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THE ^{208}Pb(α, ^{3}He)^{209}Pb REACTION AT 58 MeV †

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Abstract: The ^{208}Pb(α, ^{3}He)^{209}Pb reaction at 58 MeV has been used to search for high-spin states in ^{209}Pb. Only three levels are excited with appreciable intensity: the ground state ($2g_{\frac{9}{2}}$) and levels at 0.781 ($1i_{\frac{11}{2}}$) and 1.426 MeV ($1j_{\frac{15}{2}}$). The angular distributions for these levels have been measured and analyzed using standard DWBA calculations to obtain spectroscopic strengths. The ^{208}Pb(α, α) elastic scattering was measured and optical parameters deduced from the data. A normalization value $N = 50$ yields spectroscopic values which are close to the values measured in the (d, p) reaction. The (α, ^{3}He) reaction should easily pick out any appreciable components of the $j_{\frac{15}{2}}$ shell model state, which weak-coupling calculations predict should be fragmented. However only three weak transitions previously seen in a (d, p) experiment are observed.

E | NUCLEAR REACTIONS ^{208}Pb(α, α), (α, ^{3}He), $E = 58$ MeV; measured $\sigma(E_{\alpha}, \theta)$, $\sigma(E_{^3\mathrm{He}}, \theta)$. ^{209}Pb deduced levels, π, S, L. Enriched target.

1. Introduction

In recent years considerable experimental effort has been devoted to the study of the shell model single-particle and single-hole states in the nuclei adjacent to doubly magic ^{208}Pb. Complementary data have been accumulated from many reactions and the main features of these states now seem to be well established.

With few exceptions, 80 % or more of the shell model strength is concentrated in a single nuclear level. One of these exceptions is apparently the $1j_{\frac{15}{2}}$ single-neutron state in ^{209}Pb. A large fragment of this state is contained in a level at 1.426 MeV. The compilation in ref. [1]) lists spectroscopic factors obtained from six (d, p) experiments. Although the values range from 0.39 up to 1.38, it seems to have been generally accepted in the literature that the spectroscopic factor for the 1.426 MeV level is approximately 0.5 or, in other words, the level contains only about 50 % of the $j_{\frac{15}{2}}$ strength.

Appreciable fragmentation of the $j_{\frac{15}{2}}$ shell model state (whose parity is opposite to that of the other states in the shell) has been predicted by Hamamoto [2]) and Bes and Broglia [3]) based on the results of weak-coupling model calculations. Both calculations predict that more than 35 % of the total $j_{\frac{15}{2}}$ strength is to be found between 3.2 and 3.5 MeV excitation.

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The purpose of the work reported herein was to study the structure of ^{209}Pb with a reaction which preferentially excites states requiring high l-transfers and in particular to search for fragments of the $j_{\frac{15}{2}}$ strength. At 58 MeV the ^{209}Pb(α, ^{3}He) reaction semi-classically has a favored angular momentum transfer of seven units. This is in sharp contrast to the (d, p) and (t, d) reactions which have been used previously to study ^{209}Pb. These reactions favor the low l-transfers. For example, at 20 MeV the ^{208}Pb(d, p) reaction has a favored angular momentum transfer of two units. The (α, ^{3}He) reaction is therefore better suited to searching for small pieces of the $i_{\frac{11}{2}}$ and $j_{\frac{15}{2}}$ strength embedded in a background of mostly lower-spin states.

It is also of interest to compare spectroscopic factors obtained from the (α, ^{3}He) reaction to those measured in the (d, p) reaction. In the latter reaction there is a large momentum mismatch for the $l = 7$ transitions and consequently there is a significant contribution to the cross section from the nuclear interior involving the low partial waves in the proton channel. On the other hand, in the (α, ^{3}He) reaction the main contribution to the cross section for $l = 7$ transitions is from the surface partial waves which are best determined by elastic scattering.

2. Experimental procedure

Alpha particles accelerated to 58 MeV by The University of Michigan 83 inch cyclotron were focused on a self-supporting 1.5 mg/cm^2 ^{208}Pb target enriched to 98 %. At forward angles (out to 25 °) the ^{3}He ions were detected by an array of position-sensitive detectors placed on the image surface of the first of the three spectrographs which comprise the magnetic analysis system. At angles of 10° and larger, data were also recorded using nuclear emulsions (Ilford) which were subsequently scanned by microscope.

The target thickness was determined by comparing the α-particle elastic scattering yield from the enriched target to the yields from several self-supporting lead targets of natural isotopic abundance. The latter targets were then cut, weighed, and the enriched target thickness calculated using the relative isotopic compositions. As an independent determination, the thickness of the enriched target was also calculated from a measurement of the energy loss of ^{241}Am alphas after traversing the target. The two methods agreed within 12 %.

The elastic scattering of 58 MeV alphas from ^{208}Pb was measured in the angular range 10°–85°. The scattered alphas were detected by a position-sensitive detector placed on the optic axis of the spectrograph.

3. Experimental results and analysis

As no alpha elastic data on lead-region nuclei are available in the energy range between 42 and 104 MeV, it was necessary to measure the elastic scattering of 58 MeV alphas from ^{208}Pb to obtain optical parameters. The results are shown in fig. 1. The parameter values which best fit the experimental data were determined with an optical model search program, using as initial input the parameter set which fits the 104 MeV alpha scattering from lead [4]). The solid curve in fig. 1 was obtained from the alpha parameters listed in table 1. Attempts to obtain equally good fits with deeper real potentials (V in the neighborhood of 135 MeV and 190 MeV) were unsuccessful.

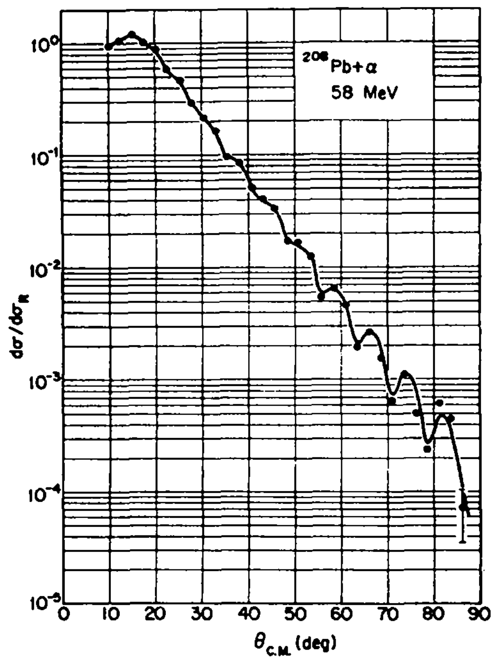

Fig. 1. Optical model fit to the measured elastic scattering of 58 MeV α-particles from ^{208}Pb. The optical model parameters are given in table 1.

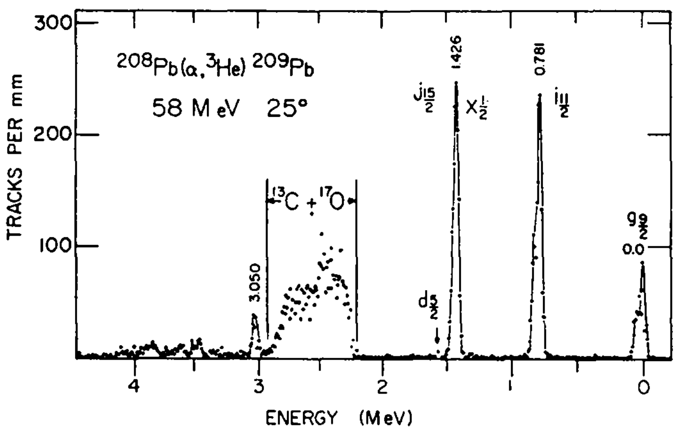

Fig. 2. Typical ^3He spectrum showing the three strongly populated neutron single-particle states in ^{209}Pb.

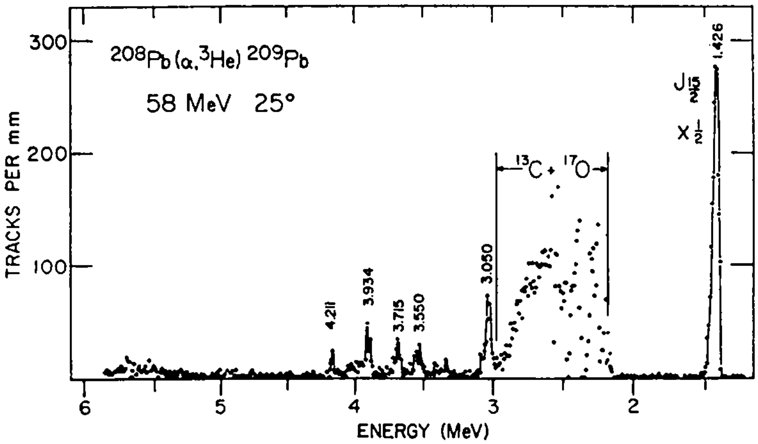

Fig. 3. The ^{3}He spectrum showing the weakly populated states at higher excitation in ^{209}Pb.

Typical ^{3}He spectra obtained in this study of the $^{208}Pb(\alpha, {}^3He)^{209}Pb$ reaction are shown in figs. 2 and 3. Fig. 3 shows the higher excitation region of the spectrum where any fragments of the $j_{\frac{15}{2}}$ strength are likely to be found. It is evident from the spectrum that the cross sections for transitions with high l-transfers are greatly enhanced over those to the lower spin states.

Distorted wave Born approximation (DWBA) calculations were performed using the computer code DWUCK [5]). Some exploratory calculations were made in which non-local and finite-range effects were included in the local-energy approximation. The fits to the experimental angular distributions obtained from these calculations were no better than those obtained from local zero-range (LZR) calculations and for this reason only LZR calculations were used in the analysis.

The cross section for the (α, ^{3}He) reaction on a spin-zero target can be written as

$$d\sigma/d\Omega = N S_{lj} \sigma_{lj}^{dw}(\theta),$$

where N is a zero-range normalization factor, S_{lj} is the spectroscopic factor, and $\sigma_{lj}^{dw}(\theta)$ is the cross section calculated by DWUCK for the orbital lj. The value of N is not well established for these reactions [6-10]); values obtained empirically from LZR calculations involving lighter targets are typically in the range 40–50. Since comparison of the experimental cross sections with DWBA predictions yields only the product NS, the uncertainty in N leads to a corresponding uncertainty in the absolute spectroscopic factors. Hence only relative S-values are likely to be reliable.

The optical model parameters used to generate the distorted waves in the DWUCK calculations are listed in table 1. The ^{3}He parameters were obtained from elastic scattering on ^{208}Pb at 47.5 MeV [ref. [11])].

The form factors were generated as eigenfunctions of a Woods-Saxon well using the separation-energy method. Calculations were made for different choices of the

TABLE 1

Optical model and bound-state parameters used in the DWBA calculations

Parameter set	V (MeV)	r_0 (fm)	a_0 (fm)	W (MeV)	r'_0 (fm)	a' (fm)	r_c (fm)
α	62.4	1.405	0.669	35.6	1.405	0.669	1.30
^{3}He [a])	175.0	1.14	0.723	17.5	1.60	0.90	1.40
neutron	V_n [b])	1.275	0.65	(λ =) [c])			

[a]) Ref. [11]).

[b]) Adjusted to give binding energy equal to separation energy.

[c]) Spin-orbit coupling of λ times the Thomas term. Calculations were made using λ values of 6, 12.5, and 25.

potential parameters and, as expected, both the absolute and relative cross sections are sensitive to the parameters chosen.

In studies of the ^{208}Pb(^{3}He, d) reaction [12,13]), it has been found that reducing the strength of the spin-orbit coupling for the transferred proton from the usual value of $\lambda \approx 25$ to a value of $\lambda \approx 6$ resulted in spectroscopic factors close to unity in ^{209}Bi. A similar result has been found in an analysis of the ^{208}Pb(^{3}He, α) reaction [14]); a value of $\lambda = 6$ yielded better relative spectroscopic factors than did a value of $\lambda = 27.5$. This reduction in the spin-orbit strength has been interpreted [12,14]) as being similar in its effects to the use of independent spin-orbit coupling, i.e., use of different radius and diffuseness parameters for the Woods-Saxon well and the spin-orbit potential. Independent spin-orbit coupling is reasonable as there is no compelling reason why the geometrical parameters should be equal.

TABLE 2

Normalization and spectroscopic values for the ^{208}Pb(α, ^{3}He)^{209}Pb reaction

nlj	E_x [a]) (MeV)	$S(N = 50)$ $\lambda = 6$	$\lambda = 12.5$	$\lambda = 25$
$2g_{\frac{9}{2}}$	0.0	1.02	0.99	0.94
$1i_{\frac{11}{2}}$	0.781	0.79	0.87	1.05
$1j_{\frac{15}{2}}$	1.426	0.73	0.67	0.57

[a]) Excitation energies are estimated to be correct to ±8 keV.

Calculations were made using values of 6, 12.5, and 25 for the spin-orbit strength λ. The resulting spectroscopic factors are shown in table 2. As noted earlier, the correct value for the normalization N is not accurately known so the value $N = 50$ was arbitrarily chosen to facilitate comparison of the relative spectroscopic values. It should be noted that this normalization compares favorably with normalization values obtained in (α, ^{3}He) reactions on lighter targets and also yields spectroscopic factors comparable to those obtained in the (d, p) reaction. The value of the product NS obtained from this analysis depends upon the choice of the radius parameter r_0 of

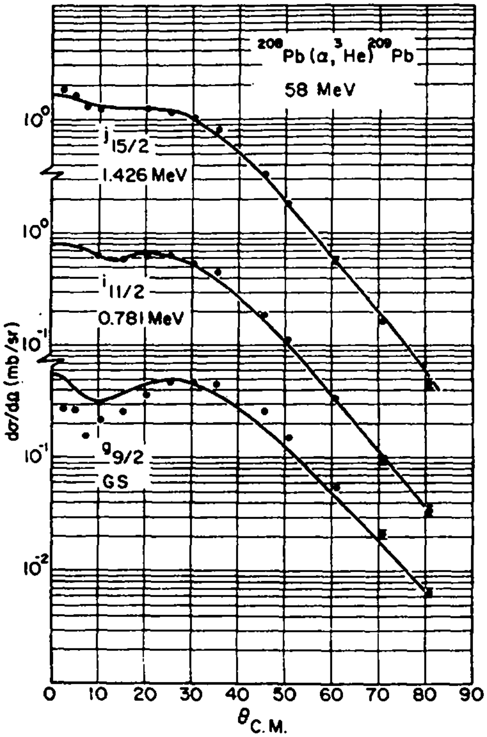

Fig. 4. Angular distributions for the three strongly populated neutron single-particle states in ^{209}Pb. The solid curves are DWBA fits.

the Woods-Saxon well; NS increases as r_0 decreases. If r_0 is reduced from 1.275 to 1.25, the normalization which yields essentially the same spectroscopic factors (for $\lambda = 6$) as listed in table 2 is $N = 55$. Reducing the strength of the spin-orbit coupling has the effect of decreasing the spectroscopic factor of the $i_{\frac{11}{2}}$ state (which is a $j = l-\frac{1}{2}$ state) relative to the spectroscopic factors for the $g_{\frac{9}{2}}$ and $j_{\frac{15}{2}}$ states (which are $j = l+\frac{1}{2}$ states).

The angular distributions measured for the three states which are strongly excited are shown in fig. 4. The solid curves are the results of the DWBA calculations. For the $l = 6$ and $l = 7$ transitions, the fits are quite good. For the $l = 4$ ground state transition, the fit is good although the dip at the forward angles is not fully reproduced.

It can be seen in fig. 3 that there are some states weakly excited between 3 and 4 MeV excitation. Angular distributions have been measured and l-assignments have been made for most of these states in a recent (d, p) experiment by Kovar *et al.* [15]. The fact that these states are excited in the (α, ^{3}He) reaction (which preferentially excites states requiring high l-transfers) provides additional evidence that the l-assignments in ref. [15]) are correct. Table 3 lists the cross sections at 25° for these weak transitions and also lists the spectroscopic factors calculated from these cross sections. The spectroscopic factors for the three $l = 7$ transitions are in excellent agreement with those obtained in ref. [15]).

4. Discussion and conclusions

In the $(\alpha, {}^3He)$ reaction on ^{208}Pb, just three states are excited with appreciable intensity. The measured $(\alpha, {}^3He)$ angular distributions are relatively structureless. Based on the shapes of the angular distributions, it would be particularly difficult to distinguish reliably between $l = 6$ and $l = 7$ transitions. The states requiring low l-transfers are seen only weakly. For example, at 35° these cross sections were measured for the following single-neutron states: $3d_{\frac{5}{2}}$ (1.57 MeV) $d\sigma/d\Omega \approx 14\ \mu b/sr$, $4s_{\frac{1}{2}}$ (2.03 MeV) $d\sigma/d\Omega < 2\ \mu b/sr$, and $3d_{\frac{3}{2}}$ (2.54 MeV) $d\sigma/d\Omega \approx 13\ \mu b/sr$. The $g_{\frac{7}{2}}$ single-neutron state at 2.49 MeV is more than five times less intense than the $g_{\frac{9}{2}}$ ground state. This large reduction in cross section is predicted by the DWBA calculations and is due to the rapid change in momentum matching conditions with increasing excitation energy.

TABLE 3

Spectroscopic factors for weak states between 3 and 4 MeV

E_x [a]) (MeV)	l [b])	S ($N = 50, \lambda = 25$)	$\frac{d\sigma}{d\Omega}$ (25°) (lab) ($\mu b/sr$)
3.050	7	0.062	83
3.550	7	0.032	36
3.715	7	0.028	29
3.934	6		37
4.211			27

[a]) The energies are estimated to be accurate to ±14 keV.
[b]) The $l = 7$ assignments are taken from ref. [15]). The $l = 6$ assignment is from ref. [16]).

TABLE 4

Comparison of spectroscopic factors for the ^{209}Pb single-particle states measured in this work to those obtained in other reactions

nlj	Copenhagen [a]) (d, p; 12 MeV)	Oxford [b]) (d, p; 18.7 MeV)	Los Alamos [c]) (t, d; 20.0 MeV)	Yale [d]) (d, p; 20.0 MeV)	This work [f]) (α, ^{3}He; 58 MeV)
$2g_{\frac{9}{2}}$	0.78	0.66	0.76	0.83(0.92) [e])	0.94
$1i_{\frac{11}{2}}$	0.96	0.75	0.86	0.86(1.14)	1.05
$1j_{\frac{15}{2}}$	0.53	0.71	0.49	0.58(0.77)	0.57

[a]) Ref. [17]). [b]) Ref. [18]). [c]) Ref. [19]). [d]) Ref. [15]).
[e]) Value in parentheses calculated using the Johnson-Soper adiabatic deuteron model which includes approximately the contributions from diffractional breakup of the deuteron.
[f]) Spectroscopic factors calculated using LZR DWBA with a normalization factor $N = 50$ and spin-orbit coupling strength $\lambda = 25$.

The spectroscopic factors for the ^{209}Pb single-particle states measured in this work are compared in table 4 to spectroscopic factors which have been obtained in other reactions. The values show some scatter but generally indicate that 30–40 % of the $j_{\frac{15}{2}}$ strength is missing. One of the motivations for the present work was to locate any missing $j_{\frac{15}{2}}$ strength and, considering the characteristics of the (α, ^{3}He) reaction, any states containing appreciable $l = 7$ strength should be readily apparent. As can be seen from table 3, the weak transitions observed between 3 and 4 MeV can account for only about 12 % of the missing strength. This leaves roughly 25 % of the $j_{\frac{15}{2}}$ strength unaccounted for.

Both the calculations of Hamamoto [2]) and of Bes and Broglia [3]) predict the $j_{\frac{15}{2}}$ strength to be appreciably fragmented and further predict that the bulk of the strength lies in two levels, one of which can be identified with the level at 1.426 MeV. Hamamoto predicts the other level to lie at 3.21 MeV with a spectroscopic factor $S = 0.255$; Bes and Broglia predict it at 3.47 MeV with a spectroscopic factor $S = 0.304$. While there is some fragmentation, it appears that the weak-coupling prediction that the $j_{\frac{15}{2}}$ state is split into two major components is contradicted by the experimental facts.

The DWBA procedure for extracting spectroscopic factors is somewhat imprecise–uncertainties of at least 20 % are often assumed. One must allow for the possibility that the spectroscopic factor for the level at 1.426 MeV is actually ≈ 0.80. If the spectroscopic factors for the three weak fragments are similarly scaled upwards, essentially all of the $j_{\frac{15}{2}}$ strength would be accounted for.

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