te, it would be many times l forbidden and inconsistent with the log*ft* value. The anisotropic γ-ray angular distribution data[1] eliminate the 0^+ possibility for all but the 93.7-

keV state, which is isotropic because of its long half-life. But the $E2$ character of the 93.7-keV γ transition eliminates the 0^+ possibility for this state as well. Therefore, all four states populated directly by ^{116}Te β decay are assigned $J^\pi = 1^+$.

The four remaining states, at 103.0, 446.0, 550.9, and 574.4 keV were assigned respective J's of 2, 3, 2, and 2 on the basis of our in-beam γ-ray angular distribution and excitation function data.[1] They are not expected to receive any direct β feeding from ^{116}Te, as this would require second-forbidden or first-forbidden unique transitions (with the latter highly hindered, cf., above). Since the parity of the 103.0-keV state was determined to be even on the basis of the 103.0-keV γ transition being an $M1$, this state can be uniquely assigned $J^\pi = 2^+$. It is tempting to prefer even parity for the other three states, but it is also dangerous, for a straightforward application of the Nordheim coupling rules predicts (cf., next section) several lower-spin odd-parity states to lie below the 8^- metastable state, including a 2^- state as the lowest one.

The additional 466.0-keV γ shown depopulating the 466.0-keV state is known to exist from our in-beam studies but was not seen at all from the β decay of ^{116}Te. This is not surprising in view of the fact that it is very weak—we have included it in the known branching ratio from the in-beam studies. Also, since the 157.2-keV γ is obscured by the larger 158-keV peak from ^{117}Sb decay, its intensity was computed from the depopulation of the 574.4-keV state, there being no direct β feeding to this state.

IV. DISCUSSION

These decay-scheme studies have corroborated and complemented the in-beam γ-ray experiments and were able to resolve several discrepancies encountered therein.[1] They have also resulted in the first complete decay scheme, as presented in Fig. 3. [In the previous work of Rahmouni,[7,9] only three of the 21 γ rays had been recognized and placed, and only the 93.7-keV γ placed correctly; in the work of Kiselev and Burmistrov,[8] only the 93.7- and 103.0-keV γ's were (properly) placed. Both groups made either inconclusive or incorrect J^π assignments, even for the ground state.] In the following we discuss possible structures for the states in (purposely) very simplified terms, using only the Nordheim coupling rules as modified by Brennan and Bernstein[18] and taking the single-nucleon components of the wave functions from the systematics of the neighboring odd-mass Sb isotopes and $N = 65$ isotones.

In ^{115}Sb the single-proton states are found (most likely) to be[19] $d_{5/2}$ (0 keV), ($g_{7/2}$) (723.57), ($s_{1/2}$) (770.44), and ($d_{3/2}$) (1071.6)—the $h_{11/2}$ state has not yet been placed in this nuclide. In ^{117}Sb they are[20] $d_{5/2}$ (0 keV), $g_{7/2}$ (527.3), $s_{1/2}$ (720), ($d_{3/2}$) (924), and $h_{11/2}$ (1322.8). Thus, the ordering is the same in both nuclides, and, with minor variations (such as $d_{5/2}$ becoming the ground state at ^{121}Sb), it remains so throughout the odd-mass Sb isotope sequence. (For more extended systematics, the 7th edition of the *Table of Isotopes*[21] gives an up-to-date, concise representation.) Because Sb is only one proton outside the $Z = 50$ closed shell, these single-proton states are expected to be "abnormally" good single-particle states, having very little configuration mixing (except perhaps for the $d_{3/2}$ state). However, it should also be noted that throughout these Sb isotopes, quasirotational bands (indicating a partial onset of deformation) based on "intruder" $\frac{9}{2}^+$ and/or $\frac{11}{2}^+$ states begin in the vicinity of 1.5 MeV.

The single neutron states have not been so well characterized, but in ^{115}Sn$_{65}$ they appear to be[22] $s_{1/2}$ (0 keV), ($d_{3/2}$) (497.4), ($g_{7/2}$) (613.0), ($h_{11/2}$) (713.7), and ($d_{5/2}$) (986.6). In ^{117}Te$_{65}$ they appear to be[23] $s_{1/2}$ (0 keV), $d_{5/2}$ (274.4), ($g_{7/2}$) (296), and ($h_{11/2}$) (≈ 310)—here the $d_{3/2}$ state has not yet been placed. The single-neutron states, occurring as they do in the middle of the shell between $N = 50$ and $N = 82$, should be only moderately good single-particle states. It should also be noted that the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ states consist primarily of neutron particles; the $d_{5/2}$ and $g_{7/2}$, of neutron holes.

The ^{116}Sb 3^+ ground state is thus fairly easily explained as $[\pi(d_{5/2})\nu(s_{1/2})^{-1}]_{3^+}$ which is expected to lie lower than the 2^+ coupling. This, incidentally, is consistent with the predominant β decay[12] of ^{116}Sb to states in ^{116}Sn. The 103.0-keV 2^+ state in ^{116}Sb could well consist primarily of the above 2^+ coupling, but there is no supporting information one way or the other.

The next lowest configuration would be expected to be $\pi(d_{5/2}) \times \nu(d_{3/2})$, which yields a sequence of states from 1^+ to 4^+, the 1^+ predicted to lie lowest. This is consistent with the properties of the 93.7-keV 1^+ state. The $E2$ γ transition deexciting it clearly is not collectively enhanced to any great degree [$t_{1/2}$ (expt) ≈ 1 μsec vs $t_{1/2}$ (calc) $= 0.79$ μsec], and our interpretation of the structures of the states would make it a single-proton $d_{3/2} \to d_{5/2}$ transition, i.e., a fast transition in single-particle terms, but one also involving a flip recoupling of the neutron state. More importantly, this structure for the 1^+ state is consistent with the low log*ft* value for its population by ^{116}Te β decay, since collective effects are less important in β decay than in γ decay. The ground state of ^{116}Te should be $[\pi(d_{5/2})^2 \nu(d_{5/2})^6\nu(g_{7/2})^8]_0$, making this the relatively fast allowed transition, $\pi(d_{5/2}) \to (d_{3/2})$.

Above this, specific assignments of straightforward double-particle configurations become increasingly difficult because of the multiplicity of configurations that can contribute to a given spin. For example, $\pi(d_{5/2}) \times \nu(d_{3/2})$, $\pi(d_{5/2}) \times \nu(d_{5/2})^{-1}$, $\pi(g_{7/2}) \times \nu(d_{5/2})^{-1}$ are only the most obvious couplings that can produce 2^+ or 3^+ states, not to mention core-coupled states. Even the 8^- metastable state can be assigned either $[\pi(d_{5/2}) \nu(h_{11/2})]_{8^-}$ or $[\pi(g_{7/2})\nu(h_{11/2})]_{8^-}$—there is currently no way to differentiate between these, although a knowledge of the missing $E5$ γ transition to the ground state might allow it to be done. We hope to tackle this problem (of most odd-odd nuclei) in the future,[1] but a thoroughgoing shell-model calculation will also be necessary.

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[1]C. B. Morgan, Ph.D. thesis, Michigan State University, 1975 (unpublished); C. B. Morgan, W. H. Bentley, R. A. Warner, W. H. Kelly, and Wm. C. McHarris (unpublished).

[2]R. W. Fink, G. Andersson, and J. Kantele, Ark. Fys. 19, 323 (1961).

[3]M. Lindner and I. Perlman, Phys. Rev. 78, 499 (1950).

[4]B. Dropesky, Ph.D. thesis, University of Rochester, 1953 (unpublished).

[5]R. W. Fink and E. O. Wiig, Phys. Rev. 94, 1357 (1954).

[6]M. Ya. Kuznetsova, V. N. Mekhendov, V. N. Rybakov, and V. A. Khalkin, At. Energ. 4, 583 (1958).

[7]O. Rahmouni, J. Phys. (Paris) 29, 550 (1968).

[8]B. G. Kiselev and V. R. Burmistrov, Yad. Fiz. 8, 1057 (1968).

[9]O. Rahmouni, C. Acad. Sc. Paris 267B, 736 (1968).

[10]E. Sheldon and R. M. Strang, Comput. Phys. Commun. 1, 35 (1969).

[11]R. B. Firestone, R. A. Warner, Wm. C. McHarris, and W. H. Kelly, Phys. Rev. C 17, 718 (1978).

[12]G. H. Carlson, W. L. Talbert, Jr., and S. Raman, Nucl. Data Sheets 14, 247 (1975).

[13]H. H. Bolotin, Phys. Rev. 136, B1566 (1964).

[14]R. S. Hager and E. C. Seltzer, Nucl. Data Tables 4, 1 (1968).

[15]N. B. Gove and M. J. Martin, Nucl. Data Tables 10, 205 (1971).

[16]A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 175 (1977).

[17]C. Ekström, W. Horgervorst, S. Ingleman, and G. Wannberg, Nucl. Phys. A226, 219 (1974).

[18]M. H. Brennan and A. M. Bernstein, Phys. Rev. 120, 927 (1960).

[19]A. Charvet, R. Chery, Do Huu Phuoc, R. Duffait, and M. Morgue, J. Phys. (Paris) 35, 805 (1974).

[20]G. Berzins, W. H. Kelly, G. Graeffe, and W. B. Walters, Nucl. Phys. A104, 241 (1967).

[21]*Table of Isotopes*, edited by C. M. Lederer and V. S. Shirley, 7th ed. (Wiley, New York, 1978).

[22]O. Rahmouni, Nuovo Cimento 57B, 389 (1968); S. Raman and H. J. Kim, Nucl. Data Sheets 16, 195 (1975).

[23]I.-M. Ladenbauer-Bellis, H. Bakhru, and A. Luzzati, Phys. Rev. 187, 1739 (1969).