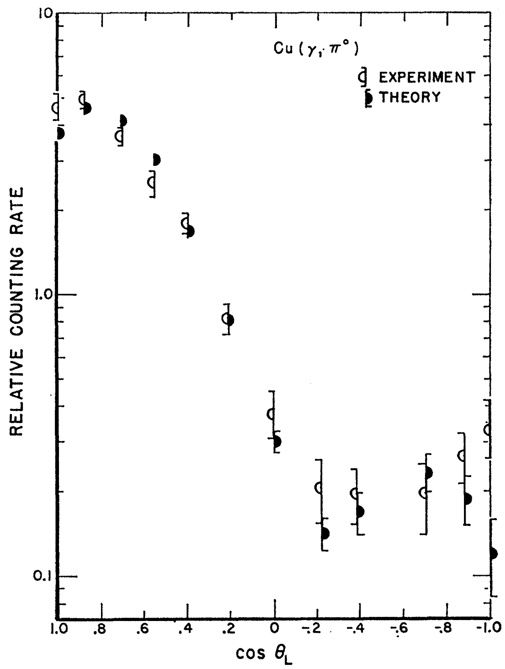

FIG. 12. Experimental data and best-shape fit for copper.

angular distributions for electron scattering, pion scattering, and neutron scattering, and from the energies of muonic x rays. The general agreement seems good.

The ability of the technique to reproduce the data is indicated in Table V, where the results of this experiment are compared to the results obtained for the same nuclei reported in the earlier SLP paper.

TABLE V. Comparison of rms radii obtained in this experiment and the earlier Schrack-Leiss-Penner (SLP) paper for a trapezoidal model with $t=2.5$ using best shape as criterion of fit.

Element	This experiment	SLP
C	2.14±0.07	2.12±0.14
Al	2.73±0.1	2.74±0.1
Cu	4.05±0.1	3.98±0.2

CONCLUSION

Nuclear size determinations from neutral pion photoproduction yield values of the rms radius of nuclear matter in generally good agreement with other techniques, but for nuclei with $A>40$ the model used for the reduction of the data does not appear to be adequate. No spin-dependent contributions are detected when the results obtained from Mg, Al, and Si are compared.

ACKNOWLEDGMENTS

The author is indebted to J. E. Leiss for continued support and to S. Penner and D. Isabelle for their assistance. Special thanks is extended to L. Franklin for his assistance in the taking of data and in various aspects of the analysis. The success of the experimental program was dependent on the skill of the synchrotron operators William Page and Alex Filipovich in producing the required photons.

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Low-Lying Levels in ^{50}V and ^{58}Co Studied with the (p,d) Reaction*

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The low-lying levels in the odd-odd nuclei ^{50}V and ^{58}Co were studied by means of the (p,d) reaction produced with 22-MeV protons from the ORNL 86-inch cyclotron. The deuteron spectra were obtained with a magnetic-spectrograph system having an over-all energy resolution of about 30 keV. The levels observed in ^{50}V are compared with recent calculations on $f_{7/2}$ shell nuclei. The levels observed in ^{58}Co are used to calculate the expected level scheme for ^{56}Co.

I. INTRODUCTION

THE study of levels in odd-odd nuclei is particularly important in attempting to characterize the nature of the nuclear residual interaction as it acts between neutrons and protons. The nature of the residual interaction as it acts between identical particles is reasonably well established by the large body of experimental data that exists on the energy levels in even-even nuclei. Similar data for odd-odd nuclei are quite scarce.

The characteristic close spacing of levels in odd-odd nuclei requires experimental study with good energy resolution. Since the spins of these levels usually span a rather large range of values, often some levels of interest cannot be populated in decay-scheme-type studies. Except for the very light nuclei, all stable odd-proton nuclei have an even number of neutrons. A

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particularly convenient way of studying levels in odd-odd nuclei is, therefore, a neutron pickup reaction such as (p,d) and (d,t).[1,2] The selection rules governing these direct reactions aid in the characterization of the observed levels.[2]

Since the levels of odd-odd nuclei manifest the nature of the proton-neutron residual interaction, they may be used as input for, or checks on, effective-interaction calculations,[3,4] or for checks on calculations using phenomenological potentials.

This paper reports on a study of the levels of two odd-odd nuclei. One of the nuclei represents a mass region for which rather extensive shell-model calculations have been reported, the other represents a region where such calculations have not been done.

II. EXPERIMENTAL

The (p,d) reactions reported in this paper were studied with 22-MeV protons from the ORNL 86-in. cyclotron. A well-collimated proton beam is passed through a beam-analysis magnet and focused on a $\frac{1}{16}$-in. slit at the entrance of the scattering chamber. The beam-analysis magnet is a uniform-field 30° wedge used in an edge-focusing condition and bends the proton beam through an angle of 60°. The scattering chamber is a small 8-in. chamber similar to the one described by Bach *et al.*,[5] and is used only as a vacuum seal allowing rotation of the detector about the target. The entrance collimator, target, and Faraday cup are supported on the exit pipe of the beam-analysis magnet.

The deuterons are detected with a second uniform-field wedge magnet which also employs non-normal entry and exit of the particles to obtain double focusing. The optics of the particle-analysis magnet are shown in Fig. 1. The deuterons are recorded on nuclear emulsion plates. A single 1- by 6-in. plate is used for most exposures. Sufficient absorbers were placed in front of the nuclear plate to prevent particles other than deuterons from reaching the emulsion.

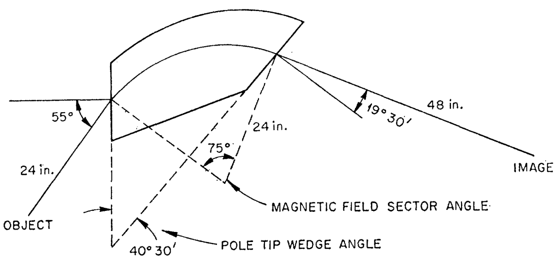

FIG. 1. Magnetic optics of the particle-analysis spectrograph.

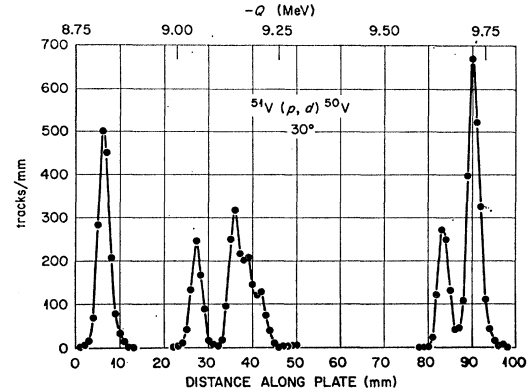

FIG. 2. Typical deuteron spectrum from the $^{51}V(p,d)^{50}V$ reaction observed at 30°. The ground-state peak is at the far left.

The thickness of both targets was about 1.0 mg/cm^2. The over-all resolution of the magnetic-analysis system is 25 to 30 keV.

III. LEVELS IN ^{50}V

From a simple shell-model standpoint, ^{50}V should have three protons in the $1f_{7/2}$ level and seven neutrons (or one neutron hole) in this same level. The low-lying states are expected to arise primarily from the coupling of this neutron hole with the three protons. These states are reached in the (p,d) reaction by picking up one of the $1f_{7/2}$ neutrons from the ^{51}V ground state. These levels have been calculated in the recent work of McCullen, Bayman, and Zamick on nuclei in the $1f_{7/2}$ shell.[4]

A typical spectrum from the $^{51}V(p,d)^{50}V$ reaction is shown in Fig. 2. Previously reported work on this reaction has shown that almost all of the $l=3$ strength appears within an MeV of the ground state.[6] That work, however, could only resolve three groups of levels in this energy band. An examination of Fig. 2 shows that there are at least seven levels in this region. A comparison of the levels seen in this work with the recent (p,d) work of Whitten and Kashy[7] is shown in Fig. 3. They were unable to resolve a broad peak at about 0.35 MeV. In our work, this peak consistently appears to be three levels.

Also shown in Fig. 3 are the levels in ^{50}V as taken from the nuclear data sheets.[8] An alternative scheme proposed in the original investigation[9] is also given. The correspondence between the (p,d) data and the older (p,n) threshold data is certainly not clear. Our observed Q value for the ground-state (p,d) reaction is

[1] R. K. Sheline, C. Watson, and E. W. Hamburger, Phys. Letters **8**, 121 (1964).
[2] R. F. Sweet, K. H. Bhatt, and J. B. Ball, Phys. Letters **8**, 131 (1964).
[3] K. H. Bhatt and J. B. Ball, Nucl. Phys. **63**, 286 (1965).
[4] J. McCullen, B. Bayman, and L. Zamick, Phys. Rev. **134**, B515 (1964).
[5] D. R. Bach *et al.*, Rev. Sci. Instr. **27**, 516 (1956).
[6] J. C. Legg and E. Rost, Phys. Rev. **134**, B752 (1964).
[7] C. A. Whitten and E. Kashy, Bull. Am. Phys. Soc. **9**, 458 (1964) and C. A. Whitten (private communication).
[8] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C.) NRC 60-6-16, 60-5-18.
[9] G. J. McCallum, A. T. G. Ferguson, and G. S. Mani, Nucl. Phys. **17**, 116 (1960).

-8.815 ± 0.020 MeV, in excellent agreement with assigned mass values.[10]

A comparison of the calculations of Ref. 4 and the levels seen in this work is shown in Fig. 4. The length of the lines is proportional to the intensity expected and observed in the (p,d) reaction. The relative peak intensities stay reasonably constant with angle. Since the Q-value dependence of the cross section is small, over the range of excitation energy considered here, we have chosen to plot an average of experimental intensities in Fig. 4. Reasonably good correspondence is seen between the calculated and observed level spacings and intensities. The only large discrepancy is the strongly excited 905-keV state which appears to resemble a state predicted to lie about half an MeV higher in excitation. It is possible that relatively minor changes in the assumed (p,n) interaction could improve the over-all agreement.

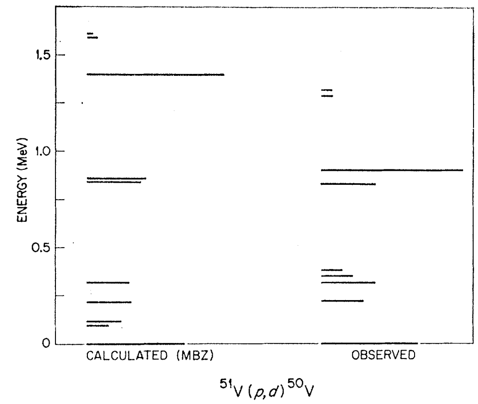

FIG. 4. Comparison of ^{50}V levels observed in this work with the calculations of Ref. 4. The length of the lines is proportional to the intensity in the (p,d) reaction.

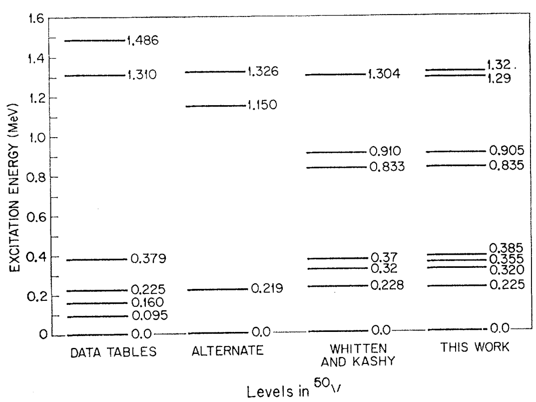

FIG. 3. Comparison of ^{50}V levels observed in this work with previously reported levels.

IV. Levels in ^{58}Co

On the basis of a simple shell-model picture, ^{58}Co should have seven protons (or one proton hole) in the $1f_{7/2}$ level and three neutrons (or one neutron hole) in the $2p_{3/2}$ level. The low-lying states are thus expected to arise primarily from the coupling of the proton and neutron holes. Four states are possible from this configuration. They have spin and parity 2+, 3+, 4+, and 5+. If the ground state of ^{59}Co differs only in having the $2p_{3/2}$ level filled with neutrons, then all four of these states will be populated in the (p,d) reaction and they will have an intensity proportional to $2J+1$.

A typical spectrum from the ^{59}Co(p,d)^{58}Co reaction is shown in Fig. 5. Previously reported work on this reaction[6,11] has shown that almost all of the $l=1$ strength is concentrated within about half an MeV of the ground state. The ground-state group is assumed to be the known 2+ and 5+ states,[8] shown by decay-scheme work to be 20 keV apart, which cannot be resolved in this work. A previously reported group at 360 keV is clearly resolved into two levels.

The weakly excited state at about 85 keV is observed at all angles. Since it does not move its position with angle, it cannot be due to a light-mass impurity in the target. Spectrographic analysis of the cobalt target showed no significant heavy-mass impurities. As a further check, a second cobalt target was prepared from an independently procured high purity metal sample. The experimental results with the second target were identical with the results from the first target and it is concluded that the 85-keV state is due to a level in ^{58}Co. This additional level, although weakly excited, points to a more complex shell model configuration than considered above.

Angular distributions for the ground-state group and the two strongly excited higher levels are shown in Fig. 6. The solid curves are typical distorted-wave Born approximation calculations for $l=1$ neutron transfers in this mass region.[11] The filling of the minima at 30°, particularly for the ground-state group, may also be an

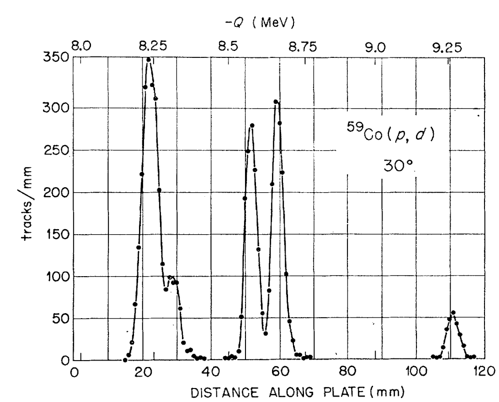

FIG. 5. Typical deuteron spectrum from the ^{59}Co(p,d)^{58}Co reaction observed at 30°. The ground-state group is at the far left.

[10] L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, *Nuclear Data Tables*, edited by K. Way (National Academy of Sciences–National Research Council, Washington, D. C., 1960), Part 1.

[11] C. D. Goodman, J. B. Ball, and C. B. Fulmer, Phys. Rev. **127**, 574 (1962).

TABLE I. Relative intensities of the levels observed in the $^{59}Co(p,d)^{58}Co$ reaction.

Level (MeV)	Relative intensity	Tentative spin	$2J+1$
Ground	0.41	2 and 5	0.50
0.09	0.05	···	···
0.35	0.27	3	0.22
0.44	0.32	4	0.28
1.03	0.07	···	···

indication of the presence of a more complex configuration. In particular, it may indicate that these final states have a certain amount of parentage from pickup of $f_{5/2}$ neutrons in the ground state of ^{59}Co.

The relative intensities for the observed levels are listed in Table I. In the $2J+1$ column we have assumed the ground-state group to be the 2+ and 5+ and the two strongly excited states to be the 3+ and 4+. Although the general trend of the intensities goes as $2J+1$, the significant deviation is probably still another indication of the presence of mixing in the neutron configuration. Evidence for such mixing has also been observed by Legg and Rost.[6]

The structure of the ground-state group may be more complex than indicated here. There is some evidence in this work that the peak shape of this group changes with angle. This may indicate that the group is more than a doublet. It seems obvious that a more complete experimental elucidation of this spectrum is needed and that such an experiment requires a resolution of 15 keV or better.

V. CALCULATIONS OF LEVELS IN ^{56}Co

If the relative intensities of Table I are taken as an indication of the spins of the strongly excited levels, then

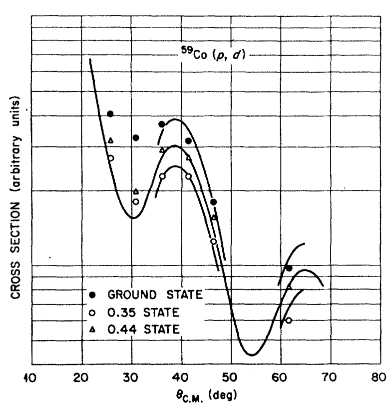

FIG. 6. Angular distributions for the strongly excited states in the $^{59}Co(p,d)^{58}Co$ reaction. The solid lines are distorted-wave Born approximation calculations for pickup of a $p_{3/2}$ neutron.

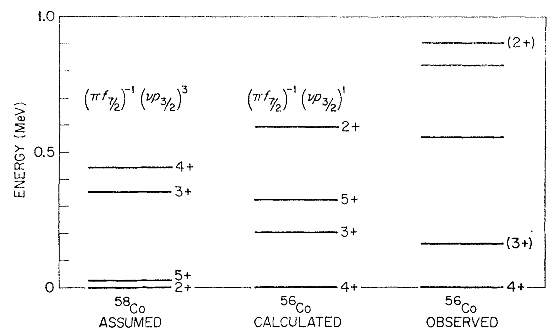

FIG. 7. The calculated spectrum of ^{56}Co, based on the tentative assignments shown at the left, compared with observed levels in ^{56}Co. The 2+, 5+ doublet in ^{58}Co is not resolved in this work.

we can tentatively assign spins to four of the levels as shown in Fig. 7. Since these levels are thought to arise primarily from the $f_{7/2}$-$p_{3/2}$ hole-hole coupling, we can test the reasonableness of this interaction by using the hole-hole interaction to obtain the hole-particle spectrum.[12] This should correspond to low-lying levels in ^{56}Co. The calculated levels are compared in Fig. 7 with levels, up to 1 MeV, observed in recent studies of ^{56}Co. The levels with tentatively assigned spin are observed in the decay of ^{56}Ni.[13] All of the levels are observed in the $^{56}Fe(p,n)^{56}Co$ reaction.[14] It is expected that the 5+ level, due to its high spin, will not be populated in the decay-scheme work. The state at 0.56 MeV seen only in the (p,n) study may correspond to this 5+ level. This same conclusion is reached by Vervier in some preliminary calculations[15] for ^{56}Co.

Although the agreement shown in Fig. 7 is not spectacular, it is somewhat better than might have been expected under the circumstances of strong neutron configuration mixing. This qualitative agreement supports the level assignments made for ^{58}Co.

VI. SUMMARY

The low-lying levels of ^{50}V are found to be in quite reasonable agreement with levels expected on the basis of calculations for nuclei in the $f_{7/2}$ region. The observed levels in ^{58}Co indicate the need to include at least two shell-model levels in the neutron configuration. The re-examination of the neutron pickup reaction in ^{59}Co with better resolution seems a prerequisite to any complete shell-model calculations in this region.

[12] A. de-Shalit and I. Talmi, *Nuclear Shell Theory* (Academic Press Inc., New York, 1963), p. 236.

[13] D. O. Wells, S. L. Blatt, and W. E. Meyerhof, Phys. Rev. **130**, 1961 (1963).

[14] J. D. Anderson, C. Wong, and J. McClure, Nucl. Phys. **36**, 161 (1962).

[15] J. Vervier, Phys. Letters **7**, 200 (1963).