Study of the (p,t) Reaction on the Pb Isotopes*

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Energy spectra of tritons from the (p,t) reaction on Pb^{208}, Pb^{207}, Pb^{206}, and Pb^{204} have been studied using 40-MeV protons. Angular distributions of the resolvable triton groups are presented. A detailed discussion of the Pb^{208} results is given in terms of the two-nucleon transfer theory of Glendenning and the wave functions of True and Ford for the Pb^{206} states.

INTRODUCTION

THE relatively simple selection rules of the (p,t) reaction[1] and its inverse, the (t,p) reaction, make them ideal probes for spin-parity assignments in even nuclei and in some odd-nucleon nuclei. An example is a recent high-resolution spectroscopic study of the levels in Fe^{56} using the latter reaction.[2] An equally important use of these reactions is the testing of proposed wave functions for the states involved in the transitions, particularly as to the relative phases of the various components in the model wave functions. With distorted-wave Born-approximation (DWBA) analysis of two-nucleon transfer reactions still in an early stage of development it is particularly important to obtain data in mass regions where we may hope good wave functions are available, such as the double-closed-shell Pb region.

EXPERIMENTAL PROCEDURE

The reactions were initiated by 40-MeV protons from the Minnesota linear proton accelerator. The general features of the experimental system have been described previously.[1] Reaction products are now detected by an array of 32 surface barrier detectors in the focal plane of the 40-in. magnetic spectrometer.[3] After proper shaping, amplification, and discrimination, the pulses are routed into a 1024-channel analyzer in a 32 by 32 configuration.

Targets used in this study were enriched foil targets, all approximately 6 mg/cm² thick. Enrichment figures were greater than 90% except in the case of Pb^{204}, which was 73%. With these targets, an over-all energy resolution of 220 keV was obtained.

RESULTS

Energy spectra and angular distributions obtained in this study are shown in Figs. 1–11. Error bars on the angular distributions include statistical errors and errors arising from the separation of closely spaced triton groups. The absolute cross sections are assigned an error of ±20%. Energies of the lower states in the

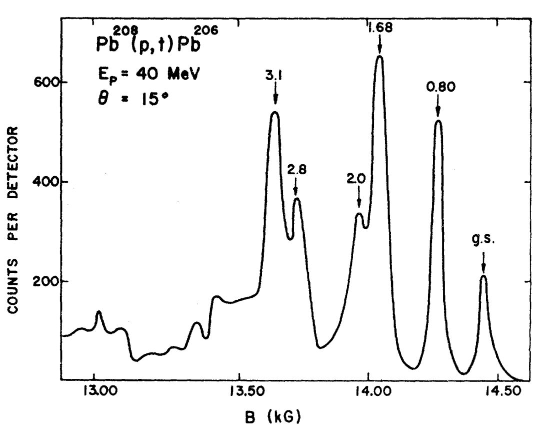

FIG. 1. Triton energy spectrum from the reaction $Pb^{208}(p,t)Pb^{206}$.

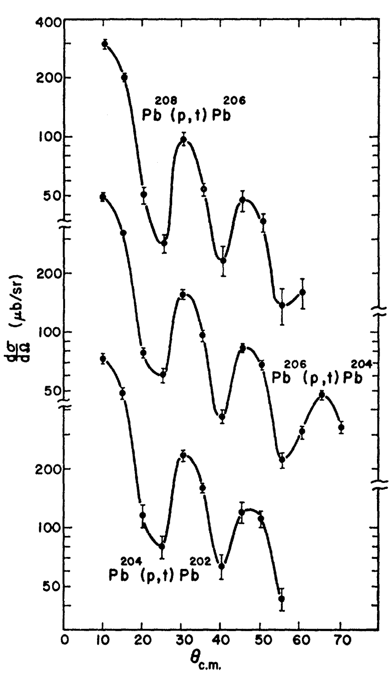

FIG. 2. $L=0$ angular distributions.

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[1] See, for example, G. Bassani, N. M. Hintz, and C. D. Kavaloski, Phys. Rev. **136**, B1006 (1964).
[2] B. Cohen and R. Middleton, Phys. Rev. **146**, 748 (1966).
[3] University of Minnesota Linear Accelerator Laboratory Progress Report, 1964, p. 126 ff. (unpublished).

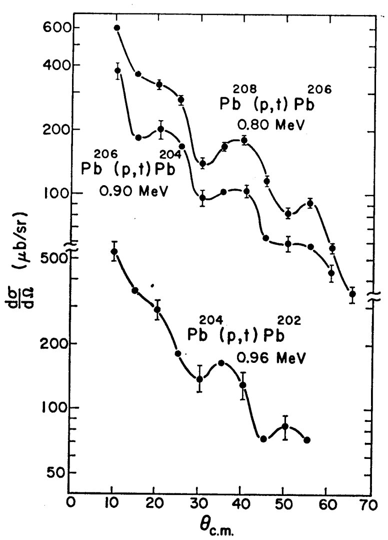

FIG. 3. $L=2$ angular distributions.

spectra were obtained from existing compilations.[4] Energy assignments of the groups at higher excitation should be good to within ±100 keV.

A comparison of the levels observed in this study with previously reported levels is presented in Table I. The assignment of L values in the cases where L is greater than 4 are estimates since no known angular distributions with higher L values have been obtained

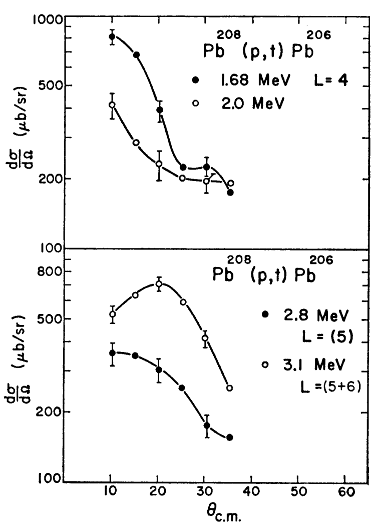

FIG. 4. Angular distributions of the 1.68-, 2.0-, 2.8-, and 3.1-MeV triton groups from the reaction $Pb^{208}(p,t)Pb^{206}$.

for comparison purposes. Discussions of the separate cases are presented here.

$Pb^{208}(p,t)Pb^{206}$

The spectrum, Fig. 1, indicates that only about 7 levels in Pb^{206} to an excitation energy of 3.4 MeV are being strongly excited. This is also true of the other Pb isotopes. Well-resolved angular distributions were obtained for the ground state and 0.80-MeV 2^+ state and are shown in Figs. 2 and 3.

The next level in Pb^{206} with any appreciable yield is the 1.68-MeV 4^+ state, whose angular distribution is shown in Fig. 4. The peak at 2.0 MeV is thought to contain the 1.99-MeV 4^+ state and the 2.20-MeV 7^- metastable state. At small angles where the $L=4$ angular distribution is peaked the energy determination is 2.0 MeV, but at larger angles the energy shifts to

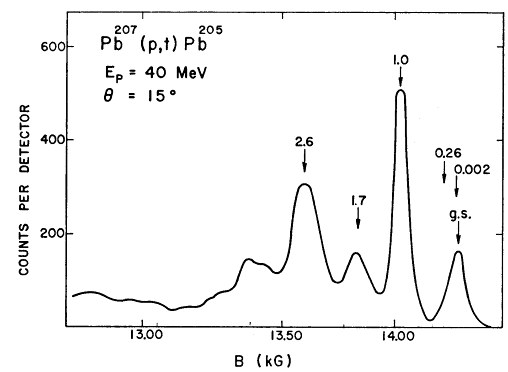

FIG. 5. Triton energy spectrum from the reaction $Pb^{207}(p,t)Pb^{205}$.

2.2 MeV. Although there are energy-resolution difficulties, the peak at 2.8 MeV is very probably the 2.78-MeV (5^-) state, and the triton group at 3.1 MeV is a combination of the 3.02-MeV (5^-) and 3.12-MeV (6^+) states. Angular distributions for these groups, shown in Fig. 4, are not inconsistent with such an interpretation. A detailed discussion of this reaction in terms of the structure of the Pb^{206} states is given below.

$Pb^{207}(p,t)Pb^{205}$

Figure 5 shows the triton spectrum for this reaction. Since the spin of Pb^{207} is $\frac{1}{2}^-$, only one value of the orbital

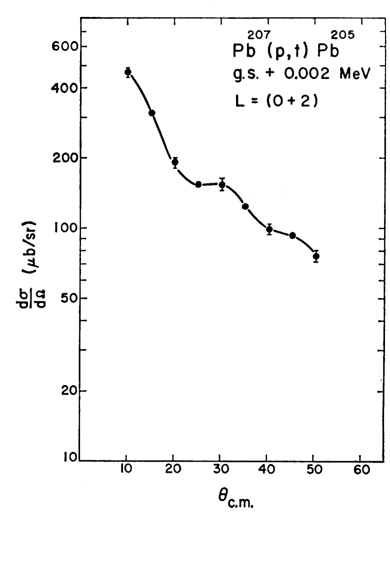

FIG. 6. Angular distribution of the ground state plus 2.3-keV state from the reaction $Pb^{207}(p,t)Pb^{205}$.

[4] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1958–1965), NCR 61-4-110.

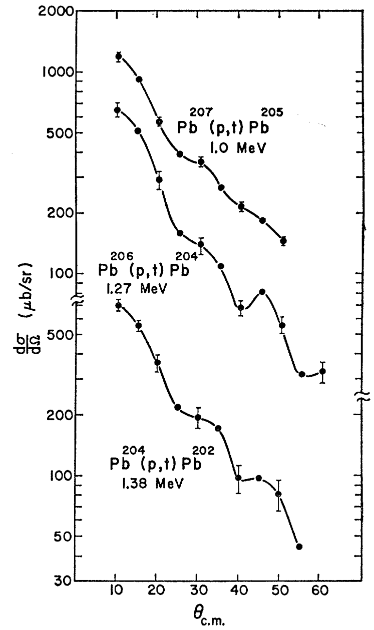

FIG. 7. $L=4$ angular distributions.

angular-momentum transfer L is allowed by the selection rules for each of the transitions. Figure 6 shows the angular distribution of the unresolved ground-state, $\frac{5}{2}^-$ $L=2$ transition and the 2.3-keV, $\frac{1}{2}^-$ $L=0$ transition. An equal splitting of the yield at 10° between the two states produces an angular distribution very similar to the observed distribution.

The large peak at 1.0 MeV is mainly the 0.988-MeV ($\frac{9}{2}^-$, $L=4$) state. However, its angular distribution,

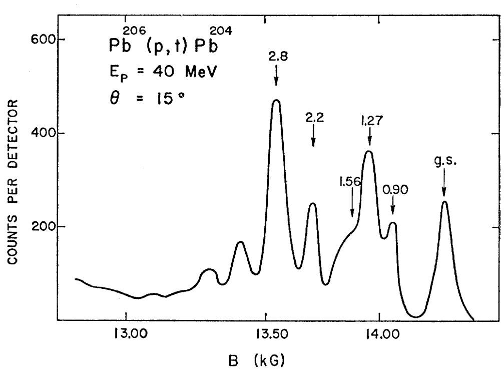

FIG. 8. Triton energy spectrum from the reaction $Pb^{206}(p,t)Pb^{204}$.

Fig. 7, deviates at larger angles from the better resolved $L=4$ distributions in this study. In particular it is too high, probably indicating excitation of the metastable state at 1.014 MeV ($13/2^+$, $L=7$). The only information that could be obtained on the groups at 1.7 and 2.6 MeV is that $L\geq 4$ for both peaks.

$Pb^{206}(p,t)Pb^{204}$

The spectrum is shown in Fig. 8. Angular distributions of the ground state, the 0.90-MeV 2^+ state, and the 1.27-MeV 4^+ state are given in Figs. 2, 3, and 7, respectively. An angular distribution could not be obtained for the weaker 1.56-MeV 4^+ level. Above an excitation of 2.2 MeV in Pb^{204}, the level density is already quite high. However, the peak at 2.2 MeV is sharp and probably arises from excitation of a 6^+ state, whose angular distribution is shown in Fig. 9. Table I indicates that a level with this spin has not been previously reported. The width of the peak at 2.8 MeV indicates excitation of more than one state. It is probably due mainly to excitation of one or more 5^-

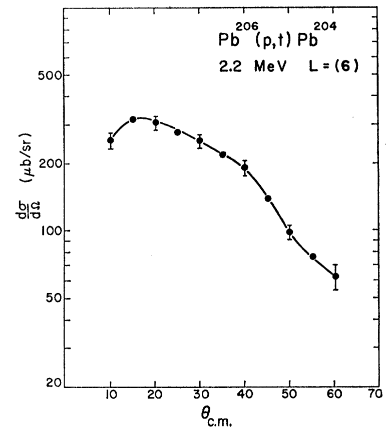

FIG. 9. Angular distribution of the 2.2-MeV state from $Pb^{206}(p,t)Pb^{204}$.

states in Pb^{204}. The angular distribution is shown in Fig. 10.

$Pb^{204}(p,t)Pb^{202}$

The isotopic enrichment of the Pb^{204} target was 73% with the main contaminant being Pb^{206}. This accounts for the triton groups above the ground state in the spectrum, shown in Fig. 11, and between the ground state and 0.96-MeV state. Angular distributions could only be obtained for the ground state, 0.96-MeV 2^+ state, and the 1.38-MeV 4^+ state. They are shown above in Figs. 2, 3, and 7.

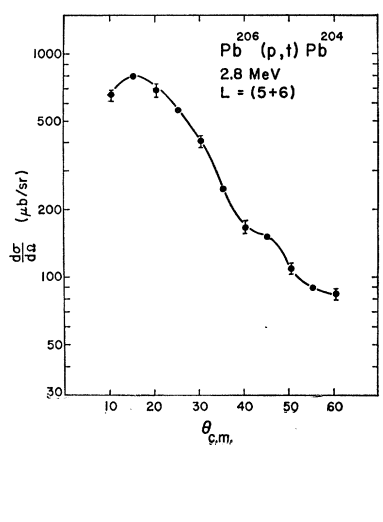

FIG. 10. Angular distribution of the 2.8-MeV state from $Pb^{206}(p,t)Pb^{204}$.

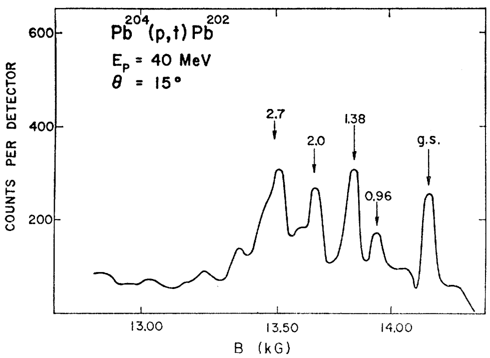

FIG. 11. Triton energy spectrum from the reaction $Pb^{204}(p,t)Pb^{202}$.

DISCUSSION

The (p,t) spectra of lighter spherical (even) nuclei are dominated by the ground-state $L=0$ transition.[5] That this is not the case in the Pb isotopes is due partly to the higher, classically favored, angular-momentum transfer in these heavier nuclei. The value of $|\mathbf{k}_p-\mathbf{k}_t|R$ where R is the nuclear radius, is about 5 in the Pb region. Thus transitions with $L=4$, 5, and 6 will be enhanced if the structure of the states involved permits it.

Since wave functions are available for Pb^{206}, from Ref. 6, a detailed discussion of the $Pb^{208}(p,t)Pb^{206}$ reaction is given here. Using the selection rules and the calculated wave functions, strengths of all the possible transitions to an excitation of 3.4 MeV in Pb^{206} can be explained. The selection rules prohibit excitation of unnatural parity levels. This rules out the 3^+, 1^+, and 6^- states in Table I. From shell-model systematics in this region, the 3^- level at 2.53 MeV would consist mainly of a single-particle excitation into the next major shell, for example, promotion of an $f_{5/2}$ neutron to the $g_{9/2}$ level. Such components would be seen only weakly in pickup reactions on Pb^{208}. The two 5^- levels at 3.28 and 3.40 MeV are proton-excited levels[6] and also would not be excited by a direct pickup reaction of two neutrons.

There remain 11 possible transitions. Structure factors according to the Glendenning theory[7] have been calculated for each of the remaining levels using the wave functions in Table XVI of True and Ford.[6] The results are given in Table II. Reference 7 can be consulted for a detailed discussion of the structure factors. Three factors are included in Glendenning's G_{NLJ}: (1) a two-particle parentage factor similar to the spectroscopic factor of one-nucleon transfer reactions; (2) a Moshinsky bracket which measures the amplitude of relative s-state in the motion of the two neutrons in the target nucleus; and (3) a factor measuring the overlap of the above state of relative motion with that of the neutrons in the triton. The very important influence of the configuration mixtures of the states in Pb^{206} has also been incorporated in G_{NLJ}. The cross sections are proportional to the square of the G_{NLJ}'s in a manner described in Ref. 7. The G_{NLJ} for various N combine coherently.

Two points to keep in mind in connection with Table II, in which the G_{NLJ} are shown, are: (1) as mentioned above, transitions with $L=4$, 5, and 6 are favored for this particular mass region and particle energy; and (2) levels with alternating positive and negative signs for the G_{NLJ}, such as the 0.803-MeV 2^+ state, are enhanced over those whose signs do not alternate.

The calculations are seen to be in complete qualitative accord with experiment. In comparing relative cross

[5] G. Bassani, N. M. Hintz, C. D. Kavaloski, J. R. Maxwell, and G. M. Reynolds, Phys. Rev. **139**, B830 (1965).
[6] W. W. True and K. W. Ford, Phys. Rev. **109**, 1675 (1958).
[7] N. K. Glendenning, Phys. Rev. **137**, B102 (1965).

TABLE I. Comparison of levels observed in this study with previously reported levels.

Residual nucleus	Observed level (MeV)	Peak cross section (μb/sr)	Empirical L value	Previously reported levels[a] Energy (MeV)	J^π
Pb^{206}	0	296	0	0	0^+
	0.80	597	2	0.80	2^+
				1.15	(0^+)
				1.34	3^+
				1.47	(2^+)
	1.68	815	4	1.68	4^+
				1.72	(1^+)
				1.82	(2^+)
				{1.99	$(4)^+$
	2.0	414	$(4+\geq 5)$	{2.20	$(7)^-$
				2.38	$(6)^-$
				2.53	(3^-)
	2.8	351	(5)	2.78	$(5)^-$
				{3.02	$(5)^-$
	3.1	715	(5+6)	{3.12	(6^+)
				3.28	$(5)^-$
				3.40	5^-
				{0	$(5/2^-)$
Pb^{205}	0	467	(0+2)	{0.0023	$(1/2^-)$
				0.263	$(3/2^-)$
				0.41	
				0.58	
				0.703	$(7/2^-)$
				0.761	
				0.79	
				{0.988	$(9/2^-)$
	1.0	1192	$(4+\geq 5)$	{1.014	$(13/2^+)$
				1.044	$(5/2,7/2^-)$
Pb^{204}	0	491	0	0	0^+
	0.90	375	2	0.899	2^+
	1.27	646	4	1.274	4^+
	1.56[b]			1.563	(4^+)
				1.82	
				1.95	
				2.06	
				2.19	9^-
	2.2	315	(6)	2.255	
				2.258	
				2.477	
	2.8	791	(5+6)		
Pb^{202}	0	723	0	0	0^+
	0.96	534	2	0.96	2^+
	1.38	697	4	1.38	4^+
				1.62	(4^+)
	2.0[b]		$L\geq 5$	2.04	5^-
				2.17	9^-
	2.7[b]		$L\geq 5$		

[a] Reference 4.
[b] Complete angular distributions could not be obtained for these levels.

TABLE II. Nuclear structure factors for the $Pb^{208}(p,t)Pb^{206}$ reaction.[a]

J	Energy (MeV)	L,J	G_{NLJ} $N=1$	$N=2$	$N=3$	$N=4$	$N=5$	$N=6$	$N=7$	Experiment relative peak cross section
0^+	0	0	...	...	...	0.0151	−0.0292	0.360	−0.0021	1.0
	1.3	0	...	...	...	0.00204	−0.0921	0.0851	−0.0028	≦0.1
2^+	0.803	2	...	...	0.0230	−0.0390	0.734			2.0
	1.47	2	...	...	−0.0432	−0.0692	−0.195			≦0.1
	1.85	2	...	...	−0.00845	−0.0930	0.0431			small, not resolved
4^+	1.68	4	−0.0170	0.0272	−0.0236	0.847				2.7
	1.99	4	−0.00306	−0.0330	−0.0734	−0.363				0.5
5^-	2.78	5	...	−0.0376	0.222	−0.276				1.1
	3.02	5	...	0.00748	−0.146	0.226				1.1
6^+	3.12	6	−0.0915	−0.0825	−1.07					1.1
7^-	2.20	7	0.0118	0.253	−0.631					0.5

[a] The dotted spaces indicate small values and these were not calculated.

sections of transitions with identical L values a good estimate is obtained by using only the dominant terms. For example, in comparing the $L=4$ transitions to the 4^+ levels at 1.68 and 1.99 MeV the calculated cross-section ratio is approximately $(0.847)^2/(-0.363)^2=5.5$. The experimental ratio is about 5.4.

Another observation is that the ground-state $L=0$ cross sections on the even isotopes increase in moving away from the closed neutron shell. These ground-state cross-section ratios on the Pb^{208}, Pb^{206}, and Pb^{204} targets are very nearly 3:5:7. Similar results have been found and discussed in other mass regions.[1,5]

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Decay of ^{137}Pr†

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A praseodymium isotope with a half-life of 75 min has been assigned to ^{137}Pr. It decays with a K-capture-to-positron ratio of 2.5 ± 0.2 and a maximum positron energy of 1.74 ± 0.05 MeV. Approximately 6% of the disintegrations are to excited states of ^{137}Ce. The energies and intensities of 28 gamma-ray transitions were measured with a Ge(Li) detector. Coincidences of the gamma rays were measured using two 3-in. NaI(Tl) crystals and a multiparameter analyzer. An energy-level diagram consistent with the observed gamma-ray energies, intensities, and coincidences has been deduced.

I. INTRODUCTION

THIS work has been part of a general program of elucidating the decay properties of neutron-deficient nuclei in the cerium-praseodymium mass region. A range in properties is expected in this region from those of spherical nuclei near the 82-neutron shell closure to those of deformed nuclei[1] at the low mass numbers.

Previous workers[2,3] reported that ^{137}Pr decays with a half-life of 1.5 ± 0.1 h, a positron endpoint of 1.7 ± 0.1 MeV, a K-capture-to-positron ratio of 2.05 ± 0.3, and an absence of gamma rays with intensities equal to or greater than 10% of the annihilation gamma-ray intensity. Because of the somewhat large discrepancy between the half-life we observed and the one previously reported, we have checked the mass assignment and repeated measurements of the positron endpoint and the K-capture-to-positron ratio. Our measurements agree with the earlier measurements within the limits of the experimental errors. Although we observed 28 gamma-ray transitions with a lithium-drifted germanium detector, the most intense transition had an intensity which was only 4% of the annihilation gamma-ray intensity. In spite of the low intensities of the gamma rays, by recording data with a multiparameter analyzer, we were able to measure gamma-gamma coincidences and construct a consistent energy-level scheme.

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[1] E. Marshalek, L. W. Person, and R. K. Sheline, Rev. Mod. Phys. **35**, 108 (1963).

[2] G. T. Danby, J. S. Foster, and A. L. Thompson, Can. J. Phys. **36**, 1487 (1958).

[3] C. Dahlstrom, J. S. Foster, and A. L. Thompson, Can. J. Phys. **36**, 1483 (1958).