PHYSICAL REVIEW C VOLUME 7, NUMBER 2 FEBRUARY 1973

States in Odd-Odd ^{62}Cu Populated by the Decay of ^{62}Zn

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(Received 16 June 1972)

The decay of 9.2-h ^{62}Zn to states in odd-odd ^{62}Cu has been studied with the aid of large-volume Ge(Li) γ-ray detectors. 19 γ rays were found to belong to this decay, and all were placed in a decay scheme containing states in ^{62}Cu at 0 ($J^{\pi}=1^{+}$), 40.94 (2^+), 243.44 (2^+), 287.98 (2^+), 426.3 (3^+), 548.4 (1^+), 637.5 (1^+), 915.6 ($[1]^+$), 1142.5 ($[0,1]^+$), 1280.8 ($[0,1]^+$), and 1429.9 keV ($[1,0]^+$). These were combined with existing in-beam γ-ray particle-transfer data to yield a rather complete ^{62}Cu level scheme. The status of shell-model calculations in this nuclear region is discussed, and it is demonstrated that a gratifying number of facts about the low-lying ^{62}Cu states can be explained using simple odd-odd configurations as predicted by the neighboring odd-mass nuclei.

I. INTRODUCTION

The odd-odd nuclide, $^{62}_{29}$Cu$_{33}$, contains a single proton and five neutrons outside the doubly closed $f_{7/2}$ shell. Consequently, its states should be amenable to interpretation in fairly straightforward shell-model terms. Also, many states and trends in nearby odd-mass nuclei are known, providing reasonably trustworthy input for predicting the properties of its odd-odd states. Unfortunately, relatively few states are known in ^{62}Cu itself, and even fewer have been well characterized. In this paper, we reexamine the decay of 9.2-h ^{62}Zn to ^{62}Cu, using the largest Ge(Li) γ-ray detectors we have been able to obtain in order to pick up weak feedings that previously had gone undetected. We then correlate our findings with those of previous investigators and with data from scattering reactions in an attempt to obtain a more coherent understanding of the structures of the ^{62}Cu states.

Since the discovery of ^{62}Zn in 1948 by Miller, Thompson, and Cunningham,[1] it has been studied by many groups. Hayward[2] determined the end-point energy of its β^+ spectrum to be 0.66 ± 0.01 MeV and observed K and L conversion electrons from a 41.8 ± 0.2-keV transition, the K/L ratio indicating it to be $E1$ or $M1$. Nussbaum *et al.*[3] determined that the first excited state of ^{62}Cu lies at 41.3 ± 0.3 keV and that $(36 \pm 3)\%$ of the ^{62}Zn feeding passes through this state. From α_K and $K/(L+M)$ they assigned the 41.3-keV transition an $M1$ multipolarity.

The first reasonably complete decay scheme was formulated by Burn, Meyerhof, Kraushaar, and Horen,[4] who performed extensive electron and NaI(Tl) γ-ray spectroscopy, including coincidence and γ-γ angular correlation experiments. They deduced states in ^{62}Cu at 0, 0.042, 0.30, 0.55, 0.63, and 0.70 MeV.

In the last few years there has been a flurry of activity about the neutron-deficient members of the $A=62$ mass chain. Four groups[5-8] have reported Ge(Li) γ-ray studies on the decay of ^{62}Zn, and two other groups[9,10] have reported on the decay of 9.7-min ^{62}Cu itself. Antman, Pettersson, and Suarez[5] performed the first high-resolution Ge(Li) γ-ray experiments (in conjunction with electron experiments), and they and Roulston, Becker, and Brown[6] demonstrated conclusively the doublet nature of the ≈ 245-keV γ-ray peak and the existence of a 507.6-keV γ ray. These data were essential to the construction of a correct decay scheme, and the two groups arrived at almost identical decay schemes containing the first five excited states in ^{62}Cu that are populated by ^{62}Zn decay. The most precise half-life determination for ^{62}Zn, 9.2 ± 0.1 h, is also the work of Antman, Pettersson, and Suarez. Bakhru[7] also performed high-resolution Ge(Li) γ-ray spectroscopy, including coincidence experiments, and he measured the half-life of the 42-keV state to be 2.5 ± 0.1 nsec. His decay scheme, however, differs in several placements from the others. And the most recent paper on ^{62}Zn decay, by Hoffman and Sarantites[8] and again including results from γ-γ coincidence experiments, shows a decay scheme almost identical to those of Refs. 5 and 6.

Nuclear reaction and in-beam studies have been reported, also. Davidson *et al.*[11] have used the ^{62}Ni$(p, n\gamma)$ reaction to study the decay of the excited states of ^{62}Cu. They performed γ-γ angular correlations in addition to γ-ray singles measurements at various excitation energies in order to learn something about spins and parities as well as the placements of the states. Sunyar *et al.*[12] used the ^{60}Ni($\alpha, np\gamma$)^{62}Cu reaction both prompt and delayed with respect to their cyclotron beam bursts to deduce additional information on half-lives and g factors. Fanger *et al.*[13] report on similar techniques using the ^{61}Ni(n,γ) reaction to study states in ^{62}Ni. The particle-transfer reactions have included ^{61}Ni(^{3}He, d)^{62}Cu experiments by Morrison,[14] ^{63}Cu(d, t)^{62}Cu experiments by Hjorth and Allen,[15] and ^{64}Zn(d, α)^{62}Cu and ^{63}Cu-(d, t)^{62}Cu experiments by Park, Daehnick, and Dittmer.[16]

The points yet to be clarified are clear: (1) None of the groups studying ^{62}Zn decay was able to detect any γ rays with energies above 637 keV, although Q_ϵ is $\approx$1620 keV. Part of this problem came from the interference of γ rays from ^{62}Cu itself, which quickly grows into the sources. But now that the decay of ^{62}Cu is known[9,10,13] with some assurance, weak γ rays from ^{62}Zn decay can perhaps be distinguished more readily. Also, the larger Ge(Li) detectors now available, having very good peak-to-Compton ratios, should allow one to detect very weak higher-energy γ rays. (2) Very little in the way of interpretation of the structures of the ^{62}Cu states has been done. We have attacked both sides of the problem, with the following results: (1) We can report eight new weak γ rays that deexcite five new excited states in ^{62}Cu. (2) We examine the structures of the ^{62}Cu states in terms of shell-model states and the trends observed in this nuclear region and find that this very straightforward method can explain much of what is observed.

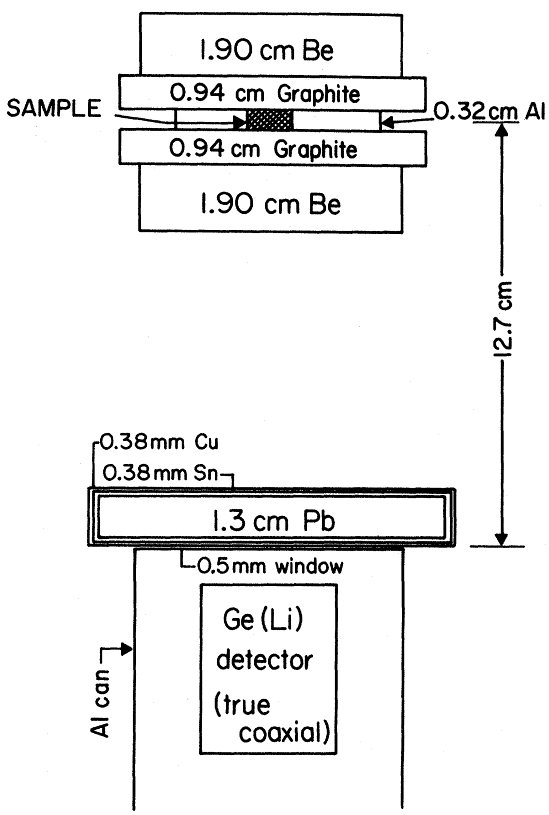

FIG. 1. Geometrical setup of one of the ^{62}Zn γ-ray counting arrangements, showing the graded-Pb absorber and the β^+-annihilation absorbers.

II. SOURCE PREPARATION

Our ^{62}Zn sources were prepared by irradiating natural Cu foils (69.17% ^{63}Cu, 30.83% ^{65}Cu) with 25-MeV protons accelerated by the Michigan State University (MSU) sector-focused cyclotron. The reaction of interest was ^{63}Cu(p, $2n$)^{62}Zn. Typically, $\approx$150-mg targets were bombarded with a 1-μA beam for 30–45 min.

The only Zn contaminant of any consequence was 38-min ^{63}Zn, which could be essentially eliminated by waiting for 4–5 h before counting the ^{62}Zn sources. The 9.7-min ^{62}Cu was quite another problem, so chemical separations were used which allowed us to separate it out periodically while counting the ^{62}Zn. The Cu targets were dissolved in a solution of 5 ml of 30% H_2O_2 and 10 ml of 6 N HCl to which 1 meq of Zn^{++} carrier had been added. The resulting solution was evaporated to dryness and the residue taken up in a minimum amount of 1.6 N HCl. This was loaded onto an anion exchange column consisting of Dowex 1$\times$8 resin. Repeated washings with 1.6 N HCl removed any remaining Cu but left Zn on the column, which was counted directly.

III. γ-RAY SPECTRA

Many γ-ray spectra were taken over a long period of time, always using the largest Ge(Li) detectors at our disposal. Most spectra were taken with two five-sided coaxial detectors having photopeak efficiencies of 2.5 and 10.4% at 1332 keV [compared with a 3$\times$3-in. NaI(Tl) detector, sources at 25 cm] and resolutions of 2.3 keV full width at half maximum (FWHM) at the same energy. We also used a true coaxial detector having an efficiency of 3.6% and a resolution of 2.0 keV FWHM. The detector systems used room-temperature FET preamplifiers, low-noise RC linear amplifiers having pole-zero compensation, near-Gaussian shaping, and base-line restoration with dc coupling, and 12- or 13-bit analog-to-

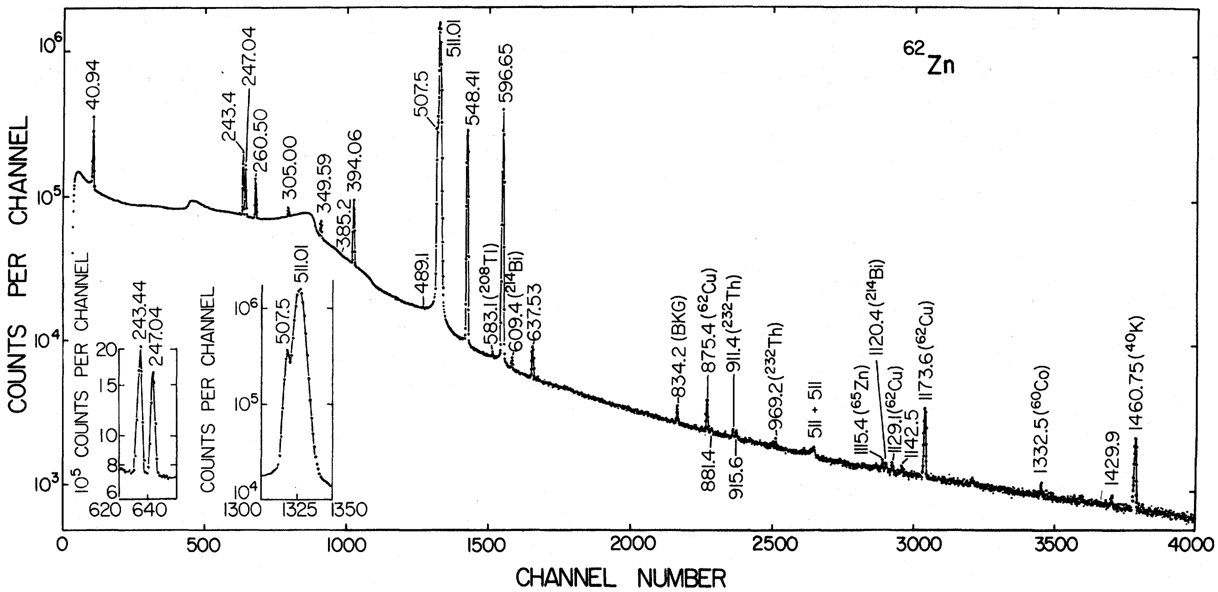

FIG. 2. ^{62}Zn γ-ray spectrum taken with the 10.4% efficient Ge(Li) detector without the use of absorbers. The insets show the doublet regions at 245 and 511 keV in greater detail.

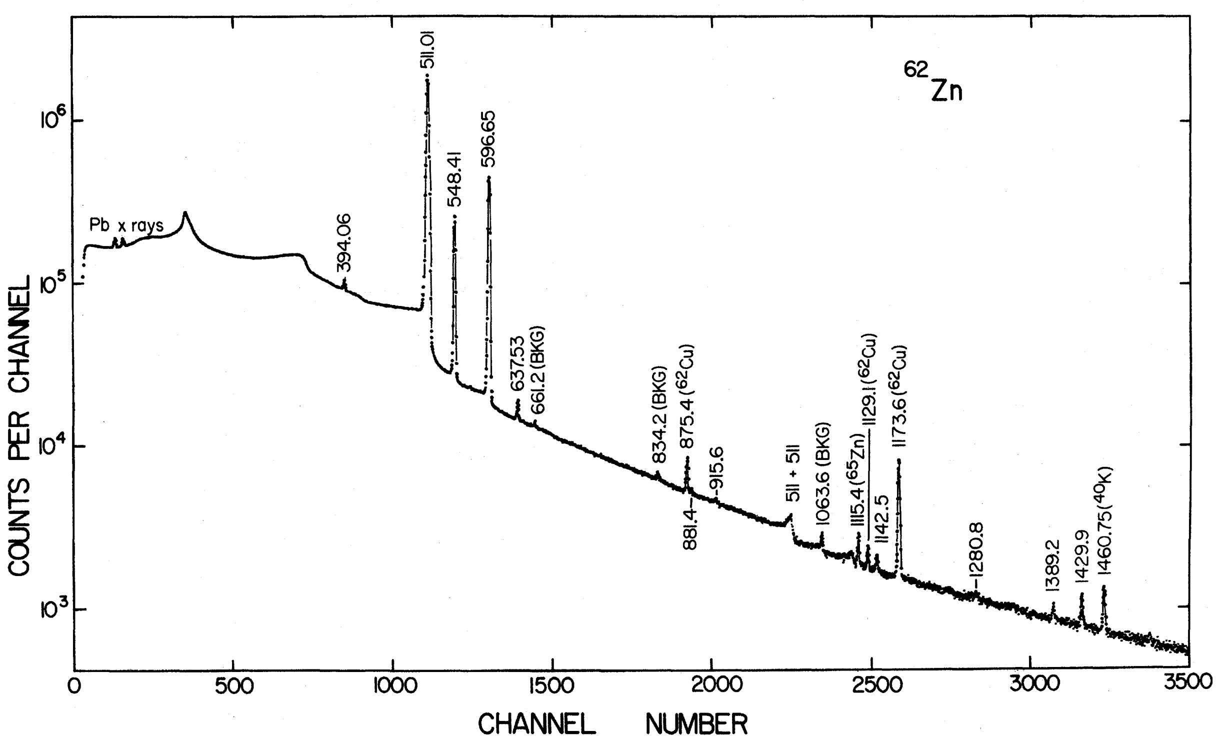

FIG. 3. ^{62}Zn γ-ray spectrum obtained in 6 h with the 10.4% efficient Ge(Li) detector and with the absorbers in place as shown in Fig. 1 so as to enhance the weak higher-energy peaks.

digital converters (ADC's) coupled to a PDP-9 or Sigma-7 computer. As it was mandatory that we optimize the higher-energy portion of the spectra yet maintain a high counting rate in order to minimize stray background peaks that could mask the weak ^{62}Zn peaks, some of the spectra were taken through a set of absorbers and with the geometry shown in Fig. 1.

Each sample was counted for several consecutive 6-h periods to insure that the peaks observed came indeed from ^{62}Zn decay. For some runs the ^{62}Cu was washed out of the column periodically as described in the previous section. Our methods of energy and efficiency calibration and of spectrum analysis have deen described elsewhere.[17] In addition to the normal procedures, however, we performed an on-the-spot relative efficiency calibration[18] with ^{110m}Ag and a background count of at least 12 h for each sample. The secondary energy calibration was performed using the stronger peaks of ^{62}Zn, its ^{62}Cu daughter, and the ^{40}K present in the natural background.

A spectrum obtained with the 10.4% detector but without absorbers is shown in Fig. 2, and one with absorbers is shown in Fig. 3. Note that six very weak higher-energy γ rays that we attribute to ^{62}Zn decay can be seen in the latter spectrum. Also, two very weak γ rays having energies of 385.2 and 489.1 keV were found after comparison with the in-beam γ-ray work of Davidson *et al.*[11] These can be seen in Fig. 4, where the raw and smoothed data are shown for comparison. The energies and relative intensities of the ^{62}Zn γ rays are listed in Table I, where they are compared with the results of the other investigations that used Ge(Li) detectors. Since the point of our investigation was specifically to obtain new information about weak transitions, we performed no coincidence experiments.

IV. DECAY SCHEME

The ^{62}Zn decay scheme is shown in Fig. 5. All energies are given in keV and (total) transition intensities are given in percent of the ^{62}Zn disintegrations. (Only for the 40.94-keV transition is the conversion correction nonnegligible, and we assumed it to be pure $M1$, using the Hager and Seltzer[19] conversion coefficients.) For the percent β^+/ϵ to the ground state, the value determined by Hoffman and Sarantites[8] was used, while for the other states our γ-ray intensity balances were used. Inasmuch as the calculated β^+/ϵ ratios do not always give correct results even for allowed transitions,[20] we give the total $\beta^+ + \epsilon$ feeding for these other states. The multipolarities are taken from Antman, Pettersson, and Suarez.[5]

TABLE I. Energies and intensities of γ rays following the decay of ^{62}Zn.

This work		Antman, Pettersson, and Suarez (Ref. 5)		Roulston, Becker, and Brown (Ref. 6)		Bakhru (Ref. 7)		Hoffman and Sarantites (Ref. 8)	
E_γ (keV)	I_γ	E_γ (keV)	I_γ	E_γ (keV)	I_γ [a] (±10%)	E_γ (keV)	I_γ	E_γ (keV)	I_γ
40.94 ± 0.06	104 ± 10	40.88 ± 0.09	(102) [b]	41.5 ± 0.2	(192)	42	100 ± 5	40.84 ± 0.15	99.4 ± 3.5
243.44 ± 0.03	11.1 ± 0.5	243.40 ± 0.05	≈7 } 11.0 ± 0.9	243.7 ± 0.5	15 }	245	10 ± 1	243.43 ± 0.20	10.3 ± 0.5
247.04 ± 0.04	8.3 ± 0.4	247.02 ± 0.09	≈4 }	247.2 ± 0.5	12 }			247.02 ± 0.20	8.2 ± 0.3
260.50 ± 0.06	5.9 ± 0.3	260.44 ± 0.10	2.6 ± 0.5	260.7 ± 0.5	8	260	4 ± 1	260.39 ± 0.08	5.9 ± 0.1
305.00 ± 0.07	1.2 ± 0.1	···	···	305.5 ± 1.0	0.8	···	···	304.80 ± 0.20	1.32 ± 0.07
349.59 ± 0.07	1.8 ± 0.1	349.69 ± 0.25	≈1	349.5 ± 1.0	1.5	···	···	349.34 ± 0.11	1.59 ± 0.16
385.2 ± 0.4	0.08 ± 0.02	···	···	···	···	···	···	···	···
394.06 ± 0.04	9.2 ± 0.4	394.12 ± 0.18	6.2 ± 1.0	394.5 ± 0.5	10.7	395	5 ± 1	393.80 ± 0.06	9.16 ± 0.12
489.1 ± 0.4	0.06 ± 0.02	···	···	···	···	···	···	···	···
507.5 ± 0.4	58 ± 10	507.57 ± 0.13	60 ± 15	507.5 ± 1.0	77	505	40 ± 3	507.41 ± 0.15	65 ± 15
548.41 ± 0.04	60.8 ± 1.0	548.33 ± 0.22	54 ± 5	548.7 ± 0.5	65	547	60 ± 4	548.25 ± 0.11	62.2 ± 0.9
596.65 ± 0.04	≡100	596.68 ± 0.20	100 ± 8	597.0 ± 0.5	100	595	100 ± 5	596.60 ± 0.11	≡100
637.53 ± 0.06	0.96 ± 0.06	636.9 ± 0.5	≤1	638.5 ± 1.0	1.5	···	···	637.20 ± 0.12	3.45 ± 0.25
···	···	···	···	···	···	682	≈4 ± 2	···	···
881.4 ± 0.8	0.08 ± 0.03	···	···	···	···	···	···	···	···
915.6 ± 0.6	0.08 ± 0.03	···	···	···	···	···	···	···	···
1142.5 ± 0.2	0.13 ± 0.03	···	···	···	···	···	···	···	···
1280.8 ± 1.5	0.03 ± 0.01	···	···	···	···	···	···	···	···
1389.1 ± 0.5	0.05 ± 0.02	···	···	···	···	···	···	···	···
1429.9 ± 0.3	0.13 ± 0.02	···	···	···	···	···	···	···	···

[a] Normalized to $I_{597.0} \equiv 100$, retaining original number of significant figures.
[b] Calculated from the adopted value for an $M1$ transition.

On the ^{62}Zn decay scheme we also show for comparison the states in ^{62}Cu below Q_ϵ (≈1620 keV) that have clearly been demonstrated to exist via other experiments. These are shown as the short lines on the right side. Below 915.6 keV these result from the ^{62}Ni($p, n\gamma$) work of Davidson *et al.*,[11] while above 915.6 these come from the tabulation of particle data in *Nuclear Data Sheets*[14-16] attributed primarily to Morrison's ^{61}Cu(^{3}He, d) experiments.[14] A complete comparison of the ^{62}Cu states seen via different experiments is given in Table II.

The J^π assignments for the 0-, 40.94-, 243.44-, 287.98-, 548.4-, and 637.5-keV states of ^{62}Cu have been well established and are discussed in detail in Refs. 5, 8, and 11. We agree with these six assignments and do not discuss them further here.

Assignments for the four additional states that we placed, at 915.6, 1142.5, 1280.8, and 1429.9 keV can be narrowed down as follows: The $\log ft$'s, ranging from 5.8 to 7.3, place the corresponding ϵ transitions in the (hindered) allowed to first-forbidden range. However, in all four cases states were populated at or very close to our assigned energies by particle-transfer reactions, usually the ^{61}Ni(^{3}He, d) reaction – and the l values were unambiguously odd. This implies even parity for all four states. Also, numerous allowed ϵ transitions are known in this nuclear region which have $\log ft$ values as high as these. Thus, we narrow the J^π assignments to 0^+ or 1^+.

It might be possible to narrow the assignment for the 1429.9-keV state to 1^+ on the basis of the γ-ray branching to the 2^+ 40.94-keV state. One usually cannot make such a narrowing down because of the possibility of collectively enhanced $E2$ transitions – e.g., were the 1429.9-keV state a 0^+ core-coupled combination of the 2^+ 40.94-keV state with the 2^+ vibration of the ^{60}Ni core (lying at 1332.5 keV), then the $E2$ transition to the 40.94-keV state would be fast. In an odd-odd nucleus, however, configuration mixing should cause such an $E2$ to be less enhanced, and also it is unlikely that such a 0^+ state could populate both the 1^+ ground and the 2^+ 40.94-keV states in the ratios observed here. On the other hand, one cannot completely discount the possibility that the 1429.9-keV transition to the ground state is a highly hindered $M1$, which could lead to the observed branching ratios. Thus, although there is a slight edge for a 1^+ assignment, 0^+ cannot be ruled out.

The assignment for the 915.6-keV state can be narrowed to 1^+ because this state feeds the 426.3-keV state, which had been assigned 3^+ by Davidson *et al.*[11] (Their assignment was based on angular distributions, and we do not have any basis for an assignment of our own, so we accept theirs for this state. Intensity balance of the γ rays connected with the 426.3-keV state might indicate a small β feeding, but the γ rays are so weak that we prefer to attribute this merely to numerical uncertainties.) Davidson *et al.* assigned 2^+ to a state at 915.5 keV. This was done because of its populating the 3^+ 426.1-keV state so strongly, for they had no angular distributions for the γ rays deexciting the 915.5-keV state. We cannot accept this assignment because of the 915.6-keV state's receiving β decay.

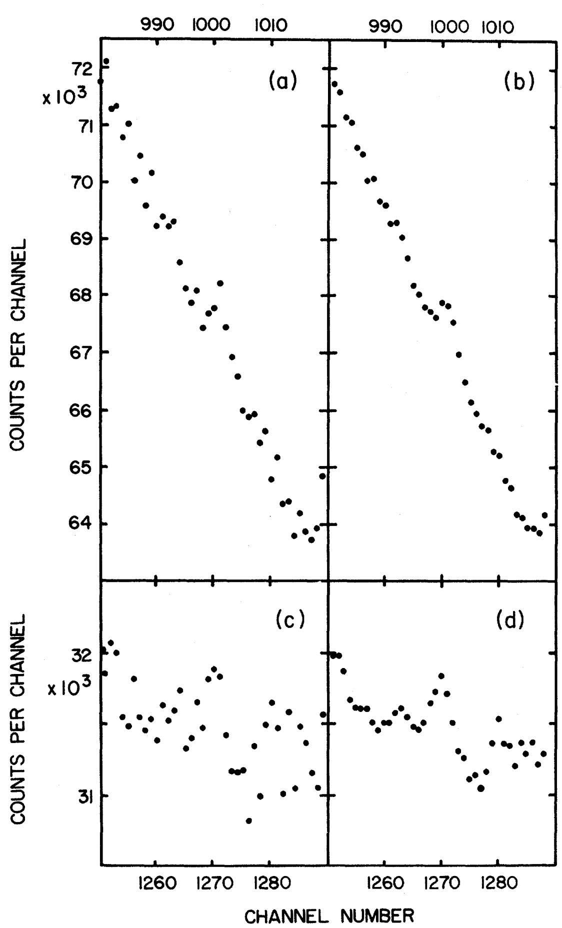

FIG. 4. Portions of several ^{62}Zn γ-ray spectra similar to that in Fig. 1 but expanded so as to show the very weak 385.2- and 489.1-keV peaks more clearly. Parts (a) and (c) show the raw data, while (b) and (d) show these same data smoothed over three channels.

V. DISCUSSION: ODD-ODD STATES OF ^{62}Cu

$^{62}_{29}Cu_{33}$ lies one proton and five neutrons away from the doubly closed shell at $Z=N=28$. Thus, the proton components of its states should be somewhat simpler to determine than the neutron components. One can make some qualitative progress, however, by using the odd-group concept (actually in this case, odd-proton vs odd-neutron group) and using the modified Nordheim coupling rules of Brennan and Bernstein.[21]

The odd-proton states can be determined straightforwardly by examining the neighboring odd-mass Cu isotopes. States in these[22] are shown in Fig. 6. Below 1 MeV the only available states are $\frac{3}{2}^-$, $\frac{1}{2}^-$, and $\frac{5}{2}^-$, which should be reasonably pure $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ states. It is also clear that the $\pi p_{3/2}$ state should dominate states near the ground in ^{62}Cu.

The states in the $N=33$ odd-mass isotones[23] are shown in Fig. 7. First, it should be noted that the odd-neutron states are much more closely spaced than the odd-proton states. Competition between the $p_{3/2}$ and $f_{5/2}$ orbits should be especially severe. Also, several rather different shell-model calculations[24, 25] on ^{61}Ni have shown that its states are rather complicated and admixed, albeit the three lowest ones are composed primarily of seniority $v=1$ components. A strict jj coupling scheme does not hold here either, which can affect the validity of the Brennan-Berstein coupling rules.

The simplest configurations expected to contribute to the lowest states in ^{62}Cu are listed in Table III. The contributing orbits are listed more or less in the order of increasing energy, with the $\pi p_{3/2}$ orbit expected to dominate the lower-lying configurations. The predicted lowest-lying states for each configuration were obtained by applying the Brennan-Bernstein coupling rules: The "strong" rule, $R1$,

$$J=|j_1-j_2|,$$

for

$$j_1=l_1\pm\tfrac{1}{2} \quad \text{and} \quad j_2=l_2\mp\tfrac{1}{2};$$

the "weak" rule, $R2$,

$$J=|j_1\pm j_2|,$$

for

$$j_1=l_1\pm\tfrac{1}{2} \quad \text{and} \quad j_2=l_2\pm\tfrac{1}{2};$$

and the particle-hole "weak" rule, $R3$, where the spin is less certain but tends torward

$$J=j_1+j_2-1.$$

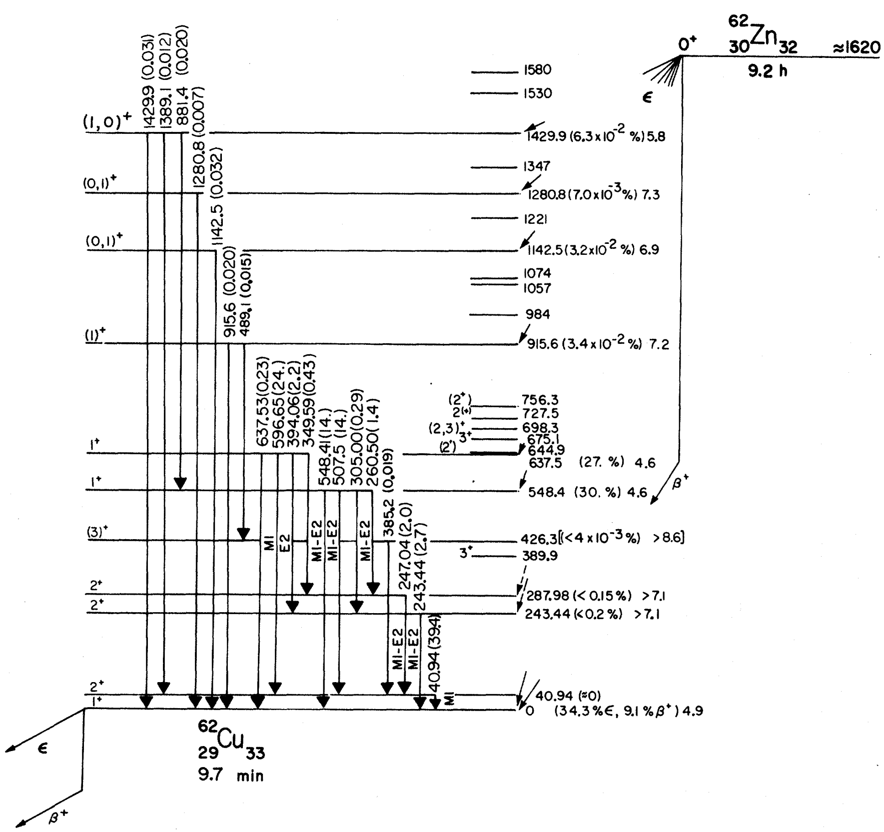

FIG. 5. ^{62}Zn decay scheme. States known from in-beam γ-ray and reactions studies (Refs. 11 and 14) are shown as short lines.

TABLE II. Comparison of ^{62}Cu states seen via different experiments.

This work (β,γ) E (keV)	J^π	Antman, Pettersson, (Ref. 5) E (keV)	J^π	Roulston, Becker, and Brown (β,γ) (Ref. 6) E (keV)	J^π	Bakhru (β,γ) (Ref. 7) E (keV)	J^π	Hoffman and Sarantites (β,γ) (Ref. 8) E (keV)	J^π	Davidson *et al.* $(p,n\gamma)$ (Ref. 11) E (keV)[c]	J^π	Morrison[a] $(^3He,d)$ (Ref. 14) E (keV)	l_p	Hjorth and Allen[b] (d,t) (Ref. 15) E (MeV)	l_n
0	1^+	0	1^+	0	$(1)^+$	0	1^+	0	1^+	0	1^+	0	1	0	1
40.94	2^+	40.88±0.01	2^+	41.5	$(2)^+$	42	2^+	40.84	2^+	40.84	2^+	42	1	0.04	1
243.44	2^+	243.40±0.05	2^+	244	+	...	...	243.43	2^+	243.43	2^+	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.26	1
287.98	2^+	287.89±0.10	2^+	289	+	287	2^+	287.86	2^+	287.86	2^+	290	1	...	...
...	...	...	...	...	...	...	...	...	...	389.9	3^+	...	...	...	...
426.3	(3^+)	...	...	...	...	...	...	...	...	426.1	3^+	428	1	0.41[d]	1
548.4	1^+	548.37±0.16	$0, 1^+$	549	$(0, 1)^+$	547	$(0, 1^+)$	548.25	1^+	548.25	1^+	551	1	0.54	1
637.5	1^+	637.45±0.25	1^+	638	$(0, 1)^+$	637	(1^+)	637.20	1^+	637.20	1^+	640	1	0.63	1
...	...	...	...	...	...	...	...	...	...	644.9	(2^+)	...	...	...	...
...	...	...	...	...	...	...	...	...	...	675.1	3^+	680	1+3	...	...
...	...	...	...	...	...	682[e]	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	698.3	$(2, 3)^+$	699	1	0.70	1
...	...	...	...	...	...	...	...	...	...	727.5	$2^{(+)}$	...	...	...	...
...	...	...	...	...	...	...	...	...	...	756.3	(2^+)	...	...	...	...
915.6	$(0, 1)^+$	...	...	...	...	...	...	...	...	915.5[d]	$(2)^+$[d]	908	1	0.90[d]	3
...	...	...	...	...	...	...	...	...	...	...	...	980	2	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1057	1+3	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1074	1	1.09	1
1142.5	$(0, 1)^+$	...	...	...	...	...	...	...	...	...	...	1144	3	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1221	1	...	...
1280.8	$(0, 1)^+$	...	...	...	...	...	...	...	...	...	...	1285	1+3	1.27[d]	...
...	...	...	...	...	...	...	...	...	...	...	...	1347	1+3	...	...
1429.9	$(1, 0)^+$	...	...	...	...	...	...	...	...	...	...	1432	1	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1484?	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1530	1	...	...
...	...	...	...	...	...	...	...	...	...	...	...	1580	2	...	...

[a] These are given only up to the Q_ϵ (≈1620 keV). As ^{61}Ni has a $\frac{3}{2}^-$ ground state, $l_p=1$ allows the ^{62}Cu final state to be $0^+ \to 4^+$, $l_p=2$ allows it to be $0^- \to 5^-$, etc.

[b] These are given only up to the Q_ϵ (≈1620 keV). As ^{63}Cu has a $\frac{3}{2}^-$ ground state, the final J^π values allowed by the various l_n waves are the same as in the $(^3He,d)$ reaction above.

[c] Davidson *et al.* quote the more precise energies of Hoffman and Sarantites wherever they are available.

[d] These states may or may not correspond to the states listed in the same row as seen via other experiments.

[e] Based on a 682-keV γ ray that was not seen by the other groups.

For the neutrons it is not at all clear whether the $p_{3/2}$ occupancy is such that it should be considered particle or hole, so both particle-particle and particle-hole predictions are listed.

Phillips and Jackson[26] measured the magnetic moment of the ground state of ^{62}Cu by the atomic-beam magnetic-resonance method and obtained $\mu_I = -0.380\mu_N$. They then performed effective-interaction shell-model calculations for ^{58}Cu, ^{60}Cu, and ^{62}Cu, similar to and based on the method of Auerbach.[25] They were able to reproduce the magnetic moments of ^{60}Cu and ^{62}Cu moderately well and the positions of the states in ^{58}Cu quite well. However, the states in ^{60}Cu and particularly in ^{62}Cu were not reproduced at all well. For example, they failed to predict the 40.94-keV 2^+ state, the 389.9- and 426.3-keV 3^+ doublet, and the 548.4- and 637.5-keV 1^+ states. As they restricted themselves to seniority-0 and -2 configurations, it was suggested that including seniority-4 and -6 components should improve the results. The principal conclusion arising from their calculations was that the wave functions of the odd-odd Cu states are indeed complex and there is no dominant configuration present even in the lower-lying states. Following their results, there has been a tendency to shy away from trying to assign definite configurations to any of these states.

We feel, however, that the Phillips and Jackson calculations suffer more from a choice of unrealistic single-particle energies. Following Auerbach's neutron-configuration calculations,[25] they set the single-particle energies at the $^{57}_{28}$Ni$_{29}$ values, viz. $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ at 0, 0.78, and 1.08 MeV, respectively. A glance at Fig. 6 will show this not to be completely suitable for the proton states. And for the neutron state it is perhaps even more unrealistic. The neutron orbits

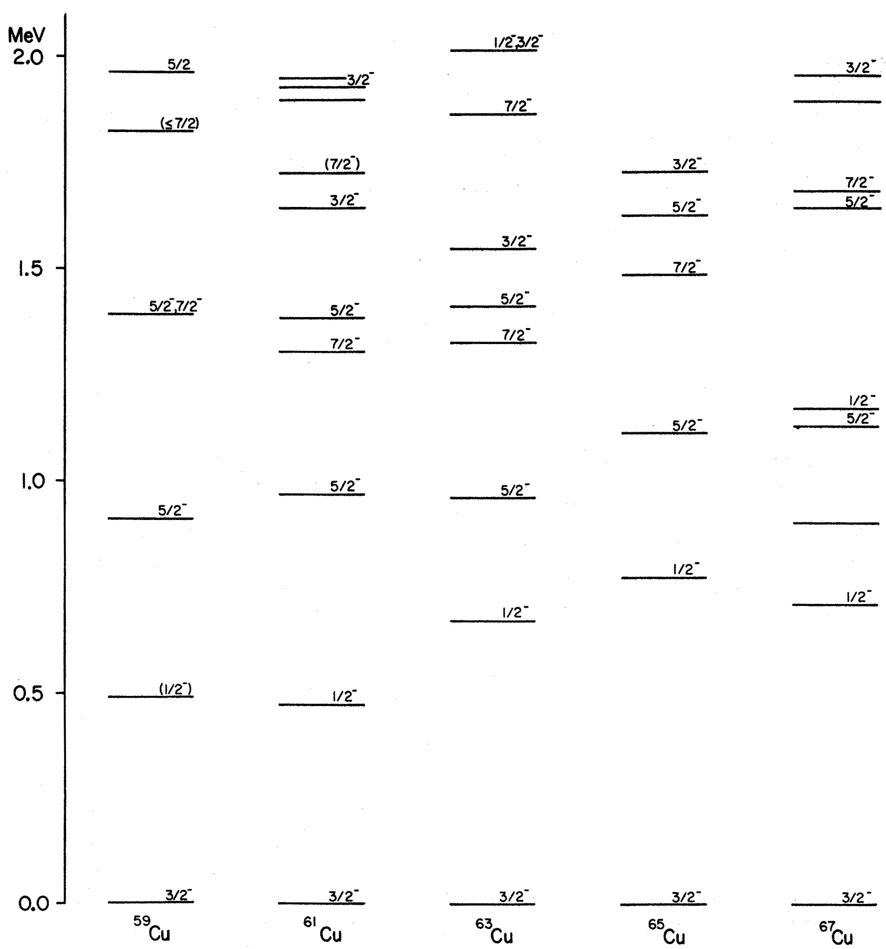

FIG. 6. States in the odd-mass Cu isotopes used in determining the odd-proton components of ^{62}Cu states. These were obtained from Ref. 22.

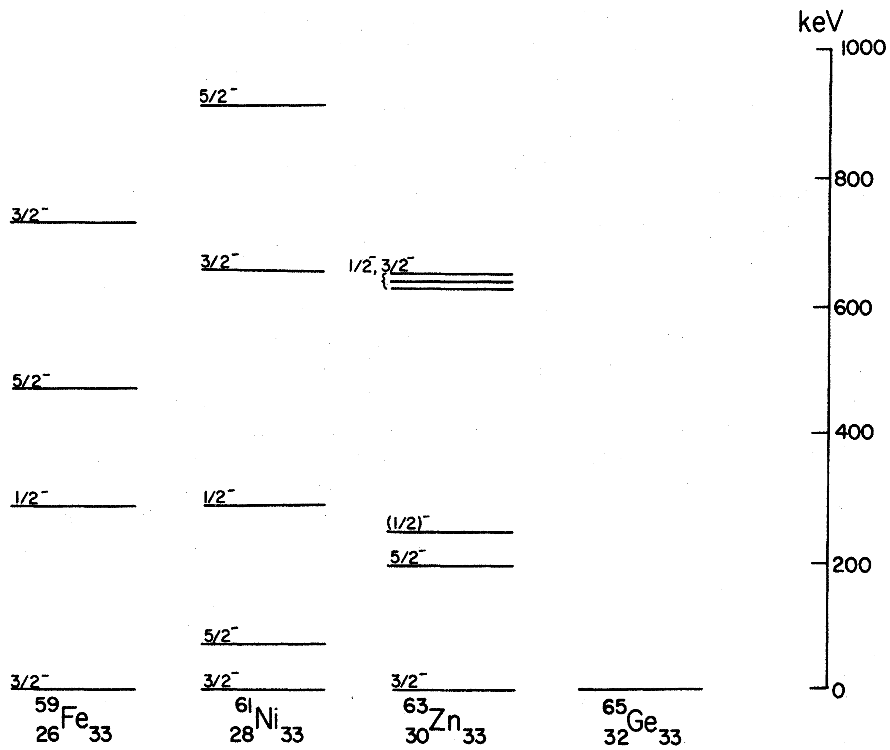

FIG. 7. States in the odd-mass $N=33$ isotones used in determining the odd-neutron components of ^{62}Cu states. These were obtained from Ref. 23.

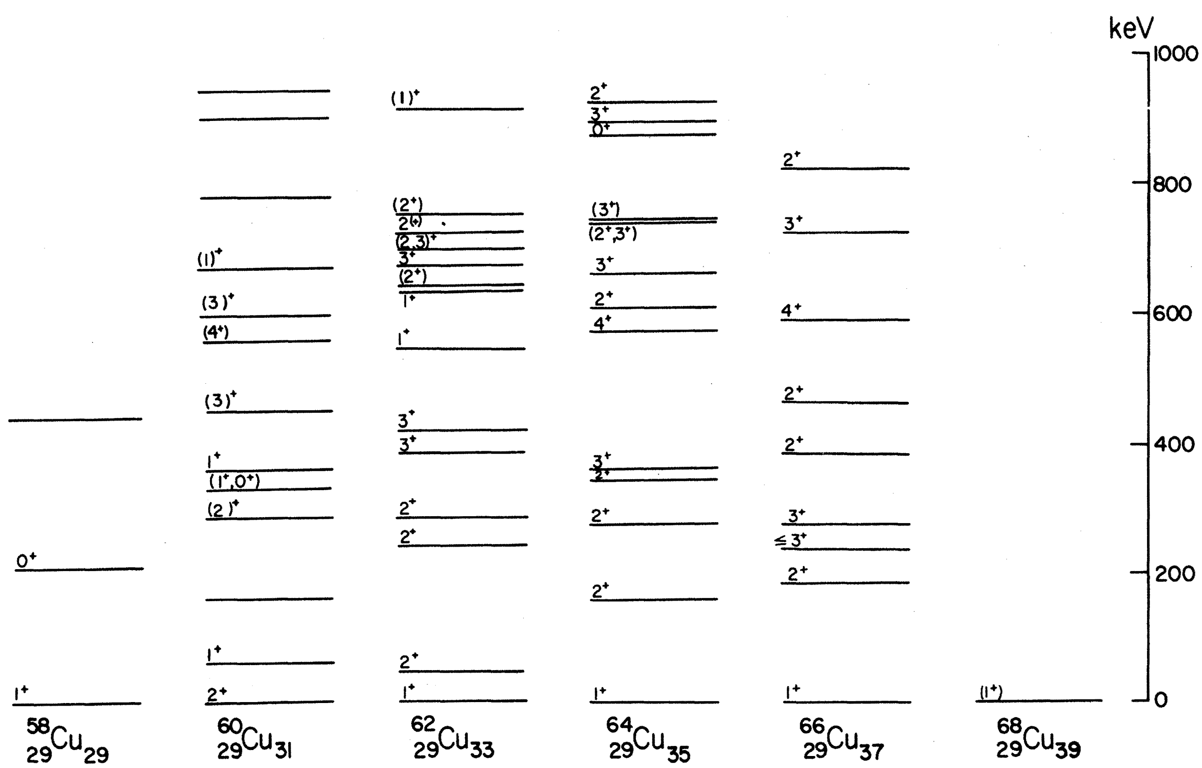

FIG. 8. Systematics of states in the odd-odd Cu isotopes. The data come from Ref. 27.

are moving rapidly with respect to one another in the region above $N=28$, and the continued presence of $\frac{3}{2}^-$ ground states in even-odd nuclei above $N=31$ implies that the $f_{5/2}$ and $p_{3/2}$ orbits have crossed. This wide variation in the positions of the single-particle orbits is also reflected in the states of the odd-odd Cu isotopes themselves, as illustrated in Fig. 8. Thus, the single-particle energies used in the calculations could well have resulted in an artificial complexity of the wave functions. In an odd-odd nucleus with the density of low-lying states as in ^{62}Cu there is undoubtedly considerable configuration mixing; yet the particle-transfer reactions,[14-16] the β-decay $\log ft$ values, and even the tendency for γ decay from higher-lying states to be selective all point toward an estimate that most of the lower-lying states must have one or a few dominant configurations. Our following remarks, necessarily qualitative pending more complete calculations, will delve into this further.

The 1^+ ground state of ^{62}Cu had been assigned the configuration, $[(\pi p_{3/2})(\nu p_{3/2})^{-1}]_{1^+}$, by Brennan and Bernstein, who considered this to be an example of the violation of their weak particle-hole coupling rule. Actually, the configuration, $[(\pi p_{3/2})(\nu f_{5/2})]_{1^+}$, is just as likely and does not violate a coupling rule. {With respect to $Z=N=28$ and bearing in mind that the occupancy of the neutrons is spread out at least over the $p_{3/2}$ and $f_{5/2}$ orbits, the configuration should be written as $[(\pi p_{3/2})(\nu f_{5/2})^{2V^2+1}(\nu p_{3/2})^{4-2V^2}]_{1^+}$, where V^2 is the probability for occupation of the $f_{5/2}$ orbit by a pair of neutrons.} The β^+/ϵ decay is consistent with either of these configurations, for it involves $\pi p_{3/2} \to \nu p_{3/2}$ ($\pi p_{3/2} \to \nu p_{1/2}$ is probably mostly involved in populating higher states) and merely indicates that in the ^{62}Zn ground state there must be sufficient vacancy in the $\nu p_{3/2}$ orbit for the transition to proceed rapidly, again consistent with the $\nu p_{3/2}$ and $\nu f_{5/2}$ orbits having crossed.

The 40.94-keV 2^+ state could have the configuration $[(\pi p_{3/2})(\nu p_{3/2})^{\mp 1}]$ as a major component. (The $\mp$ is included in the exponent because the relative occupations of the $\nu p_{3/2}$ and $\nu f_{5/2}$ orbits are not known – the – is perhaps slightly preferred because of the coupling rules but is by no means certain.) However, the configurations $(\pi p_{3/2})(\nu f_{5/2})$ and $(\pi p_{3/2})(\nu p_{1/2})$, also can produce 2^+ states, as can some higher-lying configurations involving other proton orbits. The 243.44- and 287.98-keV 2^+ states could have these configurations as components of their wave functions. Now, although there must be some configuration mixing among these three states, the γ-ray branching is an indication that each retains a dominant configuration (*indication*, nothing stronger, for the primary inference from γ-ray branching is just that the pair of connected states is similar; however, very complex states tend to "spray" in their γ-ray deexcitation because of the lack of coherent enhancement among the many components). A self-consistent picture would be that the 287.98-keV state is predominantly $[(\pi p_{3/2})(\nu p_{1/2})]_{2^+}$ and its transition to the 40.94-keV state would be $\nu p_{1/2} \to \nu p_{3/2}$, whereas the missing transition to the ground state would be the slower ($M1$) $\nu p_{1/2} \to \nu f_{5/2}$; similarly, the 243.44-keV state could be predominantly $[(\pi p_{3/2})(\nu f_{5/2})]_{2^+}$, and its transition to the ground would involve only a recoupling. None of these 2^+ states would be expected to or does receive β^+/ϵ population directly from ^{62}Zn.

The only likely configurations that can produce 3^+ states are $(\pi p_{3/2})(\nu p_{3/2})$, $(\pi p_{3/2})(\nu f_{5/2})$, and the somewhat higher-lying $(\pi p_{1/2})(\nu f_{5/2})$. The 389.9-keV 3^+ state was observed by Sunyar *et al.*[12] to have a half-life of 11.5 nsec and to decay to the 40.94- and 243.44-keV states, whereas the 426.3-

TABLE III. Possible configurations for low-lying states in ^{62}Cu.

Proton orbit	Neutron "orbit group"	States produced	Predicted lowest-lying states: Particle-particle coupling [a]	Predicted lowest-lying states: Particle-hole coupling [a]
$p_{3/2}$	$p_{3/2}$	0^+, 1^+, 2^+, 3^+	3^+, 0^+	2^+
	$f_{5/2}$	1^+, 2^+, 3^+, 4^+	1^+	1^+
	$p_{1/2}$	1^+, 2^+	1^+	1^+
$p_{1/2}$	$p_{3/2}$	1^+, 2^+	1^+	1^+
	$f_{5/2}$	2^+, 3^+	3^+	2^+
	$p_{1/2}$	0^+, 1^+	1^+	0^+
$f_{5/2}$	$p_{3/2}$	1^+, 2^+, 3^+, 4^+	1^+	1^+
	$f_{5/2}$	0^+, 1^+, 2^+, 3^+, 4^+, 5^+	5^+, 0^+	4^+
	$p_{1/2}$	2^+, 3^+	3^+	2^+

[a] Using Brennan-Bernstein's rules $R1$ and $R2$ for p-p coupling and $R3$ for p-h coupling.

keV 3^+ state has a half-life too short to be detected in their measurements. The latter was also populated quite strongly in the particle-transfer reactions. The implication is that it is primarily the $[(\pi p_{3/2})(\nu p_{3/2})^{\mp 1}]_{3^+}$ state, while the 389.9-keV state is primarily $[(\pi p_{3/2})(\nu f_{5/2})]_{3^+}$, its half-life resulting from the slow transition, $\nu f_{5/2} \rightarrow \nu p_{1/2}$ (l and j forbidden if $M1$).

The lowest known 2^+ one-phonon quadrupole vibrational state in a neighboring even-even nucleus is the 991.6-keV state[28] in ^{64}Zn, so we do not expect core-coupled states lying much below this energy in ^{62}Cu. However, by the time the 548.4- and 637.5-keV 1^+ states are reached, the level density is rising rapidly, and components of higher seniority are undoubtedly becoming more important. And even the simple configurations allow many ways of producing 1^+ states, as can be seen in Table III. Thus, these states would be expected to contain many components, and this is consistent with their nonselective γ-ray depopulation. The $\log ft$ values of 4.6, however, are the lowest in the decay scheme. The fastest β transition should be the Gamow-Teller $\pi p_{3/2} \rightarrow \nu p_{1/2}$, so both states should contain an appreciable $\nu p_{1/2}$ component, perhaps in a configuration such as $[(\pi p_{3/2})(\nu p_{1/2})]_{1^+}$.

It should be emphasized that there has been considerable oversimplification in the foregoing. However, it demonstrates that one can explain much on the basis of simple configurations. The need now is for further calculations using perhaps fairly realistic starting points.

ACKNOWLEDGMENTS

We thank Dr. H. G. Blosser and H. Hilbert for their aid in operating the MSU cyclotron. Other members of the MSU nuclear chemistry and physics spectroscopy groups, past, and present, including Dr. K. L. Kosanke, Dr. R. E. Doebler, Dr. R. W. Goles, Dr. R. R. Todd, Dr. L. E. Samuelson, and R. B. Firestone, were most helpful in data collection and reduction. We thank Dr. G. Morrison, Argonne, for very useful discussions and for sharing with us his data prior to publication. We also thank Dr. B. H. Wildenthal for his critical reading of the manuscript. Mrs. Peri-Anne Warstler was helpful in preparing the manuscript at a distance.

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‡Work supported in part by the U. S. Atomic Energy Commission.

§Work supported in part by the U. S. National Science Foundation.

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PHYSICAL REVIEW C VOLUME 7, NUMBER 2 FEBRUARY 1973

Spin-Orbit and Target Spin Effects in Helion Elastic Scattering*

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(Received 28 August 1972)

The well depth of the spin-orbit term for the helion-nucleus optical-model potential was determined by performing parameter searches for elastic scattering data at successive fixed values of V_s. Resulting plots of χ^2/N vs V_s show consistent minima for the 13 data sets used. Elastic angular distributions studied were for ^{60}Ni at four energies between 35 and 71 MeV and for three groups of neighboring even- and odd-mass targets at energies between 60 and 71 MeV. The χ^2/N vs V_s plots for all the even-mass ($I=0$) targets have minima at values of V_s between 2.0 and 3.0 MeV, while the plots for all the odd-mass ($I\neq 0$) targets have minima about 1 MeV greater (3.0 to 4.0 MeV). This difference in the best-fit values of V_s is consistent over a wide range of target mass and of scattering energy, and suggests the presence of a detectable target spin interaction in helion elastic scattering.

I. INTRODUCTION

The well established need for a spin-orbit term in the nucleon-nucleus optical-model potential suggests the use of a similar term in the helion-nucleus optical potential. Although theoretical estimates[1,2] predict a spin-orbit well depth between 2 and 3 MeV for helions, previous attempts[3-5] to measure the strength of this interaction have suffered from serious ambiguities. Hodgson[3] has pointed out that it is unwise to attempt to deduce the depth of the spin-orbit term from mere improvement of fits to one or two angular distributions, and that one should look for a consistent effect in fits to a large number of data sets. This is true because inclusion of the spin-orbit term usually produces only minor improvement. In fact many previous optical-model analyses of helion elastic scattering have ignored it altogether.

When experimental angular distributions for scattering at intermediate energies extend into the backward hemisphere, however, significantly improved fits occur when the spin-orbit term is included in the potential. In a previous study of the elastic scattering of 59.8-MeV helions from ^{27}Al, we observed that a spin-orbit well depth of about 2.3 MeV is definitely indicated when large-angle data were included in the data set.[6] When the data set was reduced to contain only the data for angles forward of about 70°, however, satisfactory fits were obtained with no spin-orbit term.[6] These results suggest that both high-energy and large-angle data are required.

In addition to the projectile spin-orbit interaction, a similar but somewhat weaker interaction proportional to the spin and orbital angular momentum of the target nucleus is expected.[7] Preliminary evidence for such a term in the optical potential for helion elastic scattering has been reported.[8] More extensive evidence, however, is clearly desirable.

We report here the results of a study of the systematic effect of the spin-orbit term on optical-model fits to 13 angular distributions for helion elastic scattering from targets of a wide range of mass and for energies between 35 and 71 MeV.

II. DATA AND ANALYSIS

The targets, scattering energies, and angular ranges of the data sets used are listed in Table I.