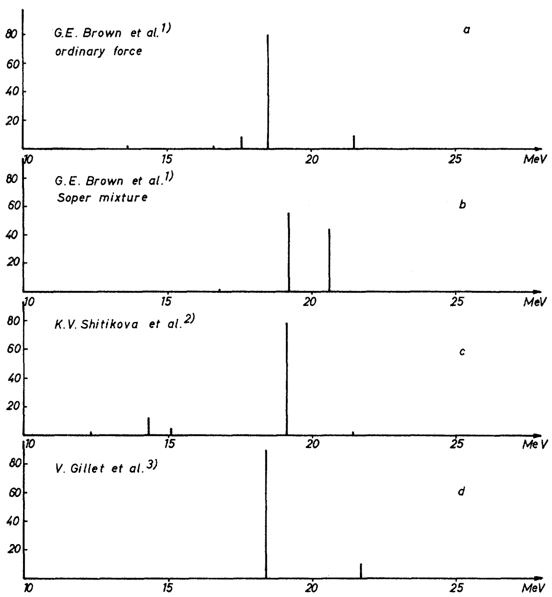

FIG. 3. Prediction of dipole strengths of various oscillator–particle-hole calculations (Refs. 1, 3, and 4).

and, therefore, to more structure. Also, as can be seen from (3), the interference of all channels is accurately treated and, consequently, some small "peaks" in the cross section are just due to a multilevel interference. The impressive agreement obtained with the high-resolution (p_0, γ) measurements shows that much of the structure in Ca^{40} is just 1p-1h structure, and extreme care seems to be necessary before interpreting such fine structure as, for example, "intermediate resonances."

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SINGLE-PROTON STATES IN Bi^{209} CORRESPONDING TO THE SHELL $82 < Z < 126$*

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The reaction $Pb^{208}(\alpha, t)Bi^{209}$ has been studied to investigate the single-proton states following $Z = 82$. The excitation energies and shell-model assignments for the observed states in Bi^{209} are as follows: ground state, $1h_{9/2}$; 0.90-MeV, $2f_{7/2}$; 1.61-MeV, $1i_{13/2}$; 2.84-MeV, $2f_{5/2}$; and 3.14-MeV, $3p_{3/2}$.

The location of single-particle and single-hole states is of fundamental importance for understanding the nuclear shell model and for its use in the explanation of detailed features of nuclear structure. Those nuclei which differ by one particle from the doubly magic nucleus Pb^{208} are of particular interest since their low-lying states should be well described as a single particle or hole in the potential well of the tightly bound $Z = 82, N = 126$ core. The single-neutron states of Pb^{209} and the neutron-hole states of Pb^{207} have been located in neutron-stripping[1,2] and -pickup[1-3] experiments and represent some of the best examples of "single-particle" excitations. Much less is known about the proton excitations in this mass region. Information concerning proton-hole states in some of the Tl isotopes has been reported recently,[4] but the single-proton states of Bi^{209} have not been observed previously in a

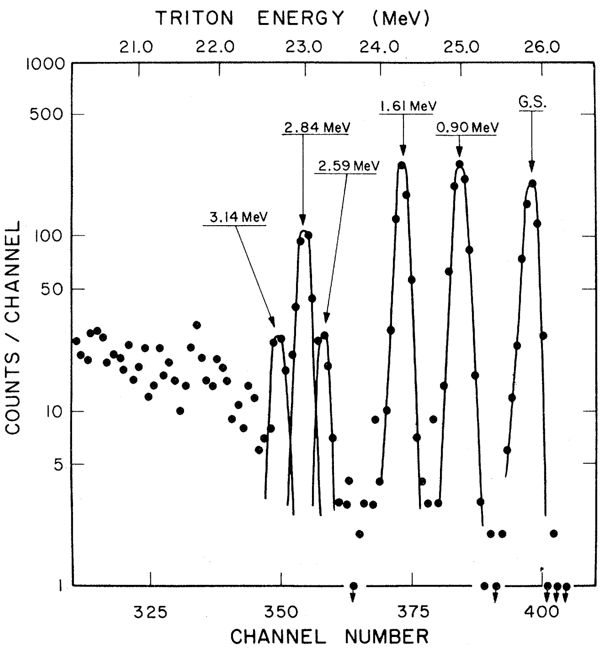

FIG. 1. Energy spectrum of tritons from the reaction $Pb^{208}(\alpha, t)Bi^{209}$ at 30°. The ground state Q value is −16.04 MeV. $E_\alpha = 42$ MeV.

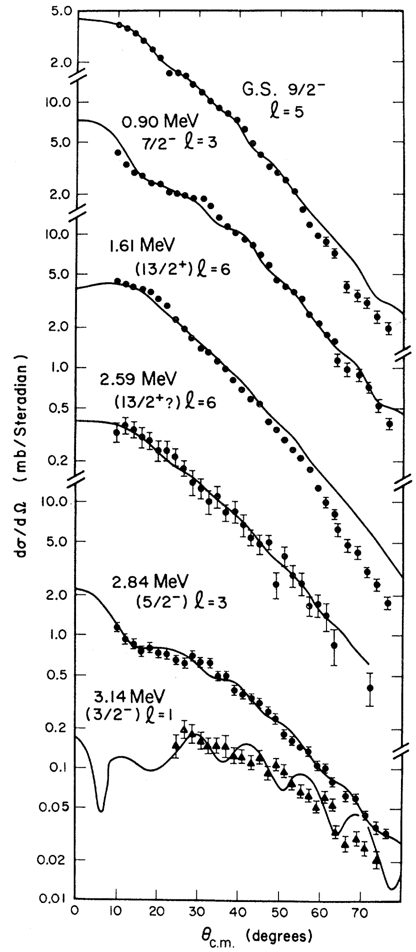

FIG. 2. Angular distributions for six peaks observed in the reaction $Pb^{208}(\alpha, t)Bi^{209}$ at 42 MeV. The points are the experimental data, and the solid curves are the results of DWBA calculations performed with the code JULIE. The theoretical distributions were fitted to the experimental points to obtain spectroscopic factors. The l values for the calculated transitions are indicated, and the spin-parity assignments are discussed in the text. The optical-model parameters used in the calculation are, for the alpha-particle channel, $V = 200$ MeV, $W = 20$ MeV, $r_0 = 1.4$ F, $r_C = 1.3$ F, and $a = 0.6$ F; and for the triton channel, $V = 299$ MeV, $W = 50$ MeV, $r_0 = 1.45$ F, $r_C = 1.3$ F, and $a = 0.6$ F.

stripping experiment designed to excite them preferentially.[5,6] Knowledge of these states is important for (1) the determination of the proton potential in the mass region $A = 208$,[7] (2) the understanding of low excitations in the region of $Z = 82$, and (3) the inclusion of the proton contribution in particle-hole calculations.[8] The ordering and spacing of the single-proton states in this mass region are also of interest for the recent theoretical work[9-13] concerning the possible stability of superheavy nuclei and, in particular, the proposed existence of relatively stable doubly magic nuclei beyond Pb^{208}. The location of the next proton magic number has been predicted to be either $Z = 114$ or possibly $Z = 126$. The exact location, if indeed any exists, depends upon the position of the proton states in the major shells above Pb^{208}. The purpose of this Letter is to present the results of an experiment on the reaction $Pb^{208}(\alpha, t)Bi^{209}$ and to identify the single-proton states in the shell $82 < Z < 126$.

A 99% enriched 1-mg/cm^2 Pb^{208} target was bombarded with 42-MeV alpha particles from the University of Washington 60-inch cyclotron. Tritons were detected and identified with a ΔE-E solid-state detector telescope. Figure 1 shows the triton spectrum obtained at 30°. The first three triton groups correspond to the ground state and first two excited states of Bi^{209} at 0.90 and 1.61 MeV. A fourth strong peak corresponds to a state at 2.84 MeV, and weaker transitions also occur to states at 2.59 and 3.14 MeV. The last three energies were measured in this experiment to ±40 keV. Angular distributions for the six states are shown in Fig. 2. The energy resolution at angles greater than 27° ranged from 150 to 170 keV. The data for angles between 10° and 27° were obtained with an aluminum absorber in front of the detector to stop the elastically scattered alpha particles. This worsened the resolution, but nevertheless the cross sections for all except the 3.14-MeV transition could be reliably extracted.

Few studies of the (α, t) reaction[14] have been reported prior to this one. The latest studies indicate[4,14] that for incident energies above about 20 MeV, the reaction proceeds predominantly via a proton-stripping mechanism, and the present experiment confirms this. A direct stripping process is implied by the strongly forward-peaked angular distributions in Fig. 2 and by the hint of diffractionlike structure. Evidence for a stripping process is the strong excitation, by the (α, t) reaction, of the low-lying states in Bi^{209} that are very weakly excited, if at all, by direct inelastic scattering of various projectiles.[15-18] Conversely, the collective states preferentially excited by inelastic scattering do not appear prominently in the (α, t) spectrum. Finally, the stripping interpretation is considerably strengthened by the theoretical angular distributions obtained from a preliminary distorted-wave Born-approximation (DWBA) calculation[19] which, as shown in Fig. 2 and discussed below, are in good general agreement with the experiment.

Based on the shell model, the single-particle states expected in the region $82 < Z < 126$ are $1h_{9/2}$, $2f_{7/2}$, $1i_{13/2}$, $3p_{3/2}$, $2f_{5/2}$, and $3p_{1/2}$. Using this as a guide, together with the known spins and parities of the first two states of Bi^{209} and the DWBA calculations, it is possible to identify from the present data five of the six expected states. The results are summarized in Table I. The spin and parity of the ground state ($\frac{9}{2}^-$) and 0.90-MeV state ($\frac{7}{2}^-$) have been established previously,[20] and they have been assumed to be the $1h_{9/2}$ and $2f_{7/2}$ single-proton states.[7] The DWBA angular distributions for $l = 5$ and $l = 3$, respectively, are in good agreement with the measured (α,t) transitions to these states. A normalization factor between theory and experiment was obtained by assuming a spectroscopic factor of 1 for the ground state. With the same normalization and optical model parameters, $S = 1.0$ is also obtained for the 0.90-MeV transition, showing that the DWBA calculation is consistent with the single-particle interpretation for the first two states.

The spin and parity of the 1.61-MeV state have not been measured previously. Of the shell model levels remaining to be identified, the present results strongly indicate that the 1.61-MeV state is the $1i_{13/2}$. The $l = 6$ DWBA angular distribution provides the best fit and yields 1.0 for the spectroscopic factor if a spin of 13/2 is assumed. This spin has been found consistent with the results of neutron inelastic scattering, but other high spins could not be excluded.[20] Identification of the 1.61-MeV state as the $1i_{13/2}$ single-proton state shows that the shell-model prediction[7] concerning the second excited state in Bi^{209} is correct.

Table I. Levels in Bi^{209} excited by the reaction Pb^{208} (α, t).

Energy level (MeV)	Shell-model proton state	Spectroscopic factor[a]
0.00	$1h_{9/2}$	1.00[b]
0.90	$2f_{7/2}$	1.04
1.61	$1i_{13/2}$	1.01
2.59		0.09[c]
2.84	$2f_{5/2}$	0.91
3.14	$3p_{3/2}$	0.90
?	$3p_{1/2}$[d]	?

[a]The estimated error in extracting the spectroscopic factors from the DWBA calculation is about ±20 %.

[b]The calculation was normalized assuming $S = 1.00$ for this state.

[c]This spectroscopic factor is based on an assumed spin of $13/2^+$ as discussed in the text.

[d]This state was not identified in this experiment. Its location, based on shell-model arguments, is expected between 3.5 and 4.0 MeV (see text and Ref. 22).

A number of states have been observed previously in Bi^{209} at excitations between 2.5 and 3 MeV.[21] There is good evidence from the present results that the state at 2.84 ± 0.04 MeV is the $2f_{5/2}$ single-proton state. An excellent fit is obtained with an $l = 3$ angular distribution, and the relatively pure single-particle nature of the state is shown by the spectroscopic factor of 0.91. The difference of 1.8 MeV between the $f_{7/2}$ and $f_{5/2}$ states is in fair agreement with other experimental spin-orbit splittings in the lead region if a $2l + 1$ dependence is assumed. However, it is smaller than the $f_{5/2}$-$f_{7/2}$ splitting that has been predicted based on shell-model calculations (see below).

The angular distributions of the two remaining transitions indicate a high l transfer to the state at 2.59 MeV and a low l transfer to that at 3.14 MeV. Although the detailed structure of the experimental angular distribution for the 3.14-MeV transition is less pronounced than that predicted by the DWBA calculation for $l=1$, the average behavior is quite well reproduced. The oscillatory structure in the theoretical distribution depends on the optical-model parameters that are used. A better $l=1$ fit was obtained with different optical-model parameters without much change in either the angular distributions for the higher l transfers or the relative spectroscopic factors. However, the present parameters (see caption for Fig. 2) were used here since they are similar to those employed successfully in fitting other data.[4] The spectroscopic factor of 0.90 based on a spin of $\frac{3}{2}$ for the 3.14-MeV state indicates a relatively pure $3p_{3/2}$ shell-model assignment. A $3p_{1/2}$ assignment is excluded since the observed cross section would exceed the sum-rule limit by about a factor of 2. Considering the spin-orbit splitting, the $3p_{1/2}$ strength would be expected to lie between 3.5 and 4 MeV. Assuming a single state at 3.6 MeV,[22] the corresponding cross section was calculated and found to be too small (a maximum of 0.07 mb/sr) to have been clearly distinguishable with the resolution employed in the present experiment.

The state at 2.59 ± 0.04 MeV does not fit into the simple shell-model scheme that describes the other five states. It is too low in energy to be the $3p_{1/2}$ state and its angular distribution is inconsistent with $l=1$. An $l=6$ DWBA fit is shown in Fig. 2 although other high l transfers give equally acceptable fits. The choice of $l=6$ is speculative and is suggested by the existence in this energy range of the multiple of positive-parity states that comprises the collective $E3$ excitation.[16-18,23] The $13/2^+$ component of this group is located[23] at 2.597 MeV and is the only one that could mix with any of the single-particle states in the shell following $Z=82$ which, except for the $i_{13/2}$ state, all have negative parity. If the 2.59-MeV transition in fact corresponds to the $13/2^+$ state, then about 9 % of the $i_{13/2}$ strength could be mixed into it.

The main conclusion from the results presented here is the location of the single-proton states in the shell $82<Z<126$ for $A=209$. They demonstrate for Bi^{209} the relatively pure single-particle structure that is found in Tl^{207}, Pb^{207}, and Pb^{209}, the other three nuclei neighboring Pb^{208}. They also indicate that improvement is needed in the proton potentials that have been used thus far for calculations in the lead region,[7,11,24,25] since the $2f_{5/2}$, $3p_{3/2}$, and $3p_{1/2}$ states have been predicted to be unbound in Bi^{209}, i.e., above 3.8-MeV excitation.

The location of the single-proton states is also significant for the insight which is provided into the attempts to predict relatively stable superheavy nuclei. Because of the increased binding associated with shell structure, a possible location for such nuclei is in the region of a superheavy doubly magic nucleus, if one exists.[9] An important question, therefore, is the identity of the next magic numbers after ${}_{82}Pb^{208}_{126}$ and the strength of the shell effects in that region. The next magic neutron number is generally assumed[9-11,13] to be 184, although 164 has also been suggested.[12,26] For the proton number, most calculations indicate that although $N=126$ forms a strong shell closure at Pb^{208}, $Z=126$ may not be magic near $A=300$.[27] A large gap is predicted,[9-12,28] however, at $Z=114$ where the $2f_{7/2}$ state is most probably the last to be filled.[29] The next proton state is the $2f_{5/2}$, so that the critical spacing which determines the stability of a hypothetical doubly magic nucleus at $Z=114$ (${}_{114}X^{278}_{164}$ and ${}_{114}X^{298}_{184}$ have been suggested as candidates) is the $2f_{5/2}$-$2f_{7/2}$ splitting. The value obtained from the present experiment for this splitting in Bi^{209} is 1.9 MeV, and it is noteworthy that this is smaller by at least 1 MeV than is indicated by the calculations for $A=209$ mentioned above. Since the predictions of levels in superheavy nuclei depend strongly on parameters extrapolated from the lead region, and moreover, since the calculations indicate that the $f_{5/2}$-$f_{7/2}$ splitting decreases with increasing A, it is probable that the gap at $Z=114$ for A near 300 also has been overestimated. Therefore, the gap could be appreciably less than the calculated value of about 2 MeV [11] obtained for ${}_{114}X^{298}_{184}$ or about 2.8 MeV [12] for ${}_{114}X^{278}_{164}$. The extent to which this reduced level spacing diminishes the possible closed-shell effects at $Z=114$, and indeed whether 114 remains as the best candidate for the next proton magic number, must be determined from further calculations with realistic potentials that are at least consistent with the single-proton and proton-hole states in the lead region.

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he received at the Wright Nuclear Structure Laboratory, Yale University during the preparation of the paper.

Note added in proof.—After this Letter was submitted, a Letter by Woods et al. on the reaction $Pb^{208}(He^3,d)$ was published.[30] Several of the conclusions stated in that work conflict with the results presented here. Most important, the energies given by Woods et al. for the $3p_{1/2}$ and $3p_{3/2}$ levels are incorrect. They did not observe the 3.14-MeV level, identified here as the $3p_{3/2}$ state, because the corresponding region of their spectrograph plate was obscured. This level is, in fact, one of the most strongly excited in the (He^3,d) spectrum.[6] Moreover, the level at 3.64 MeV is undoubtedly the $3p_{1/2}$ state[22] rather than the $3p_{3/2}$ state as they propose, and therefore the conclusions in Ref. 30 about the DWBA theory based on the mistaken assignments are no longer justified. Finally, we note that the reported absence of a level in the (He^3,d) spectrum corresponding to the 2.59-MeV excitation in the (α,t) spectrum is consistent with an $l=6$ assignment and tends to support the idea, discussed above, of the admixture of the $1i_{13/2}$ single-particle strength into the $13/2^+$ component of the $E3$ multiplet.

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