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Nuclear Physics **A109** (1968) 481—488; © *North-Holland Publishing Co., Amsterdam*

THE REACTIONS ^{203,205}Tl(α, t)^{204,206}Pb

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Received 4 December 1967

Abstract: The reactions ^{203,205}Tl(α, t)^{204,206}Pb were investigated at an incident energy of 44 MeV, the reaction products being momentum analysed in a double $\Delta E+E$ particle identification system with semiconductor counters. The resulting energy resolution was 120 keV. Transitions were observed to the ground state and the lowest 2^+ state of ^{204,206}Pb and to a number of states at higher excitation energies, starting at about 2.9 MeV in ^{204}Pb and about 2.6 MeV in ^{206}Pb. Angular distributions were measured for the triton groups corresponding to the ground and first excited states of ^{204}Pb. The distributions have a forward peaked shape which can be reproduced well by a DWBA calculation assuming a simple proton stripping process.

F | NUCLEAR REACTIONS ^{203,205}Tl(α, t), $E = 44$ MeV; measured $\sigma(E_t, \theta)$. ^{204,206}Pb deduced levels, spectroscopic factors. Enriched targets.

1. Introduction

Proton pick-up experiments [1]) on ^{204}Pb and ^{206}Pb have revealed a strong fragmentation of the single proton hole strength in ^{203}Tl and ^{205}Tl. This situation is quite different from the situation in ^{207}Tl (one proton hole in the ^{208}Pb core) where the hole strength is found to be concentrated on the five states expected from the shell model. The splitting of the strength in the lighter Tl isotopes is interpreted in terms of proton holes coupled to the "phonons" of the even-mass lead core. Thus, for instance, the $\frac{1}{2}^+$ ground states of ^{203,205}Tl contain 20-30 % admixtures to the pure $3s_{\frac{1}{2}}^{-1}$ configuration, these admixtures probably arising mainly from the 2d hole orbitals coupled to the lowest 2^+ excitation of ^{204}Pb and ^{206}Pb, respectively. The pick-up results of ref. [1]) are supported by the results of the recent intermediate coupling calculations by Sartoris and Covello [2]) and Alaga and Ialongo [3]). These authors use a rather large value of the coupling strength, which gives rise to a considerable mixing of the proton hole states and the collective neutron states of the lead core.

The present investigation of the Tl(α, t) reaction was undertaken to test in particular the properties of the Tl ground states. Using a proton stripping reaction on a Tl

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March 1968

target we expect an $l_p = 0$ transition to the 0^+ ground state and an $l_p = 2$ transition to the first excited 2^+ (collective) state of the final lead nucleus. Additional transitions are expected to states with considerable proton particle-hole amplitude. Such states are known [4]) to occur in ^{208}Pb starting at about 2.6 MeV. Between 1 and 2.5 MeV excitation energy many non-collective neutron hole states are known [5-7]) in ^{204}Pb and ^{206}Pb. According to the model employed in refs. [2, 3]) these states should not be excited in a proton capture reaction on a Tl target.

2. Experimental procedure and results

Alpha particles accelerated in the Saclay cyclotron to an energy of about 44 MeV were used to bombard separated isotope thallium targets. These were the same targets previously used [8]) for the study of the Tl(t, p) reactions. The target thickness was of the order of 0.25 mg/cm^2 for ^{205}Tl and 1 mg/cm^2 for ^{203}Tl. The isotopic enrichment was given as 99 % for the ^{205}Tl target and 92.6 % for the ^{203}Tl target. The reaction products were analysed by a double $\Delta E - E$ particle identification system employing semiconductor counters. The details of the experimental setup are described elsewhere [9]). The angular resolution was $\pm 0.5°$ and the energy resolution in the triton spectrum was about 120 keV FWHM. No impurity groups from other elements could be seen in the triton spectra in the region corresponding to 0-5 MeV excitation energy in lead. The groups from ^{12}C and ^{16}O were not seen because of low Q-values.

Spectra obtained at $\theta_{lab} = 26.4°$ are shown in fig. 1. The more prominent ^{206}Pb groups are visible in the spectrum of ^{204}Pb. The only unfortunate consequence of this for the measurement of the low-lying states of ^{204}Pb is the partial overlap of the ^{204}Pb ground-state group and the ^{206}Pb 2^+ group. However, the relative intensity of the latter impurity group is less than 2 % at all angles measured.

It is seen from fig. 1 that the observed spectra are in qualitative agreement with the model expectations [2,3]). Below about 2.3 MeV the only transitions with measurable intensity are those to the ground state and the first excited 2^+ state. In ^{204}Pb the region between 2.6 and 2.9 MeV excitation energy is masked by groups from ^{206}Pb. Above about 3 MeV we find in both nuclei a number of strong groups which are in part poorly resolved. The excitation energies of the more prominent groups are indicated on the figure. Other data on particle-hole spectra of even lead isotopes, obtained with 15-50 keV energy resolution, indicate extremely complicated structures (refs. [4,7,10-12])). Hence, with 120 keV resolution we expect to see only the gross structure of the proton-particle hole spectra. For this reason no attempt was done to identify the observed groups with known states of ^{204}Pb and ^{206}Pb and we do not consider the angular distribution data for the high-lying states to be significant.

Angular distributions were taken between 17° and 60° for the ground-state group and the first excited 2^+ group. Since the initial state in both Tl isotopes has $J^\pi = \frac{1}{2}^+$, the usual angular momentum and parity selection rules for transfer reactions restrict these two transitions to be pure $l_p = 0$ and $l_p = 2$, respectively. Since, furthermore, the Q-values of the two studied reactions differ by as little as 0.6 MeV we expect the angular distributions for the two isotopes to be quite similar. It was therefore decided to measure the 0^+ and 2^+ distributions only for the thicker of the two targets (^{203}Tl). With a beam current of the order of 5-50 nA the necessary counting time was 2-3 h

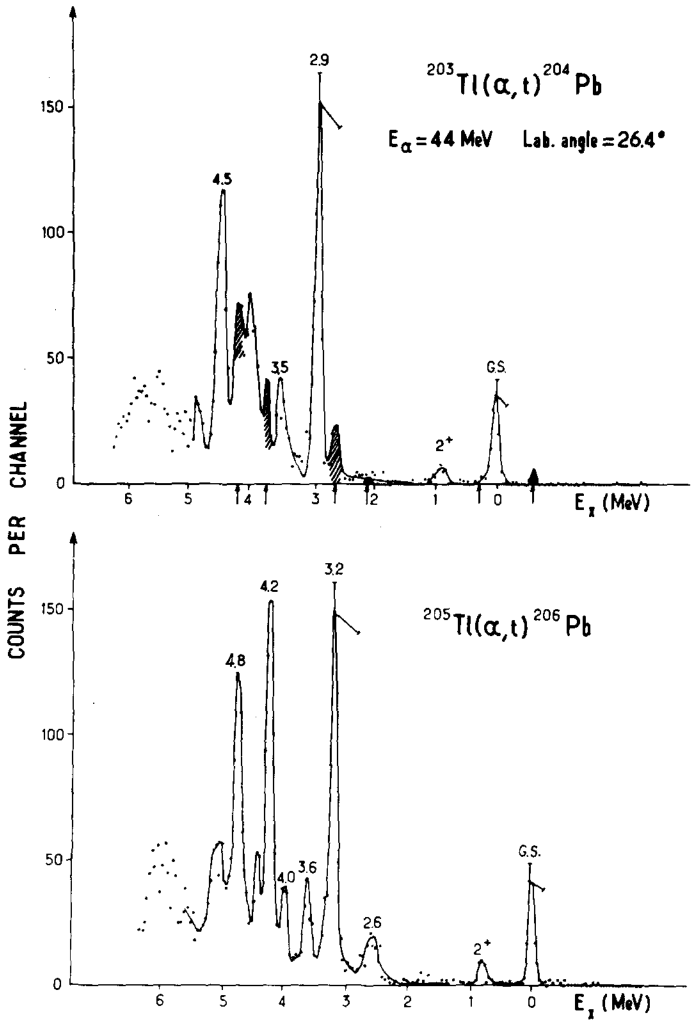

Fig. 1. Observed triton spectra. On the upper spectrum the arrows and the hatched areas indicate contributions from the ^{206}Pb groups. Approximate excitation energies are given (MeV) for some prominent peaks above 2.6 MeV.

per angle. The 17° point was measured at a beam current of only 1 nA due to the high counting rate of the elastically scattered alpha particles.

The resulting distributions (fig. 2) are characterized by a strong forward peaking, the average slope of the two distribution curves being similar. Because of the moderate statistical accuracy which could be obtained in the present experiment it is not possible to make definite statements concerning a possible fine structure in the shape of the angular distributions. In the inverse (t, α) reaction at a 13 MeV the $l_p = 0$ angular distributions were found to exhibit small diffraction-like oscillations (refs. [1,4]).

3. DWBA predictions

The reaction mechanism of the (α, t) reaction at energies above about 20 MeV is likely to be that of a simple proton stripping process. In their recent study [13]) of the ^{208}Pb(α, t)^{209}Bi reaction at 42 MeV, Lilley and Stein discuss this hypothesis on the basis of angular distribution shapes and energy spectra. They emphasize the striking difference between, on the one hand, the ^{209}Bi spectrum observed in the (α, t) reaction and, on the other hand, the ^{209}Bi spectra found in various direct inelastic scattering processes. This property of the Pb(α, t) reaction and the forward-peaked angular distributions are taken in ref. [13]) as strong evidence for a predominant stripping mechanism. The present results on Tl exhibit qualitatively the same features. Thus, our angular distributions have a similar forward-peaked structure as those of ref. [13]) and we also find the (α, t) spectra to be quite different from those observed in direct inelastic scattering [12,14,15]) on the residual nuclei. Hence, we likewise base our interpretation on the assumption of a simple stripping mechanism.

In order to test quantitatively the calculated [2,3]) wave functions for the Tl ground states a set of distorted wave (DW) calculations were performed using the code JULIE, originated by R. M. Drisko. The calculations employed the zero-range approximation and treated the alpha particle and the triton as point particles. The optical model parameters used in the calculations (the LS set, table 1) were taken from Lilley and Stein's work [13]) on the ^{208}Pb(α, t) reaction. These parameters are similar to those of the ALD set [1]), used for DW predictions of the inverse Pb(t, α) reaction at 13 MeV, the main difference being the use of a somewhat deeper imaginary potential in the LS set than in ALD set. The predicted (α, t) cross sections were found to be insensitive to the application of lower cut-offs in the radial integrals in the range from 0 to 8 fm. It is interesting to note that the LS parameter set predicts strong oscillations in the alpha particle elastic scattering cross section in the backward hemisphere. Such oscillations have been observed [16]) in alpha scattering on ^{208}Pb at 44 MeV and there is approximate agreement between the predicted and the measured positions of maxima and minima. There are no data available on triton elastic scattering in the lead region.

The predicted shapes for the $l_p = 0$ and $l_p = 2$ angular distributions agree well with the data in the angular interval studied (fig. 2). To test the sensitivity of the predicted shapes to variations in the values of the optical model parameters we also performed a set of DW calculations, using the ALD set [1]). However, this choice gives rise to a strongly oscillating pattern for $l_p = 0$, in disagreement with the data. Poor agreement was also found for several other combinations of triton and alpha particle potentials, suggested in the literature [1,17-19]) for this mass and energy region. We also tried the 183.7/142.4 type potential suggested by the Heidelberg group [20]) for the Cr(^{3}He, α) reaction. This potential has six different parameters in each channel and further includes a spin-orbit term in the ^{3}He channel. The resulting DW prediction was found to give almost as good agreement with the observed shapes as the LS set. Also the absolute values of the predicted $l_p = 0$ and $l_p = 2$ cross sections differ little between the 183.7/142.4 Heidelberg set and the LS set. We favour the latter because of the smaller number of parameters used, and because of the close relation to the ALD parameters which were found to be satisfactory for the (t, α) reaction at 13 MeV.

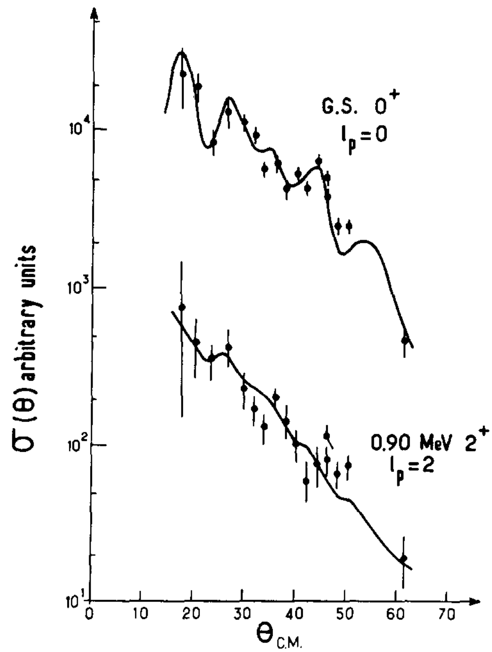

Fig. 2. Angular distributions for the ground state and the lowest 2^+ group of ^{204}Pb. The curves are DW predictions obtained with the LS set. The $d_{\frac{3}{2}}$ and $d_{\frac{5}{2}}$ DW predictions differ in magnitude but have identical shapes.

4. Discussion

Using the measured relative cross sections for ^{204}Pb(0) and ^{204}Pb(2) and the corresponding DW cross sections for $l_p = 0$ and $l_p = 2$, respectively, we may test the theoretical predictions [2,3]) for the ^{203}Tl ground state. In the work of Sartoris and Covello [2]) the wave function for ^{203}Tl(0) is given as

$$\psi = 0.875\,|s_{\frac{1}{2}}\,00\rangle - 0.377|d_{\frac{3}{2}}\,12\rangle + 0.238|d_{\frac{5}{2}}\,12\rangle + 0.130|s_{\frac{1}{2}}\,20\rangle. \qquad (1)$$

The basic states in this description are the eigenvectors $|l_j NR\rangle$, where l_j are the quantum numbers of the proton hole and R is the angular momentum of the N-phonon state of the lead core. The lowest 2^+ state of lead thus corresponds to $N, R = 1, 2$.

The stripping cross sections for the ground state and the lowest 2^+ state, respectively, are related to the amplitudes of eq. (1) by the relations:

$$\mathrm{d}\sigma(0^+) = A \times 0.875^2 \, \mathrm{d}\sigma_{\mathrm{DW},\, s_{\frac{1}{2}}}$$

$$\mathrm{d}\sigma(2^+) = A \times (0.377^2 \, \mathrm{d}\sigma_{\mathrm{DW},\, d_{\frac{3}{2}}} + 0.238^2 \, \mathrm{d}\sigma_{\mathrm{DW},\, d_{\frac{5}{2}}}) \tag{2}$$

where A is a common proportionality factor.

For comparison with the experiment we use the summed cross sections in the 17-60° interval. Employing the LS parameters we find a predicted ratio of cross section sums $\sum \mathrm{d}\sigma(2^+)/\sum \mathrm{d}\sigma(0^+) = 0.23$. This result is close to the corresponding experimental ratio of summed cross sections, which is 0.26 ± 0.02.

The calculations of Alaga and Ialongo [3]) are made for ^{201}Tl but the results are taken to be representative also for ^{203,205}Tl. These authors predict a somewhat smaller $|s_{\frac{1}{2}}\, 00\rangle$ amplitude in the Tl ground state and the calculated cross-section ratio is therefore larger than that of ref. [2]). Using the wave function given for ^{201}Tl(0) at Varenna [3]), we find in a similar way as above a cross section ratio $\sum \mathrm{d}\sigma(2^+)/\sum \mathrm{d}\sigma(0^+) = 0.38$, which is slightly higher than the experimental result. Thus, the present data support the qualitative features of both calculations, the results of ref. [2]) being somewhat favoured as regards the Tl ground state wave function. However, in view

TABLE 1

Optical model parameters

Potential	Particle	V	W	r_0	r'_0	a	a'	r_C	λ [a])
LS	α	200	20	1.4	1.4	0.6	0.6	1.3	0
(ref. [13])	t	200	50	1.45	1.45	0.6	0.6	1.3	0
ALD	α	200	15	1.4	1.4	0.6	0.6	1.3	0
(ref. [1])	t	200	50	1.4	1.4	0.6	0.6	1.3	0
	p	[b])	0	1.25	0	0.65	0	1.25	32

V and W are in MeV, r_0, r'_0, a and a' in fm. The form of the optical model potential used is given in ref. [1]).

[a]) The wave function of the captured proton was calculated from a Woods-Saxon potential with a spin-orbit coupling of strength λ, where λ is given in Thomas units (cf. for instance ref. [12])).

[b]) Adjusted to give a binding energy of the proton of $B = 19.81 + Q$ (MeV), i.e. the experimental separation energy.

of the approximate character of the nuclear model employed it is probably not justified to look for a detailed, quantitative agreement with experiment.

Both sets of theoretical calculations predict that the ^{203}Tl and ^{205}Tl ground states should be closely similar. In fact, we find about the same cross section ratio $d\sigma(2^+)/d\sigma(0^+)$ in ^{206}Pb and in ^{204}Pb for angles near 30°, and in both nuclei the excitation of non-collective neutron states below 2.3 MeV is found to be small. From the ^{206}Pb impurity in the ^{204}Pb spectra we can also deduce the ratio of the two ground-state spectroscopic factors. Using the isotopic analysis of the ^{203}Tl target we find an experimental cross-section ratio $\sum d\sigma(0; 206)/\sum d\sigma(0; 204) = 0.9 \pm 0.1$. The corresponding ratio of DW cross sections is equal to 1.1. Thus the ratio of the ground state spectroscopic factors is $S_{205}/S_{203} = 0.8 \pm 0.1$. The error given here is purely statistical and does not include a possible error on the isotopic analysis of the ^{203}Tl target.

In the inverse (t, α) reaction at 13 MeV the ground state spectroscopic factors were found [1]) as $S_{205} = 1.4$ and $S_{203} = 1.3$, respectively, the ratio thus being 35 % higher than that found in the present experiment. However, in ref. [1]) the S values were determined for two different targets and are related through the target thickness measurements, having an estimated error of ±30 %.

The sudden onset of strong proton-particle hole states near 3 MeV excitation energy in the two final lead nuclei is reasonable in view of the evidence from ^{208}Pb, where a large part of the proton $(1h_{\frac{9}{2}}3s_{\frac{1}{2}}^{-1})$ strength was found [4]) in the 3-4 MeV region. The experimental and theoretical understanding of this type of states in the lead region is still rudimentary, and further direct reaction studies of such excitations with improved energy resolution would be desirable.

It is a pleasure to thank Mr. R. Chaminade and his group, and the crew of the 44 MeV cyclotron for their skilful assistance. We are grateful to Dr. S. Hinds for the loan of the Tl targets. One of us (O.N.) is indebted to the Department of Nuclear Physics, Saclay, for kind hospitality.

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