$M1$ Strength in ^{208}Pb from (p,p') and $(d,{}^3\mathrm{He})$ Reactions

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A strong 1^+ state which has a large component of the $\pi(h_{11/2}{}^{-1}h_{9/2})$ configuration was found at 5.845 MeV of excitation in ^{208}Pb from the reactions ^{208}Pb(p,p') and ^{209}Bi$(d,{}^3\mathrm{He})$. The 4.841-MeV state which was recently suggested to be of 1^+ is shown to be a 1^- state.

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The missing 1^+ ($M1$) strength in ^{208}Pb has been a big puzzle for some time. There is a group of fragmented states at around 7.5 MeV of excitation,[1,2] which together has about one-fifth of the shell-model limit of strength.[3] In a simple shell model two strong 1^+ states which are made of $\pi(h_{11/2}{}^{-1}h_{9/2})$ and $\nu(i_{13/2}{}^{-1}i_{11/2})$ configurations are expected at around 6 MeV of excitation.[4] In more elaborate shell-model calculations reported by Vergados[5] two 1^+ states which were almost entirely made of $\pi(h_{11/2}{}^{-1}h_{9/2})$ and $\nu(i_{13/2}{}^{-1}i_{11/2})$ configurations were predicted to be at 5.45 and 7.52 MeV of excitation. Thus we may expect some 1^+ strength in the region of the excitation energy lower than 7 MeV, even if there is a significant quenching of the $M1$ strength in ^{208}Pb. There is now ample evidence[6] for the $M1$ quenching in medium-heavy nuclei. Recent studies[6-8] on f-p-shell nuclei and zirconium isotopes by (e,e') and (p,p') reactions suggest that the observed $M1$ strengths in those nuclei are less than one-half of the shell-model limit. We decided to undertake a careful search for 1^+ states at the excitation energy region between 4 and 7 MeV by the reactions ^{208}Pb$(p,p')^{208}$Pb and ^{209}Bi$(d,{}^3\mathrm{He})$. Our scheme for finding 1^+ states was first to locate the states with $\pi(h_{11/2}{}^{-1}h_{9/2})$ components via the reaction ^{209}Bi$(d,{}^3\mathrm{He})$, and then to assign the spins from the shapes of proton angular distributions of the reactions ^{208}Pb$(p,p')^{208}$Pb leading to the states. In order to obtain successful results from this scheme, an experiment on the reaction ^{208}Pb$(d,{}^3\mathrm{He})^{207}$Tl was also necessary for the reasons stated later in the paper. The reaction ^{209}Bi$(d,{}^3\mathrm{He})^{208}$Pb was previously studied by McClatchie, Glasshausser, and Hendrie.[9] However, the energy resolution in their experiment was not sufficient for resolving such weak states as 1^+ states of $\pi(h_{11/2}{}^{-1}h_{9/2})$ configuration. In the case of the reaction ^{208}Pb(p,p') there is a fine work by Wagner *et al.* with 35-MeV protons.[10] Nevertheless at 35-MeV proton incident energy, numerous collective natural-parity states dominate the reaction yields, and unnatural-parity states with simple particle-hole character are expected to be weakly excited in the (p,p') reaction.[11] With the 65-MeV protons which we used in the present experiment, we hoped for a better enhancement in exciting 1^+ states.

The experiments were performed at the Research Center for Nuclear Physics, Osaka University. The reactions ^{208}Pb(p,p'), ^{208}Pb$(d,{}^3\mathrm{He})$, and ^{209}Bi$(d,{}^3\mathrm{He})$ were studied in the present work. The 65-MeV proton beams and the 50-MeV deuteron beams obtained from the azimuthally varying field (AVF) cyclotron were used in the experiments. The same self-supporting ^{208}Pb target with thickness of 1.0 mg/cm^2 was used in the (p,p') and $(d,{}^3\mathrm{He})$ experiments. The ^{209}Bi target was a self-supporting foil of 0.18 mg/cm^2. The outgoing particles were momentum analyzed by the magnetic spectrograph RAIDEN[12] and detected by a position-sensitive proportional counter of 1 m in length.[13] The energy resolution in the ^{208}Pb(p,p') experiment ranged from 12 to 16 keV [full width at half maximum (FWHM)], and the measurements were made in the angular range between 6° and 90°. A typical spectrum of inelastically scattered protons is shown in Fig. 1. In the reaction ^{209}Bi$(d,{}^3\mathrm{He})$, the energy resolution was about 25 keV (FWHM). In the two $(d,{}^3\mathrm{He})$ reactions the ^{3}He spectra were measured in the angular range between 6° and 24°.

The purpose of the ^{208}Pb$(d,{}^3\mathrm{He})^{207}$Tl experiment was to obtain clean experimental shapes of ^{3}He angular distributions for the pickups of $3s_{1/2}$, $2d_{3/2}$, $1h_{11/2}$, and $2d_{5/2}$ proton orbitals in the angular range where the differences in the shapes for different orbitals were the largest. Another purpose of this experiment was a consistency check for the absolute values of the cross sections with the previous result at 50 MeV.[14] When we compared the cross sections for the four states of $1/2^+$ (ground state), $3/2^+$ (0.35 MeV),

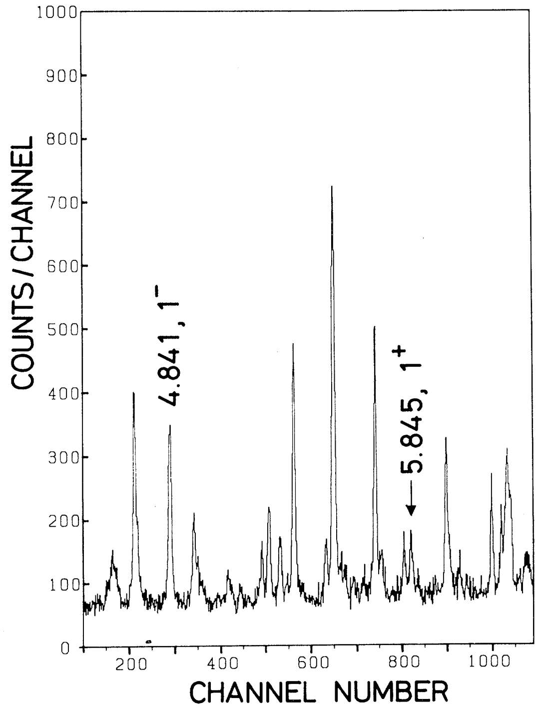

FIG. 1. Inelastic proton spectrum at $\theta_{lab} = 10°$.

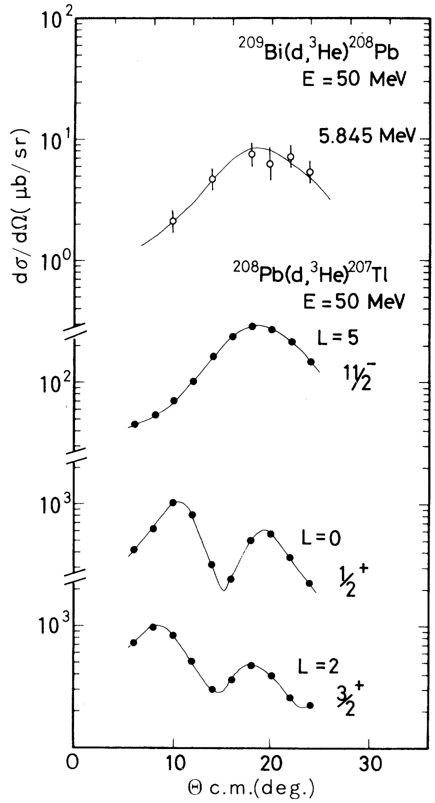

FIG. 2. Measured cross sections for the reactions ^{209}Bi(d, ^{3}He) ^{208}Pb (5.845-MeV state), and ^{208}Pb(d, ^{3}He)^{207}Tl leading to the $11/2^-$ (1.34-MeV), $1/2^+$ (ground) and $3/2^+$ (0.35-MeV) states, respectively. The solid lines for the ^{207}Tl states are drawn merely to guide the eye. The solid line for the 5.845-MeV state indicates the shape of the experimental angular distributions for the $11/2^-$ (1.34-MeV) state in ^{207}Tl.

$11/2^-$ (1.34 MeV), and $5/2^+$ (1.67 MeV) in ^{207}Tl between the two experiments, it was found that our results were 10%–15% lower than theirs[14] in the angular range between 16° and 22° where all the angular distributions showed plateaus. Our results of the ^{208}Pb(d, ^{3}He) experiment are shown in the lower half of Fig. 2.

In the reaction ^{209}Bi(d, ^{3}He)^{208}Pb, the absolute values of the cross sections for the ground state, the 3.708-MeV 5^- state, and the 3.96-MeV 5^- state obtained in our measurements were in an excellent agreement with those by McClatchie, Glasshausser, and Hendrie.[9] We estimated that the average difference in the cross sections between the two experiments was less than 3%. Thirteen states which had $L = 5$ character were found in the energy region between 4.5 and 6.0 MeV of excitation. The summed yield of the thirteen states amounts to (89 ± 10)% of the yield of the $11/2^-$ state at 1.34 MeV in ^{207}Tl obtained from the present reaction ^{208}Pb(d, ^{3}He)^{207}Tl. Spin values are already known for four of the thirteen states from previous studies of the ^{208}Pb(e, e') and ^{208}Pb(p, p') experiments.[15,16] They are the 8^+ state at 4.610 MeV and three 10^+ states at 4.895, 5.072, and 5.922 MeV. The excitation energies of the other nine states are 4.861, 5.087, 5.159, 5.195, 5.214, 5.320, 5.341, 5.720, and 5.845 MeV, respectively, with errors of 5–12 keV.

When these nine states were examined in the reactions ^{208}Pb(p, p'), it was found that all of them were very weakly excited. And there was only one state among the nine which showed forward-peaked angular distributions, indicating a low spin value. This state was the one at 5.845 MeV of excitation (see Fig. 1). The precise value of the excitation energy was determined from the ^{208}Pb(p, p') experiment. The ^{3}He angular distribution for this 5.845-MeV state is shown in the upper part of Fig. 2. The solid line indicates the shape of the experimental ^{3}He angular distribution of the reaction ^{208}Pb(d, ^{3}He) leading to the $11/2^-$ state at 1.34 MeV of excitation in ^{207}Tl. The proton angular distribution for the 5.845-MeV state is shown in Fig. 3. In the lower part of the

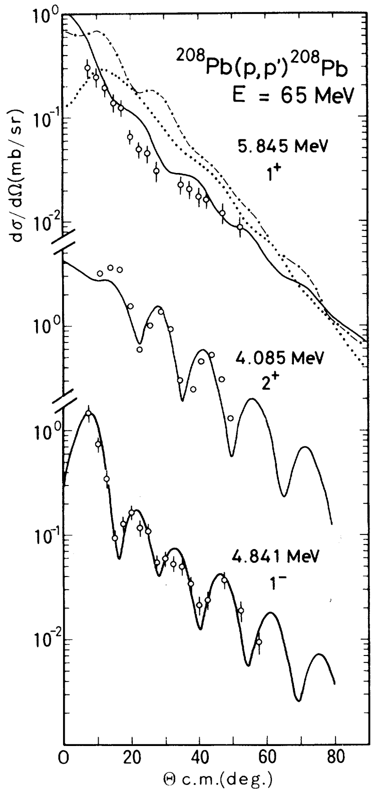

FIG. 3. Comparison of the measured inelastic angular distributions for the 5.845-, 4.086-, and 4.841-MeV states with the theoretical calculations. The fit for the 4.086-MeV state was obtained with a 2^+ collective form factor. For the other fits see the text.

figure the angular distributions for the 2^+ state at 4.086 MeV and for the 4.841-MeV state which was recently suggested to be of 1^+ are shown for comparison.[17] The shape for the 5.845-MeV state is clearly different from those for the other two states. Monotonic decrease and lack of strong diffraction pattern are the characteristics of the angular distribution for the 5.845-MeV state. These features are the same as those found in the shape of 1^+ states in the reaction ^{48}Ca(p,p') at 65 MeV.[8] Shapes for higher-spin states with positive parity, namely 3^+, 4^+, ... states, are quite different and any possibility of a higher spin for the 5.845-MeV state can be easily ruled out. The solid line for the 5.845-MeV state is a distorted-wave calculation with Michigan State three-range Yukawa interactions (M3Y)[18] which were obtained by a computer code DWBA74.[19] The spin and parity of 1^+ were assumed for the state and Vergados's wave function,

$$\psi_1{}^+ = -0.779\,|h_{11/2}{}^{-1}h_{9/2}\rangle - 0.61\,|i_{13/2}{}^{-1}i_{11/2}\rangle$$

was used, and the exchange effects were included in the calculations. The dot-dashed line is a similar calculation with the pure $(h_{11/2}{}^{-1}h_{9/2})$ proton configuration for the 1^+ state. No renormalization was made in the fits shown in the figure. The former fit is clearly better than the latter one. However, we found that when the proton amplitude of the $(h_{11/2}{}^{-1}h_{9/2})$ component was increased from Vergados's 0.779 value to 0.90 with the corresponding decrease in the neutron amplitude the shape of the angular distribution was very similar to that with Vergados's wave function with an increase of about 40% in magnitude at the forward angles.

The dotted line is another distorted-wave calculation for a 2^+ state with the pure $(h_{11/2}{}^{-1}h_{9/2})$ proton configuration. The angular distribution for the 2^+ state has the maximum at around 12° and decreases at very forward angles. This feature did not change even when a more realistic wave function for the 2^+ state[20] was used. Thus the distorted-wave analysis is consistent with the 1^+ assignment for the state.

The experimental spectroscopic factor S^2 of the $\pi(h_{11/2}{}^{-1}h_{9/2})$ component for the 5.845-MeV state was deduced from the ^{208}Pb$(d,{}^3$He$)^{207}$Tl and ^{209}Bi$(d,{}^3$He$)^{208}$Pb reaction results. We define the spectroscopic factor S^2 as

$$\sigma_{\rm expt}(5.845\text{-MeV } 1^+ \text{ state}) = (3S^2/120)\sigma_{\rm expt}(h_{11/2}{}^{-1}),$$

where $\sigma_{\rm expt}(5.845\text{-MeV } 1^+ \text{ state})$ is the reaction yield of the 5.845-MeV state in the reaction ^{209}Bi$(d,{}^3$He$)^{208}$Pb, and $\sigma_{\rm expt}(h_{11/2}{}^{-1})$ is the reaction yield of the 1.34-MeV $11/2^-$ state in ^{207}Tl from the reaction ^{208}Pb$(d,{}^3$He$)^{207}$Tl. The number 120 in the equation comes from $\sum_{J=1}^{10} 2J+1$ for the $\pi(h_{11/2}{}^{-1}h_{9/2})_J$ configuration. The number 3 is due to the assigned spin value of 1 for the 5.845-MeV state. The S^2 value extracted from our experiments was found to be $S^2 = 1.0 \pm 0.1$. The literal meaning of $S^2 = 1$ is that this state is a pure $(h_{11/2}{}^{-1}h_{9/2})$ proton state, if we assume a simple shell model and disregard minor kinematical differences between the reactions ^{209}Bi$(d,{}^3$He$)^{208}$Pb and ^{208}Pb$(d,{}^3$He$)^{207}$Tl. As we mentioned earlier our $\delta_{\rm expt}(h_{11/2}{}^{-1})$ value is about 10%–15% lower than that obtained by Parkinson *et al.*[14] Adopting their experimental value for $\sigma_{\rm expt}(h_{11/2}{}^{-1})$ we estimated the lower limit for the S^2 value to be 0.75. This value of 0.75 is larger than the values obtained from shell-model calculations. Vergados's wave function for the isoscalar 1^+ state, which we used in the present analysis, gives $S^2 = 0.61$ for the $\pi(h_{11/2}^{-1}h_{9/2})$ component.

In the lowest part of Fig. 3, the proton angular distributions for the 4.841-MeV state are shown. This state was recently suggested to be 1^+ from a nuclear resonance fluorescence experiment.[17] However, no $(h_{11/2}^{-1}h_{9/2})$ component was found for this state in the $(d, {}^3\mathrm{He})$ experiment, and the proton angular distribution shape was clearly different from that for the 5.845-MeV state. Instead, we obtained an excellent fit for this state with an $L=1$ form factor which was recently derived by Harakeh and Dieperink for isoscalar dipole resonance,[21] which is shown in the figure as a solid line. We suggest that J^π of this 4.841-MeV state is 1^-.

Recently Wienhard *et al.*[22] found an isoscalar 1^+ state at 5.84 MeV of excitation with $B(M1) = 0.5\mu_N^2$ by a nuclear resonance fluorescence experiment. Another work on the 5.841-MeV 1^+ state with the reactions $^{208}\mathrm{Pb}(p,p')$ and (d,d') was recently reported to be in progress.[23]

In summary we suggest that the 5.845-MeV state in $^{208}\mathrm{Pb}$ is a 1^+ state which exhausts more than 75% of the $\pi(h_{11/2}^{-1}h_{9/2})$ strength. And we also suggest that the J^π of the 4.841-MeV state is 1^- contrary to the recent suggestion[17] of 1^+.

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[1]R. J. Holt, H. E. Jackson, R. M. Laszewski, and J. R. Specht, Phys. Rev. C 20, 93 (1979).

[2]J. D. Horen, J. A. Harvey, and N. W. Hill, Phys. Rev. Lett. 38, 1344 (1977).

[3]G. F. Bertsch, Nucl. Phys. A354, 157c (1981).

[4]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. II, p. 638.

[5]J. D. Vergados, Phys. Lett. 36B, 12 (1971).

[6]See the Proceedings of the International Conference on Spin Excitations in Nuclei, Telluride, Colorado, March 1982 (to be published).

[7]N. Anantaraman, G. M. Crawley, A. Galonsky, C. Djalali, N. Marty, M. Morlet, A. Willis, and J.-C. Jourdain, Phys. Rev. Lett. 46, 1318 (1981).

[8]Y. Fujita, M. Fujiwara, S. Morinobu, T. Yamazaki, T. Itahashi, S. Imanishi, H. Ikegami, and S. I. Hayakawa, Phys. Rev. C 25, 678 (1982).

[9]E. A. McClatchie, C. Glasshausser, and D. L. Hendrie, Phys. Rev. C 1, 1828 (1970).

[10]W. T. Wagner, G. M. Crawley, G. R. Hammerstein, and H. McManus, Phys. Rev. C 12, 757 (1975).

[11]F. Petrovich and W. G. Love, Nucl. Phys. A354, 499c (1981).

[12]H. Ikegami, S. Morinobu, I. Katayama, M. Fujiwara, and S. Yamabe, Nucl. Instrum. Methods 175, 335 (1981).

[13]Y. Fujita, K. Nagayama, S. Morinobu, M. Fujiwara, I. Katayama, T. Yamazaki, and H. Ikegami, Nucl. Instrum. Methods 173, 265 (1980).

[14]W. C. Parkinson, D. L. Hendrie, H. H. Duhm, J. Mahoney, J. Saundinos, and G. R. Satchler, Phys. Rev. 178, 1976 (1969).

[15]J. Lichtenstadt, C. N. Papanicolas, C. P. Sargent, J. Heisenberg, and J. S. McCarthy, Phys. Rev. Lett. 44, 858 (1980).

[16]G. S. Adams, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, W. G. Love, and F. Petrovich, Phys. Lett. 91B, 23 (1980).

[17]W. Biesiot and Ph. B. Smith, Phys. Rev. C 24, 808 (1981).

[18]G. Bertsch, J. Borysowicz, H. McManus, and W. G. Love, Nucl. Phys. A284, 399 (1977).

[19]J. Raynal and R. Schaeffer, unpublished.

[20]T. Suzuki, K. Shimizu, and A. Arima, private communication.

[21]M. N. Harakeh and A. E. L. Dieperink, Phys. Rev. C 23, 2329 (1981).

[22]K. Wienhard *et al.*, to be published.

[23]G. P. A. Berg, in Ref. 6.