B. Determination of $A_2(\gamma)$ and $A_4(\gamma)$ Coefficients

The $\gamma(570)$-$\gamma(1064)$ angular-correlation measurements yielded the results shown in Table II for the $A_2(\gamma)$ and $A_4(\gamma)$ coefficients, which are compared there with the values given by other authors.[9]

C. Determination of $b_2(K)$, $b_2(L)$, and $b_2(M)$ Particle Parameters

From Tables I and II, experimental values of the particle parameters $b_2(K)$, $b_2(L)$, and $b_2(M)$ were derived for both cascades and are quoted in Table III.

D. Determination of $A_4(e)A_4(\gamma)$ Coefficients

The b_4 particle parameters were derived from a recurrent relation taking the experimental values obtained for the b_2 parameters (see Table IV). Accordingly, from the values of the $A_4(\gamma)$ coefficients, the corresponding $A_4(e)$ coefficients were obtained and are quoted in Table V.

V. DISCUSSION

Experimental determination of particle parameters for the three main shells corresponding to the 570- and 1064-keV transitions in Pb^{207} are presented. Previous work performed by Kleinheinz *et al.*[9] is in fairly good agreement for the K shell and $L+M$ shells. The method introduced for measuring electron-γ angular correlations, turns out to be comparable with methods in which magnetic β-ray spectrometers have been used.

Furthermore, agreement is found with the theoretical values of particle parameters obtained by Hager and Seltzer[5] for the three main shells. Accordingly, the conversion process in Pb^{207} seems to exhibit neither anomalous behavior nor an interaction with the K hole when the 1064-keV conversion occurs.

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Reaction ^{116}Sn(α, ^{3}He) at 65.7 MeV*

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Differential cross sections for ^{116}Sn(α, ^{3}He) with 65.7-MeV α particles were measured from 15° to 80°. Data were obtained for ^{3}He groups corresponding to excitation energies of 0.0, 0.16, 0.32, 0.72, 1.03, 1.25, 1.58, and 3.20 MeV in ^{117}Sn. The angular distributions were well fitted by zero-range distorted-wave predictions. The spectroscopic factors are generally in good agreement with those obtained in a (d, p) experiment.

I. INTRODUCTION

In a previous paper,[1] spectroscopic factors from distorted-wave analyses of ^{90,91,92}Zr(α, ^{3}He) experiments at 65 MeV were compared with similar results from Zr(d, p) experiments at 15 MeV. The spectroscopic factors agree for $l=2$ transfers to states of low excitation, but large discrepancies were observed for transfers assigned by the (d, p) experiment as $l=4$. For these transitions, the (α, ^{3}He) spectroscopic factors were consistently twice as large as the (d, p) spectroscopic factors. The present study of ^{116}Sn(α, ^{3}He) at 65.7 MeV was undertaken in order to check the validity of the distorted-wave theory for (α, ^{3}He) reactions. Two considerations led to this choice. First, the residual nucleus has well-separated levels populated by $l=0$, 2, 3, 4, and 5 transfers; and second, data are

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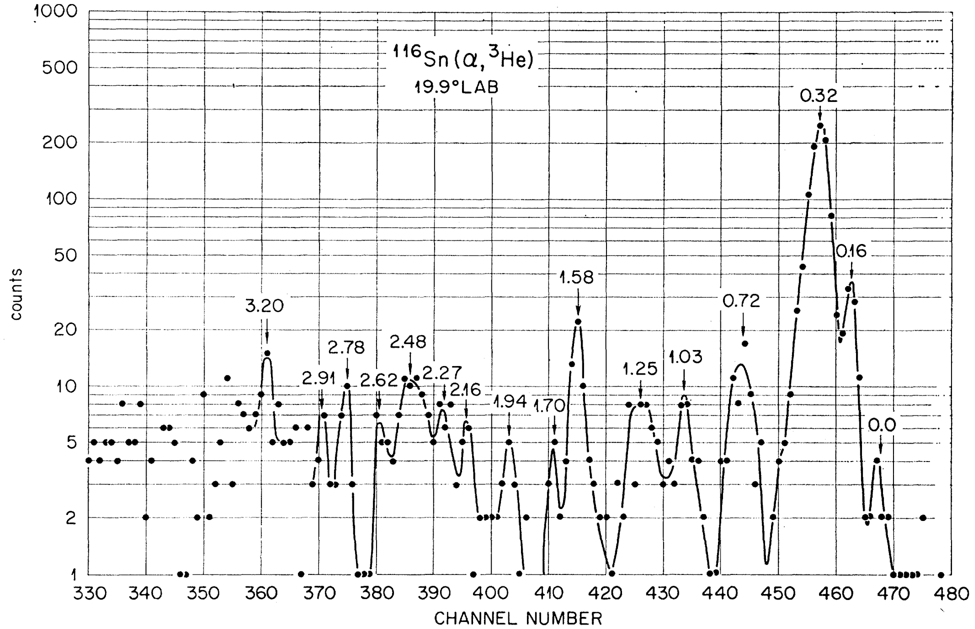

FIG. 1. The ^{116}Sn(α, ^{3}He) spectrum at 19.9° lab. The excitation energies are given for the prominent peaks.

available[2] on the same levels from the reaction ^{116}Sn(d, p) at 15 MeV. The elastic and inelastic scattering of the α particles were recorded simultaneously; the cross sections and distorted-wave analyses of these data have already been reported.[3]

II. EXPERIMENTAL DETAILS

The measurements were made in the 30-in.-diam scattering chamber at the Oak Ridge Isochronous Cyclotron with the slit and detector arrangement described previously.[1] A (ΔE, E) counter telescope consisting of two silicon detectors was used to separate ^{3}He particles from α particles. The angular acceptance of the counter telescope was ~1° and the data were taken at 1° intervals between ~15° and 80°.

Two isotopically enriched metal foils were used as targets. The thinner one, 1.20 mg/cm^2, was 95.7% ^{116}Sn and was used for angles below 50° lab; the other was 5.0 mg/cm^2 thick. Straggling in the target was estimated to be 42 keV for the thin target and 90 keV for the thick target. The beam energy spread was about 65 keV and the kinematic spread about 50 keV. The remainder of the over-all resolution of ~110 keV for the thin target runs and 140 keV for the thick target runs was presumably due to the detectors.

III. DISTORTED-WAVE ANALYSES

The distorted-wave calculations were made in the zero-range approximation with local potentials by use of the computer program JULIE.[4] The form factor is the radial bound-state wave function of the stripped neutron. It is taken as the solution of Schrödinger's equation for a Woods-Saxon potential with $r_0=1.2$ F, $a=0.7$ F, and a depth adjusted to give an eigenvalue equal to the binding energy of the transferred nucleon. The effect of including a spin-orbit term was investigated.

TABLE I. Optical-model parameters used in distorted-wave calculations.[a]

Particle	V_0 (MeV)	W_0 (MeV)	r_0 (F)	a (F)	r' (F)	a' (F)
α	100.0[b]	53.7	1.352	0.667	$r_0'=r_0$	$a'=a$
^{3}He	196.9[c]	17.37	1.04	0.811	1.60	0.797

[a] The Coulomb potential was taken to be that of a uniformly charged sphere of radius $1.4A^{1/3}$ F.

[b] Potential A of Ref. 5.

[c] Potential C of Ref. 3.

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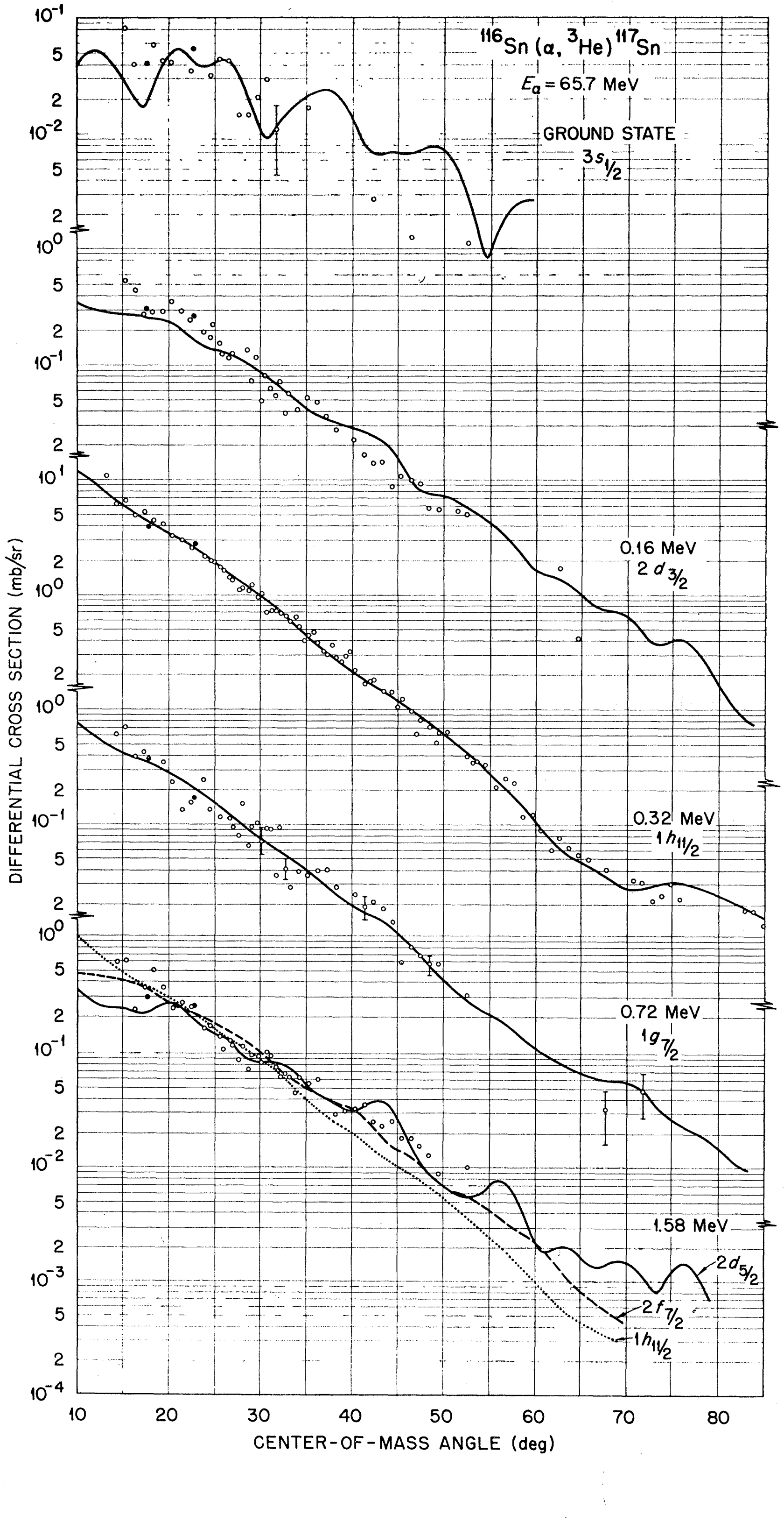

FIG. 2. Comparison of the ^{116}Sn(α, ^{3}He) angular distributions with zero-range distorted-wave calculations.

TABLE II. Spectroscopic factors for ^{116}Sn(α, ^{3}He) at 65.7 MeV with two choices of spin-orbit potential for the bound-state neutron.

Present results				(d, p) at 15 MeV[a]				
E^* (MeV)	Assumed l_j	S^b	S^c	E^* (MeV)	l_j	S	$S(\alpha, {}^3\text{He})/S(d, p)$ $r_s=1.2^b$	$r_s=1.06^c$
0.0	$s_{1/2}$	0.76	0.76	0.0	$s_{1/2}$	0.65	1.17	1.17
0.16	$d_{3/2}$	0.47	0.43	0.16	$d_{3/2}$	0.55	0.85	0.78
0.32	$h_{11/2}$	0.62	0.75	0.32	$h_{11/2}$	0.81	0.77	0.93
0.72	$g_{7/2}$	0.19	0.17	0.72	$g_{7/2}$	0.13	1.46	1.31
1.03	$d_{5/2}$	0.082		1.03	$d_{5/2}$	0.061	1.34	
1.25[d]	$d_{5/2}$	0.22		1.19	$d_{5/2}$	0.033		
1.25[d]	$f_{7/2}$	0.066		1.31	($f_{7/2}$)	0.029	1.93[e]	
				1.51	($d_{5/2}$)	0.020		
1.58[d]	$d_{5/2}$	0.43		1.59	($d_{5/2}$)	0.006	13.0[f]	
				1.67	($d_{5/2}$)	0.007		
1.58[d]	$f_{7/2}$	0.13						
1.58[d]	$g_{7/2}$	0.22						
1.58[d]	$h_{11/2}$	0.058						
3.20	$f_{7/2}$	0.113		3.22	($f_{7/2}$)	0.120	0.94	

[a] Reference 2.

[b] With spin-orbit parameters $r_s=1.2$ F, $a_s=0.7$, $\lambda=25$ (case A).

[c] With spin-orbit parameters $r_s=1.06$ F, $a_s=0.74$, $\lambda=25$ (case D).

[d] Calculations made with alternative spin values. The peak at 1.58 is probably primarily due to $h_{11/2}$ transfers.

[e] With $d_{5/2}$ part seen in (d, p) subtracted before comparison.

[f] Comparison of (α, ^{3}He) $d_{5/2}$ spectroscopic factor with sum of three values from (d, p).

A detailed study of the effect of optical-model parameters and a radial cutoff was made in earlier work.[1] For the exit channel of the present experiment (49–52-MeV ^{3}He) the potential[5] which best fits the elastic scattering of 51.3-MeV ^{3}He from ^{92}Zr was used (see Table I). This potential is very similar to one that has been found to give good fits to the elastic scattering of 20–50-MeV ^{3}He from various nuclei.[5–7]

The entrance-channel potential is based on elastic scattering of 65-MeV α particles from ^{116}Sn (Ref. 3). A wide choice of satisfactory α-particle parameters is available because of ambiguities in the fits.[3] Some theoretical arguments have been advanced for a potential satisfying the criterion that the real part of the α-particle optical potential be equal to the sum of the ^{3}He real potential and the potential for the bound-state neutron.[8] An attempt to find a potential satisfying this criterion at 65 MeV was unsuccessful.[3] It was found in earlier work[1] that an α-particle potential with $V_0 \simeq 100$ MeV fit the (α, ^{3}He) angular distributions well without radial cutoffs. The same is true for ^{116}Sn(α, ^{3}He), as was shown by a few trial calculations with various α-particle potentials. However, for all sets of potentials giving satisfactory fits to the angular distributions, the resulting spectroscopic factors were essentially the same. The potentials used for the results reported here are listed in Table I.

TABLE III. Bound-state parameters used in distorted-wave calculations.

	Central potential		Spin-orbit potential		
Case	r_0 (F)	a (F)	r_s (F)	a_s (F)	λ
A	1.2	0.7	1.2	0.7	25
B	1.2	0.7	···	···	0
C	1.2	0.7	1.2	0.7	6
D	1.2	0.7	1.06	0.74	25

The final state of the residual nucleus was assumed to consist of a single shell-model configuration. The distorted-wave cross section is given by

$$\frac{d\sigma}{d\Omega}=\frac{2J_B+1}{2J_A+1}\frac{NRS}{2s+1}\sigma_{\text{JULIE}}(\theta),$$

where J_A and J_B are the spins of the target and residual nuclei, respectively, and $s=\frac{1}{2}$ is the spin of the transferred neutron, S is the spectroscopic factor, and NR accounts for the overlap of the α particle and the ^{3}He-n system as well as the strength of the interaction causing the transition. The value of NR of 92.1 used here was obtained empirically in Ref. 5; it is in good agreement with a theoretical prediction by Bassel.[7]

IV. RESULTS AND DISCUSSION

The ^{3}He spectrum at 19.9° lab is shown in Fig. 1. The energy scale was established by use of the 0.0- and 0.32-MeV levels seen in the ^{116}Sn(d, p) experiment.[2] The other excitation energies agree well with levels seen in the (d, p) experiment. Angular distribu-

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[6] E. F. Gibson, B. W. Ridley, J. J. Kraushaar, M. E. Rickey, and R. H. Bassel, Phys. Rev. **155**, 1194 (1967).

[7] R. H. Bassel (private communication).

[8] R. Stock, R. Bock, P. David, H. H. Duhm, and T. Tamura, Nucl. Phys. **A104**, 136 (1967).

TABLE IV. Comparison of distorted-wave predictions for the cases listed in Table III. The average of the cross-section ratios from 15° to 40° is given.

Excitation energy (MeV)	Neutron orbital	Cross-section ratio A/D	B/D	C/D
0.16	$2d_{3/2}$	0.915	1.022	0.997
0.32	$1h_{11/2}$	1.206	0.928	0.994
0.72	$1g_{7/2}$	0.833	1.110	1.042

tions for five of the groups are shown in Fig. 2. Limited angular distributions were obtained for groups at 1.03, 1.25, and 3.20 MeV, but are not shown here.

The smooth curves in Fig. 2 are distorted-wave predictions; the corresponding spectroscopic factors are given in Table II. The spin values of the first four angular distributions were taken from the (d, p) results. The present data are consistent with these assignments. The slope of the 0.16-MeV $d_{3/2}$ prediction does not quite agree with the data. The result in Table II was obtained with the normalization shown in Fig. 2; the spectroscopic factor is 1.36 times larger if the normalization is made at forward angles.

The bound-neutron potential for the calculations of Fig. 2 included the usual spin-orbit term having a strength of 25 times the Thomas potential for nucleons ($\lambda = 25$). Optical-model analyses of elastic scattering of polarized protons have shown that the radius of the spin-orbit term is smaller than the radius of the central part of the potential.[9] The average parameter for the spin-orbit well given in Ref. 9 are $r_s = 1.064$ F and $a_s = 0.738$ F. With these parameters the spin-orbit contribution to the cross section would be smaller than with the conventional prescription mentioned above. A need for decreasing the spin-orbit effect has been observed also from comparison of experimental cross sections for $^{208}\text{Pb}(^3\text{He}, d)$ at 51 MeV with distorted-wave predictions.[10] Good agreement with the data could be achieved by reducing λ from 25 to 6 without changing r_s.

These ideas were explored for several of the transitions in the present work. Distorted-wave calculations were made with the four combinations of spin-orbit parameters listed in Table III. Case A is the conventional prescription while case B omits the spin-orbit term entirely. The predicted cross sections with $r_s = 1.2$ F and $\lambda = 6$ (case C) are very nearly the same as for $r_s = 1.06$ and $\lambda = 25$ (case D), as shown in Table IV. Thus the $\lambda = 6$ result from Ref. 10 supports the choice of the Ref. 9 geometry for the spin-orbit term.

Table II lists the spectroscopic factors for case A and, for some transitions, also for case D. The latter agree better with the (d, p) spectroscopic factors of Ref. 2. In fact, omitting the spin-orbit term (case B) gives better agreement than case A. However, the significance of these comparisons is somewhat questionable because the (d, p) calculations used arbitrary cutoffs in the radial integrals. Also, the spin-orbit potential used in the (d, p) work is not described in Ref. 2.

The tentative assignment of $f_{7/2}$ made in the (d, p) work for the state at 3.20 MeV is entirely consistent with the present results. The groups at 1.03 and 1.25 MeV are weak and the one at 1.25 MeV is a doublet or triplet, so the poor agreement with the (d, p) results may not be significant.

Three predictions are shown in Fig. 2 for the group at 1.58 MeV. Three states observed in the (d, p) experiment near 1.58 MeV were tentatively assigned spins and parities of $\frac{5}{2}^+$. The predicted $d_{5/2}$ angular distribution follows the $(\alpha, ^3\text{He})$ data well, but as shown in Table II the $d_{5/2}$ strength required is 13 times the sum of the strengths of the three states observed in the (d, p) experiments. The $f_{7/2}$ prediction fits the angular distribution well, but the spectroscopic factor in Table II implied by such an assignment would require that the (d, p) cross section be about ten times larger than was actually observed. A similar argument rules out the possibility of a $g_{7/2}$ assignment. An $h_{11/2}$ assignment is consistent with the (d, p) results. The present experiment leads to $S = 0.054$ if an allowance is made for the $d_{5/2}$ contribution known from the (d, p) experiment. A careful examination of the (d, p) angular distributions lends support to this idea—there is excess yield near 40° for the 1.59-MeV group in comparison with the neighboring $l = 2$ transitions. The $h_{11/2}$ angular distribution at 0.32-MeV peaks near 45°. If the excess yield in the 1.59-MeV group is assumed to be an $h_{11/2}$ transition, the observed intensity is consistent with our value of S.

V. CONCLUSIONS

The spectroscopic factors for the six well-resolved states agree quite well with the (d, p) results for l transfers from 0 to 5. This suggests that the discrepancies between $\text{Zr}(d, p)$ and $\text{Zr}(\alpha, ^3\text{He})$ discussed in Ref. 1 arise from incorrect assignments of angular-momentum transfer. If some of the groups previously assigned as $l = 4$ are, in part, $l = 5$, the discrepancies would disappear. [Recent experiments on $^{91}\text{Zr}(d, p)$ at 33 MeV with 25 keV resolution[11] show, in fact, that a number of previously observed particle groups are multiplets and include $l = 5$ transfers. Also many $l = 4$ groups were previously unresolved from stronger transitions of lower l value.]

The group at 1.58 MeV contains a transition to a level which is given a tentative assignment of $h_{11/2}$.

There is some evidence from the spin-orbit effect of the bound-state neutron that the spin-orbit radius should be smaller than the radius of the real well.

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