μ_{129} is proportionately smaller, for their product is fixed by the PAC experiment; the smaller value of μ_{129} is represented by the dotted line in Fig. 6, intersecting μ_{ground} at the point A'. We observe that the triangle $A'B'C'$ is larger than the triangle ABC; that is, the assumption that the true value of τ is greater than 144 psec leads to a greater discrepancy in the rotational interpretation. Only a smaller value of τ will cause the triangle to collapse, but a smaller value of τ is expressly not allowed because of the observed linewidth in the Mössbauer experiment, which establishes a lower limit for the mean life. In conclusion, we would note the complete absence of the next member of the rotational band which should lie at about 310 keV with a spin of $\frac{7}{2}$. It seems clear, then, that iridium-191 is not a rotational nucleus as conjectured.

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Levels in Pb^{207} from the $Pb^{208}(He^3, \alpha)Pb^{207}$ Reaction at 28 MeV

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α particles leading to states below 4.4 MeV excitation have been observed in the $Pb^{208}(He^3, \alpha)Pb^{207}$ reaction at 28 MeV. Angular distributions have been measured for strong groups leading to the known single-neutron hole states. Distorted-wave Born-approximation calculations show good agreement with the shapes of the measured angular distributions, and yield relative spectroscopic factors close to those predicted by the simple shell model, except for the $h_{9/2}^{-1}$ state at 3.43 MeV. Sixteen other weakly excited states are observed above an energy of 2.6 MeV. Most of these are apparently not observed in other reactions leading to Pb^{207} excited states.

INTRODUCTION

THE low-lying levels of Pb^{207} which are strongly populated in the $Pb^{208}(d, t)^{207}$ reaction[1] have been well identified as single-neutron hole states in the Pb^{208} doubly magic core. Because of the apparently simple nature of these states, we have studied the $Pb^{208}(He^3, \alpha)Pb^{207}$ reaction in order to determine the characteristics of this type of reaction on heavy nuclei.

Previous measurements have shown that this reaction provides useful spectroscopic information on light[2] and medium weight[3] nuclei. One of the striking features on heavy nuclei is that the cross sections for large angular momentum transfers ($l \sim 6$) are much greater than those for smaller l values. This occurs because a low-l transfer taking place at the nuclear surface suffers a strong hindrance due to the momentum mismatch between incident and emerging particles.

In the present measurements, the He^3 beam energy was 28 MeV, only slightly above the height of the Coulomb barrier. A distorted-wave Born approximation (DWBA) calculation yielded good fits to the measured angular distributions, and the relative spectroscopic factors extracted were consistent with the simple shell-model predictions for the low-lying states of Pb^{207}. Reasonably good discrimination of transfer l values could be obtained. The angular distributions and the relative spectroscopic factors were not strongly sensitive to the choice of parameters used in the DWBA calculation.

During the course of the present work, information concerning a recent study[4] of the $Pb^{208}(He^3, \alpha)Pb^{207}$ at

* Supported by a grant from the National Science Foundation.
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[1] G. Muehllehner, A. S. Poltorak, W. C. Parkinson, and R. H. Bassel, Phys. Rev. **159**, 1039 (1967).
[2] R. Stock, R. Bock, P. David, H. H. Duhm, and T. Tamura, Nucl. Phys. **A104**, 136 (1967).
[3] C. R. Bingham, M. L. Halbert, and R. H. Bassel, Phys. Rev. **148**, 1174 (1966).
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47.5 MeV became available. At that energy it was found that relative spectroscopic factors could be determined, but discrimination of transfer l values was difficult. In these studies at higher energies, it was found that spectroscopic factors for the weak transitions involving low-l transfers had uncertainties arising from contributions to the transition amplitude from the nuclear interior. In the present measurements, at energies near the height of the Coulomb barrier, these contributions from the interior of the nucleus appear to be less important and the data are more easily fitted.

EXPERIMENTAL

Measurements were carried out using the 28-MeV He^3 beam from the University of Rochester Model MP tandem Van de Graaff accelerator. Beam currents were typically 1 μamp on a 1 mm×1 mm target spot. Targets were prepared by evaporating isotopically enriched material (99.3% Pb^{208}) (obtained from Stable Isotopes Division, Oak Ridge National Laboratory) on carbon backings about 20 μgm/cm^2 in thickness. The target used in initial measurements had a thickness of about 160 μgm/cm^2 and yielded an energy resolution of about 40-keV full width at half-maximum (FWHM). This resolution was considerably worse than was expected, and apparently was caused by target deterioration under beam bombardment. In order to obtain better energy resolution for some of the weakly excited groups, measurements were made at a few angles using a target about 60 μgm/cm^2 in thickness. The energy resolution obtained with this target was about 25-keV FWHM.

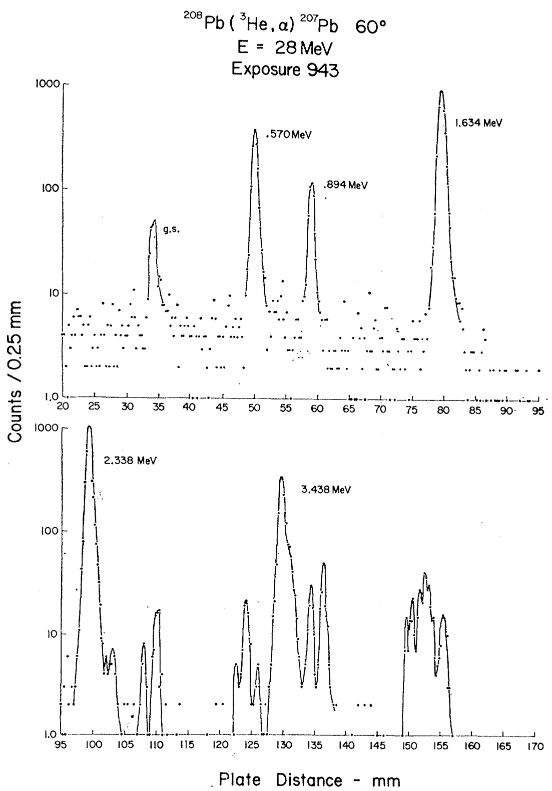

FIG. 1. Spectrum of α particles observed in the $Pb^{208}(He^3, \alpha)Pb^{207}$ reaction. The continuum near the ground-state group is probably produced by tritons as discussed in the text.

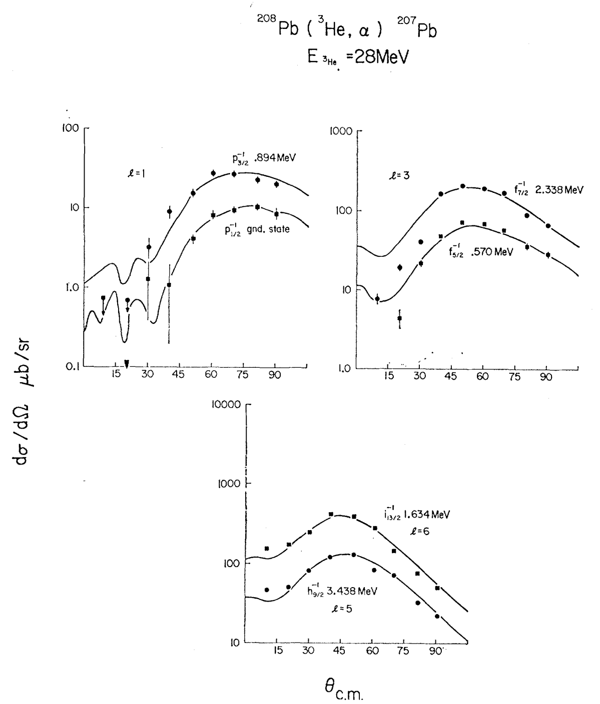

FIG. 2. Angular distributions of α's leading to known single-neutron hole states in Pb^{207}. The error bars indicate statistical uncertainties. The solid curves are the result of DWBA calculations.

Reaction products were analyzed in an Enge split-pole spectrograph and recorded on nuclear emulsions. Ilford-type KO emulsions provided reliable registration of α particles, with good discrimination against deuterons and protons. The plates were covered by an aluminum absorber 12 mil thick. The incident beam was monitored with a scintillation detector placed at a fixed angle of 45° in the scattering chamber, and absolute cross sections were obtained by comparison with the cross section for elastic scattering of He^3 from Pb^{208}. The latter was calculated[5] to be 0.97 times the Rutherford cross section.

Data were recorded at 10° intervals between 10° and 90° with the thick target and at 30°, 45°, 60°, and 75° with the thin target. A typical scan of one of the exposures taken with the thin target is shown in Fig. 1. The weak continuum up to an excitation energy of 1.5 MeV was observed in all exposures, and is probably caused by relatively low-energy tritons from the $Pb^{208}(He^3, t)Bi^{208}$ reaction proceeding to states

[5] G. R. Satchler (private communication).

TABLE I. Optical-model potentials used in DWBA calculations.

		V_0 (MeV)	W_0 (MeV)	r_0 (fm)	a (fm)	r_c (fm)	r_0' (fm)	a' (fm)
Set A	He^3	175	17.5	1.14	0.723	1.4	1.6	0.81
	α	206.8	25.8	1.41	0.519	1.3	1.41	0.519
	Bound state			1.25	0.65			
Set B	He^3	175	17.5	1.14	0.723	1.4	1.6	0.66
	α	187	25	1.35	0.574	1.3	1.35	0.574
	Bound state			1.25	0.65			

of high excitation in the residual nucleus. The absence of this background at plate positions corresponding to excitation energies above 1.5 MeV in Pb^{207} is probably due to the reduction in (He^3, t) cross section caused by the Coulomb barrier of the Bi^{208}. α's and tritons focused to the same spot in the focal surface have similar ranges, and it was not possible to make a clear discrimination between the α tracks in the known groups and the tracks in the continuous background. The measured cross sections have been corrected for the presence of this background under the peaks corresponding to known states.

Angular distributions for transitions to the previously identified single-neutron hole states are shown in Fig. 2. In addition to statistical uncertainties indicated by the error bars, the experimental points have relative uncertainties of about 5%. The absolute cross sections are believed to be accurate to within 20%. The solid curves are the result of a DWBA calculation,[5] normalized as described below. The calculation was performed with code JULIE, using the optical-model parameters shown as set A in Table I. The He^3 parameters were those used by Wildenthal *et al.*[6] in an analysis of the $Pb^{208}(He^3, d)Bi^{209}$ reaction at 51 MeV, and the α parameters were those used by Blair and Armstrong[7] in a study of the (t, α) reaction. The bound-state well had a Woods-Saxon shape with depth adjusted to give the observed binding energy. A spin-orbit potential was also included in the bound-state well. The spin-orbit potential had the Thomas form with the parameters of the bound-state well and a strength $V_{so}=1.5$ MeV. Wildenthal *et al.*[6] found that such a small value of V_{so} was necessary if the spin-orbit potential was constrained to have the same parameters as the bound-state well. Satchler *et al.*[4] have shown that similar results were obtained with the more usual value $V_{so}=6.88$ MeV provided that the radius and diffuseness of the spin-orbit well are adjusted independently of the bound-state well. A zero-range, local interaction was used in the calculation, without radial cutoff. A cutoff of 5 fm produced little change in the shape or magnitude of the predicted cross section; 8 fm produced increases of 16, 8, and 3% in the predicted cross sections for $l=1$, 3, and 6, respectively, with only small changes in shape.

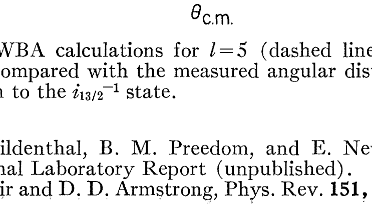

FIG. 3. DWBA calculations for $l=5$ (dashed line) and $l=6$ (solid line) compared with the measured angular distribution to the transition to the $i_{13/2}^{-1}$ state.

The agreement between measured and calculated angular distributions is seen to be generally good. The most serious disagreement occurs for small-l transfers at forward angles where both measured and calculated cross sections are quite small. The l dependence of the cross section is seen to be strong enough to provide an easy discrimination of angular distributions for l values differing by two units. The differences between the calculated angular distributions for l values differing by one unit may be rather small and comparable with those produced by varying the optical parameters or cutoff radius. The degree of discrimination possible is illustrated in Fig. 3, in which the data for the $l=6$ transition are compared with calculations for $l=6$ and $l=5$. The agreement is seen to be significantly better for the calculation with $l=6$.

An interesting feature of this reaction, also noted by Satchler *et al.*,[4] is the large enhancement of the cross section for high l values, similar to the behavior observed on lighter nuclei at lower energies.[8] In the (p, d) or (d, t) reactions, transitions involving small l transfers have the largest intrinsic cross sections. Thus measurements of both (p, d) and (He^3, α) cross sections will often provide complementary information in studying the single-particle structure of nuclei.

[6] B. H. Wildenthal, B. M. Preedom, and E. Newman, Oak Ridge National Laboratory Report (unpublished).
[7] A. G. Blair and D. D. Armstrong, Phys. Rev. **151**, 930 (1966).
[8] A. G. Blair and H. E. Wegner, Phys. Rev. **127**, 1233 (1962).

In order to extract relative spectroscopic factors, the DWBA results were normalized in order to yield the theoretical spectroscopic factor $S=14$ for the strongest transition in the spectrum, that to the $i_{13/2}^{-1}$ state at 1.634 MeV. The normalizing factor required had a value of 16. This may be compared with values of about 25 found in several studies[2,3,9] of the (He^3, α) reaction on lighter nuclei. Using the normalizing factor of 16 for the DWBA results, a comparison of measured and calculated cross sections yields the spectroscopic factors shown in column 4 of Table II.

Recently, elastic-scattering results have become available which have been used[4] to fix the optical-model parameters for the DWBA calculations. These parameters are shown as set B in Table I. The He^3 parameters are very similar to those of set A except for the decrease in a, but the α parameters are quite different. Calculations for comparison with the present data have been carried out by Satchler *et al.* using parameter set B. In this calculation $V_{so}=6.88$ MeV, with independent well parameters $r_{so}=1.10$ fm and $a_{so}=0.50$ fm for the bound-state spin-orbit potential.

The shapes of the calculated angular distributions are very similar to those obtained with parameter set A and provide equally good fits to the measured angular distributions. The normalizing factor required to yield a spectroscopic factor $C^2S=14$ for the $i_{13/2}$ transition is found to have the value 17.2. Using this value, spectroscopic factors for the other transitions are obtained as shown in Table II. The agreement between the two sets of spectroscopic factors is generally good, although those obtained with optical parameters of set A are in somewhat better agreement with the theoretical values expected for pure single-hole transitions. The parameter set B with independent spin-orbit potential should probably be preferred, however, since it best reproduces the elastic-scattering measurements and uses the more realistic spin-orbit term. The differences between the two calculations are perhaps indicative of the uncertainties to be expected in deducing spectroscopic strengths from (He^3, α) measurements on heavy nuclei. For either set of optical parameters, the spectroscopic factors indicate that all states except the $h_{9/2}^{-1}$ state at 3.438 MeV can be described as relatively pure single-neutron hole states.

TABLE II. Single-hole states in Pb^{207}.

s.p. level	Energy (MeV)	S_{theory}	S_{expt}[a] relative to $S_{13/2}=14$	S_{expt}[b] relative to $S_{13/2}=14$
$p_{1/2}$	0	2	2.1	3.2
$f_{5/2}$	0.570	6	5.8	6.0
$p_{3/2}$	0.897	4	4.1	6.5
$i_{13/2}$	1.634	14	14	14
$f_{7/2}$	2.339	8	7.8	9.7
$h_{9/2}$	3.438	10	5.4	6.0

[a] Parameter set A, normalizing factor 16.
[b] Parameter set B, normalizing factor 17.2.

TABLE III. Energies of weakly excited states in $Pb^{208}(He^3, \alpha)Pb^{207}$.

Present results (keV)	$Pb^{207}(pp')$[a] (keV)	$Pb^{206}(d, p)$[b] (keV)
	2625 } $p_{1/2}^{-1}\times 3^-$	2623
	2665	
2689		
	2725	2728 $0^+\times g_{9/2}$
2754		
3206	3200 } $p_{1/2}^{-1}\times 5^-$	
	3225	
3244		
3332		
	3380	
	3405	
	3430	
3492	3505	
	3575	
3607	3615	
	3640	3632 $2_1^+\times g_{9/2}$
3681		
	3710 } $p_{1/2}^{-1}\times 5^-$	
	3815	
	3855	
	3890	
	3990	
	4090 } $p_{1/2}^{-1}\times 2^+$	
	4125	4112
4143		
4173	4180	
4214		
4235		
4259		
4304	4290	4314
4336	4340	4332 $2^+\times g_{9/2}$
4361		
	4380	4385

[a] Energies of the $P_{1/2}^{-1}+3^-$ doublet from Ref. 13; other energies from Ref. 14.
[b] Reference 15; proposed configuration assignments from Ref. 16.

The discrepancy between the measured and calculated spectroscopic factor for the $h_{9/2}^{-1}$ state is probably beyond the limits of experimental uncertainties. In view of the generally good agreement for the other states, there seems little reason to suspect the DWBA results, and the conclusion is that the $h_{9/2}^{-1}$ state is strongly fragmented. This conclusion is in agreement with a recent result for the (p, d) reaction,[10] but not with earlier (d, t) measurements.[1]

This tendency for the single-particle or single-hole states to become fragmented at energies above about 3 MeV has been observed in the $Pb^{208}(t, \alpha)Tl^{207}$ reaction[11] and in the $Pb^{208}(He^3, d)Bi^{209}$ reactions.[6] Calcu-

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[10] D. A. Bromley and J. Weneser, Comments Nucl. Particle Phys. **2**, 151 (1968).

[11] S. Hinds, R. Middleton, J. H. Bjerregaard, O. Hansen, and O. Nathan, Nucl. Phys. **83**, 17 (1966).

lations[12] of the structure of particle-hole multiplets in Bi^{208} also predict that multiplets show little mixing of different particle-hole configurations at low excitation but at energies of about 3 MeV and higher mixing becomes appreciable. Thus the present result is another indication that the low-lying states of nuclei with $A=208\pm1$ are very well described by the simple shell model, but that configuration mixing becomes important at energies in the vicinity of 3 MeV.

A number of other states were observed at excitation energies above about 2.5 MeV, as shown in Fig. 1. Since the states were generally very weakly excited, and in many cases were not clearly resolved from one another, no attempt was made to measure angular distributions. States were definitely identified at the excitation energies shown in Table III. The uncertainty in the energies shown is estimated to be ±10 keV, arising mainly from uncertainties in locating the position of poorly resolved groups with limited statistics. The quoted uncertainty is about twice the scatter of the values of the excitation energies measured at different angles.

Also shown in Table III are excitation energies reported for states arising by weak coupling of a $p_{1/2}$ hole to core excitations[13,14] and by coupling of a particle to the ground and excited states[15,16] of Pb^{206}. The reported uncertainties in these energies are all 10 keV or less. If the quoted uncertainties are correct, it is seen that the present reaction is exciting many different states than those reported in other measurements. The nature of these levels is not known, but it may be noted that they fall into several distinct groups, centered about 2.72, 3.26, 3.60, and 4.25 MeV. The fact that the spacings between these groups are very close to the values found for the single-neutron hole states themselves suggests that these new states arise by coupling of the hole states to some structure. The energies are quite close to the values expected for weak coupling of the hole states to the 3^- core-excited state of Pb^{208} at 2.61 MeV. It is unlikely that this is the correct description of these states, however. The $Pb^{207}(p,p')$ measurements seem to give a clear identification of the levels at 2.625 and 2.664 MeV as the $3^-\times p_{1/2}^{-1}$ states, and the two lowest weakly excited states in the present results fall at 2.689 and 2.754 MeV, well beyond the quoted uncertainties in the energy determination.

[12] T. T. S. Kuo, Nucl. Phys. **A122**, 325 (1968).
[13] J. C. Hafele and R. Woods, Phys. Letters **23**, 579 (1966).
[14] G. Vallois, J. Saudinos, O. Beer, M. Gendrot, and P. Lopato, Phys. Letters **22**, 659 (1966).
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[16] W. R. Hering, A. D. Achterath, and M. Dost, Phys. Letters **26B**, 568 (1968).

CONCLUSIONS

The present results indicate that at relatively low incident energies the (He^3,α) reaction should be useful for quantitative spectroscopic measurements on heavy nuclei. Transfer l values may be determined more reliably than at higher energies, and DWBA calculations indicate that the predicted angular distributions do not change appreciably for reasonable changes in optical parameters. Relative spectroscopic factors obtained with two sets of optical potentials show reasonable agreement with one another and with the predictions of a simple shell model for the states studied.

The present results confirm the observation that the $h_{9/2}^{-1}$ state is strongly fragmented. In addition to the single-neutron hole states, four groups of weakly excited states have been observed. Their relative excitation energies indicate that they probably involve a weak coupling of the hole states to some excited configurations.

ACKNOWLEDGMENT

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