ergy Research and Development Administration.

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[a] On leave from Tokyo Institute of Technology, Tokyo, Japan.

[b] On leave from Institute of Nuclear Physics, Cracow, Poland.

[c] Permanent address: Physikalisches Institute der Universität zu Köln, Köln, Germany.

[d] On leave from Purdue University, W. Lafayette, Indiana.

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Observation of the $T_> = \frac{45}{2}$ Components of Deep Hole States in ^{207}Pb via the (^{3}He,α) Reaction at 70 MeV

S. Gales,[a] G. M. Crawley, D. Weber, and B. Zwieglinski[b]
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

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A number of narrow lines are observed around 20 MeV excitation energy in ^{207}Pb in the study of ^{208}Pb(^{3}He,α) at 70 MeV. Their excitation energies and relative spacing suggest that these peaks arise from the neutron pickup from the inner filled *sdhg* shell between magic numbers 82 and 50 with isospin number $T = \frac{45}{2}$. In addition, distorted-wave Born-approximation (DWBA) calculations of the angular distributions agree in shape with the data. The solution of the Lane coupled-channels equations leads to a DWBA cross section in reasonable agreement with experiment.

In the past few years a number of experiments have been carried out in heavy nuclei in order to locate the $T_<$ components of inner hole states using neutron pickup reactions.[1-9] In general, both the $T_<$ and the $T_>$ components of these inner neutron hole states are populated, the latter ($T_>$) observed as sharp peaks at high excitation energy above a continuous background.[4,5,8-10] These studies are of importance because they provide quantitative information on the spreading of simple configurations into the underlying background in a region of very high level density. A simple calculation of the Coulomb displacement energy predicts that these levels are located between 19 and 24 MeV excitation energy in ^{207}Pb and the possibility of observing the $T_> = \frac{45}{2}$ states in this nucleus is completely dependent upon the concentration of the single-hole analog strength and the ratio of such cross sections to the physical background arising from the high level density. Finally, the recent calculations of the form factor of such inner hole states[8,11] using the Lane coupled-channels equations[12] (CC), which have been fairly successful in reproducing the strength of the $T_>$ hole-analog states in heavy nuclei as compared to the usual separation-energy method (SE), could be tested in ^{207}Pb under extreme condition (binding energy of -30 MeV and high isospin number $T_> = \frac{45}{2}$).

In order to study these phenomena in more detail, the reaction ^{208}Pb(^{3}He, α)^{207}Pb was investigated at 70 MeV incident energy using a 50-cm-long delay-line counter backed by a plastic scintillator in the focal plane of the Enge spectrograph. This arrangement gives very clear identification of the α particles and an excitation energy range of about 28 MeV in ^{207}Pb could be easily explored. The energy resolution was dominated by the target thickness ($\simeq 10$ mg/cm^2) and was about 200 keV full width at half-maximum (FWHM). The excitation energy calibration of the counter was obtained by using the known energies of the first few excited states in ^{207}Pb and some strong lines from the reactions ^{12}C(^{3}He, α)^{11}C and ^{16}O(^{3}He, α)^{15}O. The portion of the spectra in the excitation energy range of interest (18–26 MeV) recorded at 6° and 12° lab angles is plotted in Fig. 1. Two strong peaks, each of them consisting of a close doublet, are clearly observed at almost all angles. In addition, a very weak state is also observed around 23-MeV excitation energy with a peak cross section occurring near a laboratory angle of 12°. A simple Coulomb displacement-energy calculation using a semiempirical formula[13] indicates that the $3s_{1/2}$ and $2d_{3/2}$ ground and first excited hole-analog configurations in ^{207}Pb should lie around 19.4 MeV (0.350 keV apart). The measured excitation energies listed in Table I for the first doublet agree very well with this assumption. Furthermore, the spacing of these two levels, together with the population 1 MeV above of the next doublet, reproducing the level sequence of low-lying states in ^{207}Tl (see Table I), are believed to be strong arguments in favor of the identification of these levels as the analog states of the $3s_{1/2}$, $3d_{3/2}$, $1h_{11/2}$, and $2d_{5/2}$ proton hole states in the ^{207}Tl parent nucleus, respectively.[14] The measured total width of the levels observed here of about 200 keV is also quite comparable to the total width of single-particle analog resonances[14] observed in ^{209}Bi at about the same excitation energy.

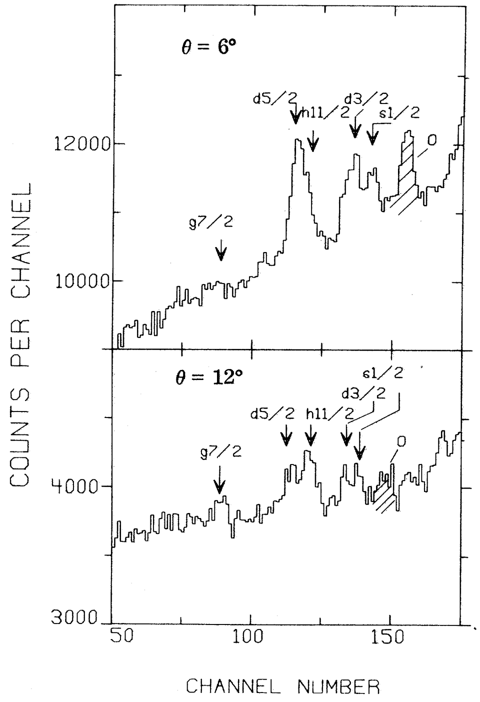

FIG. 1. α-particle spectra from the reaction ^{208}Pb(^{3}He,α)^{207}Pb at laboratory angles of 6° and 12°. The arrows indicate the position of the $T = \frac{45}{2}$ deep-hole configurations in ^{207}Pb. The symbol O refers to a state arising from (^{3}He,α) reaction on ^{16}O.

To test further the assumption that these peaks arise from pickup of a neutron from the *sdhg*

TABLE I. Summary of the results from the reaction ^{208}Pb(^{3}He,α)^{207}Pb to hole-analog states.

E_x (MeV)	$E_x - E_0$ [a] (MeV)	E_x [b] (Parent) (MeV)	ΔE_c (MeV) Expt	Calc [c]	nlj	C^2S_n SE	CC	C^2S_p [b]	$\frac{2j+1}{2T_0+1}$ [d]
19.31 ± 0.04	0.00	0.00	18.67		$3s_{1/2}$	0.38	0.12	0.042	0.044
19.69 ± 0.04	0.38	0.351	18.70		$2d_{3/2}$	0.40	0.13	0.10	0.090
20.65 ± 0.06	1.34	1.341	18.67	18.71	$1h_{11/2}$	1.34	0.58	0.24	0.27
21.00 ± 0.06	1.77	1.674	18.76		$2d_{5/2}$	0.46	0.16	0.08	0.13
22.89 ± 0.08	3.58	3.474	18.77		$(1g_{7/2})$	(1.54)	(0.45)	0.07	0.18

[a] E_0 is the excitation energy of the ground-state analog.

[b] Excitation energies and the C^2S_p numbers are from Ref. 14. $C^2S_p = C^2S/(2T_0 + 1)$ where T_0 is the isospin of the target.

[c] The Coulomb displacement energy was calculated using the semiempirical formula $\Delta E_c = 1430\bar{z}/A^{1/3} - 992$ of Ref. 13.

[d] $(2j + 1)/(2T_0 + 1)$ are the expected values for the strength of hole-analog configurations in a pure shell-model picture.

shell, angular distributions were measured from 6° to 25° lab angle in 3° steps. In order to determine the angular momentum transfers and the strengths of the transitions observed, a number of calculations were carried out using the code DWUCK.[15] The ^{3}He optical parameters were originally determined from the study of elastic scattering of ^{3}He on ^{208}Pb at 47.5 MeV,[16] whereas the α optical potential was that used previously by Goldberg *et al.*[17] in their analysis of α elastic scattering on the lead isotopes. These parameters were found to reproduce quite well the shape and the strengths of the well-known low-lying $f_{5/2}$, $i_{13/2}$, and $f_{7/2}$ hole states in ^{207}Pb.[18] A normalization constant of $N = 23$ was used in the calculations and no finite range or nonlocal corrections were employed. Special care was taken to describe correctly the form factor of the deeply bound states populated in this experiment. The binding energy of the neutron is about − 30 MeV and it is well known that in this case the usual separation energy procedure (SE) gives too low DWBA cross sections.[19] A more realistic way to compute such form factors is to use the Lane coupled-channels equations.[12] As pointed out a number of years ago by Stock and Tamura,[19] a surface-peaked Woods-Saxon potential $-4(V_1/A)\vec{t}\cdot\vec{T}\,df(x)/dx$ where $x = r - r_0A^{1/3}$ and $V_1 = 142$ MeV was added to the usual binding potential. V_1 is related to the usual isospin coupling strength $U_1 = 25$ MeV by the expression $U_1 \simeq 2aV_1/r_0A^{1/3}$. The coupled-channels equations were solved using the computer code DNUM.[20] The geometrical parameters of the nuclear well used in both calculations (SE and CC) were $r = 1.25$ fm, $a = 0.65$ fm, and $\lambda = 25$. This approach has been shown to give realistic DWBA (distorted-wave Born-approximation) cross sections in good agreement with experiment for highly excited hole-analog states in Zr and Sn isotopes[8,11] for levels with isospin ranging from $\frac{11}{2}$ to $\frac{21}{2}$.

The results of the CC calculations for the reaction ^{208}Pb(^{3}He, α)^{207}Pb are shown in Fig. 2 together with the experimental angular distributions. In extracting the experimental cross section for the narrow peaks, a straight-line background was assumed which passed through the nonenhanced regions of the spectrum. For each level the DWBA predictions assuming a single l transfer are plotted. Clearly the shape of the angular distributions for each final state assuming an l transfer equal to that for the known parent configuration (see Table I) is well reproduced by the DWBA calculation. In all cases, the shape of the angular distribution is independent of the method used to compute the neutron form factor.

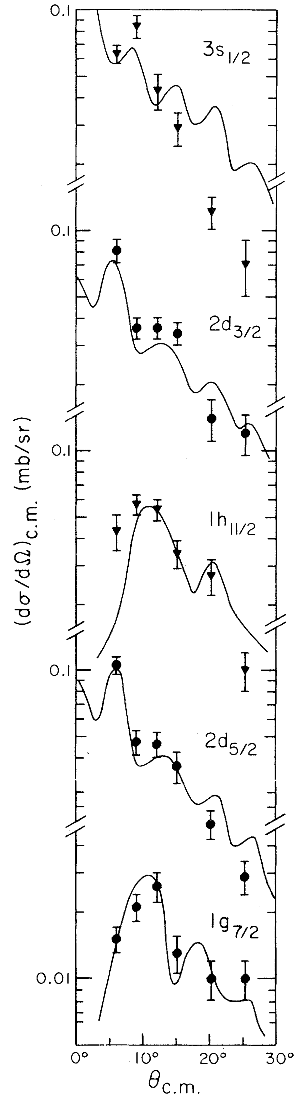

FIG. 2. Angular distributions for the reaction ^{208}Pb(^{3}He,α)^{207}Pb leading to hole-analog states. The nlj value of the neutron-hole configuration is indicated for each final state. Error bars arise mainly from the uncertainties in the background determination. Solid lines are DWBA calculations for the listed quantum numbers (see text).

In Table I the deduced strengths C^2S_n are compared with the shell-model sum-rule limit equal to $(2j+1)/(2T_0+1)$, where j is the spin of the hole state and T_0 the isospin of the target, and with the proton-hole strengths of their parent states. This analysis shows that the SE method gives spectroscopic factors which are larger by a factor of 5 to 10 than the ones deduced for the parent states or expected from the sum-rule limit. These discrepancies cannot be explained by the dependence of the cross sections on the optical-model parameters. A quite remarkable improvement is obtained by using the Lane coupled-channels form factor. Although the resulting values (see Table I) are still large, they are within 20 to 40% for the well-matched l values ($l=2$ at $E_x \simeq 20$ MeV) which can be explained by the uncertainties in extracting the peak cross section (10–20)% and by the dependence of the DWBA cross sections upon the optical parameters (20 to 40%). For the $l=0$, 5, and 4 transitions which are badly matched at an excitation energy of 20 MeV, the poorer agreement could be due partially to this additional effect. However, one cannot exclude completely the possibility that a fraction of the observed cross section for the deep-hole analog states could arise from the mixing of the $T_>$ configuration with the high density of $T_<$ levels in the vicinity, which would not be explained by the present DWBA calculations.

In summary, five narrow states ($\Gamma \leq 300$ keV) have been observed around 20 MeV in ^{207}Pb using the reaction ^{208}Pb(^{3}He, α). The measured excitation energies and the shapes of the angular distributions support strongly the assumption that the levels arise from the pickup of a neutron from the *sdhg* shell with isospin component $T = 45/2$. This is the highest isospin value ever observed in a transfer reaction to an analog state. For a comparison of the measured strengths with the DWBA predictions, one can clearly see that the solution of the coupled-channels equations gives a reasonable description of the deeply bound state but does not completely reproduce the expected values for the shell-model sum-rule limit. It is remarkable that the full strength of the analog states is still concentrated in a very narrow range of excitation energy. Finally, a better description of the highly excited $T_>$ levels can only be obtained by a correct treatment of the mixing of the doorway state with the surrounding $T_<$ levels.

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[a] On leave from Institut de Physique Nucléaire, Orsay, France.

[b] On leave from Institute of Nuclear Research, Warsaw, Poland.

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