PHYSICAL REVIEW C VOLUME 40, NUMBER 5 NOVEMBER 1989

# $7^+$ states in $^{26}$Al observed in the $^{24}$Mg($\alpha,d$) and $^{25}$Mg($^3$He,$d$) reactions

M. Yasue,* H. Sato, M. H. Tanaka, T. Hasegawa,† T. Tanabe, and K. Nisimura‡
*Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan*

H. Ohnuma, H. Shimizu,§ K. Ieki,** and H. Toyokawa
*Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152, Japan*

K. Ogawa
*Laboratory of Physics, Kanto Gakuin University, Kanazawa-ku, Yokohama 236, Japan*

S. I. Hayakawa
*Asikaga Institute of Technology, Asikaga 326, Japan*

R. J. Peterson
*Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309*
(Received 22 June 1989)

The $7^+$ states in $^{26}$Al were studied by the $^{24}$Mg($\alpha,d$)$^{26}$Al reaction at $E_\alpha=63.7$ MeV and by the $^{25}$Mg($^3$He,$d$)$^{26}$Al reaction at $E_h=55.2$ MeV. Five $7^+$ states were newly identified, in addition to the known 8.14-MeV $7^+$ state, from the ($\alpha,d$) angular distributions. Comparisons of the ($\alpha,d$) and ($^3$He,$d$) cross sections showed that the 11.81-MeV state was excited through the $(d_{5/2}g_{9/2})$ component and the other $7^+$ states through the $(f_{7/2})^2$ component.

High-spin states are usually considered to be of fairly pure configuration, and often used as a test ground for various reaction and structure theories. Unnatural-parity stretched states like $6^-$ states in *sd*-shell nuclei are of particular interest because of the possible roles of the nucleon degrees of freedom in nuclei. Unfortunately, $6^-$ states in some *sd*-shell nuclei, at least, have been found not as pure as was considered in a simple-minded way. They have rather complicated configurations, and the $6^-$ strength is distributed among many states.

Recently the spreading of the $(d_{5/2}^{-1}f_{7/2})_{6^-}$ particle-hole strength in $^{26}$Al and $^{26}$Mg has been studied through one-nucleon[1–3] and two-nucleon[4] transfer reactions. A difference was observed between the spreading of the $6^-$ strength in $^{26}$Al observed in the ($^3$He,$d$) reaction and that in the ($\alpha,d$) reaction. In the ($^3$He,$d$) reaction the lowest $T=0$ and $T=1$ states are most strongly excited, and the strength decreases with the excitation energy. It has been found that only about 20% of the sum-rule limit for the $0f_{7/2}$ single-particle strength concentrate in the lowest $6^-$ state and small fractions of the remaining strengths spread over high-lying $6^-$ levels. Such a strength distribution was well accounted for by a deformed nucleus model.[1,3,5–7] In the ($\alpha,d$) reaction, on the other hand, the lowest $6^-$ state carries ten times more strength than the others, the rest of the ($\alpha,d$) strength being distributed[4] among the high-lying states nearly equally.

Another possible source of information on the spreading of the $f_{7/2}$ strength is $7^+$ states. So far only one $7^+$ state is known in $^{26}$Al at 8.14 MeV. This state was seen excited through the $(0f_{7/2})^2$ configuration in the $^{24}$Mg($\alpha,d$)$^{26}$Al reaction.[8,9] This high spin would be a signature of the $f_{7/2}$ shell, and the population of the $7^+$ states would reflect the fragmentation of the $f_{7/2}$ strength, provided that no $(d_{5/2}g_{9/2})_{7^+}$ states were present to confuse the spectroscopy. However, a density-dependent Hartree-Fock (DDHF) type variational calculation[10] shows that the *p-n* averaged binding energy for the $(d_{5/2}g_{9/2})$ configuration is only 5 MeV above that for the $(f_{7/2})^2$ configuration. Therefore the spreading of the $7^+$ strength may be an indication of these two configurations lying close in excitation energy. In addition, several $7^+$ states with higher seniorities are expected within the *sd*-shell model space.

The configuration of the $7^+$ states may be sorted out by comparing their ($\alpha,d$) and ($^3$He,$d$) cross sections. The $(d_{5/2}g_{9/2})_{7^+}$ component is expected to be observed in both the $^{25}$Mg($^3$He,$d$)$^{26}$Al and the $^{24}$Mg($\alpha,d$)$^{26}$Al reactions, while the $(f_{7/2})^2_{7^+}$ component can be seen only in the latter reaction. The $7^+$ states within the *sd*-shell cannot be excited in direct one- and two-nucleon transfer reactions.

Our interest in the present work is to search for the $7^+$ states in $^{26}$Al via the ($\alpha,d$) and ($^3$He,$d$) reactions and assign their configurations. First we identify states that have ($\alpha,d$) angular distribution shapes described only by a calculation with transferred $(NLJ)=(067)$. If a $7^+$ state thus identified is not observed in the ($^3$He,$d$) reaction, its configuration must contain $(f_{7/2})^2$ but not $(d_{5/2}g_{9/2})$. If it is observed also in the ($^3$He,$d$) reaction, and its angular distribution is that of the $0g_{9/2}$ transfer,

 

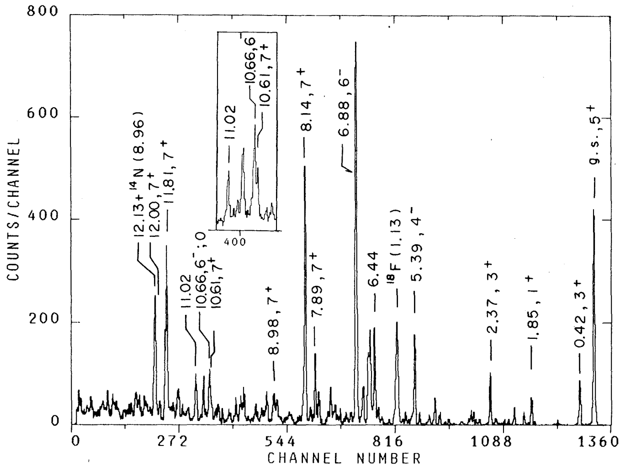


FIG. 1. Typical momentum spectrum for the $^{24}Mg(\alpha,d)^{26}Al$ reaction at $E_\alpha = 63.7$ MeV and at $\theta_{lab} = 12.5°$. The inset is an expanded partial spectrum at $\theta_{lab} = 5°$.

then it contains the $(d_{5/2}g_{9/2})$ configuration. Obtained $7^+$ strength distribution will then be compared with that of the $6^-$ states.

The $^{24}Mg(\alpha,d)^{26}Al$ and $^{25}Mg(^3He,d)^{26}Al$ experiments were carried out at $E_\alpha = 63.7$ MeV and $E_h = 55.2$ MeV using beams from the sector focusing cyclotron at the Institute for Nuclear Study, University of Tokyo, and a magnetic spectrometer.[11,12] Details of the experimental procedure are described elsewhere.[1,4]

Figure 1 shows a typical momentum spectrum for the $(\alpha,d)$ reaction at $\theta_{lab} = 12.5°$, where the energy resolution (FWHM) was 40 keV. Among eighty levels observed in the region of excitation energy from 0 to 14 MeV, only six have angular distribution shapes characteristic of the transferred $(NLJ) = (067)$. Here $N$, $L$, and $J$ are the principal quantum number, the orbital angular momentum quantum number, and the total angular momentum quantum number of a pair of transferred nucleons. These six angular distributions are shown in Fig. 2, where error bars indicate only relative errors. Errors in the absolute values are about 10%.

The curves in the figure represent zero-range DWBA calculations with an assumption of a deuteron cluster transfer[13] using the program TWOSTP.[14] Parameters used in the DWBA calculations are the same as those in Refs. 1 and 4. The experimental $(\alpha,d)$ cross section is related to the DWBA calculation through an enhancement factor ε by

$$\sigma_{exp} = D_0^2 s C^2 \varepsilon \sigma_{cal} .$$

Here, $C^2 = 1$ is the isospin factor for the $^{24}Mg(\alpha,d)^{26}Al$ reaction, $s$ is the light particle spectroscopic factor and equal to 3 for the $(\alpha,d)$ reaction, $D_0^2$ is a zero-range normalization constant, whose value is set to $20\times10^4$ $MeV^2\,fm^3$ according to Ref. 15, and $\sigma_{cal}$ is the cross section calculated by TWOSTP. Details of the DWBA analysis are given in our previous work.[4,16]

Two curves for the 11.806-MeV state, shown in Fig. 2, demonstrate the difference between the calculated $L = 5$ and 6 cross sections. The experimental angular distribution for the 11.806-MeV state is well reproduced by the $L = 6$ curve and clearly different from the $L = 5$ curve. Typical results calculated with the same $L$ and different $J$ are shown by three curves for the 7.89-MeV state. For a transfer of $L = 6$, the calculated $J = 7$ curve has a shape somewhat different from the $J = 6$ and 5 curves at small angles.

Angular distributions for the states shown in Fig. 2 have shapes well reproduced only by $(NLJ) = (067)$, indicating the $J^\pi$ values of these states are $7^+$. Excitation energies of these states are listed in Table I. Since their angular distributions are well fitted by the simple DWBA calculation, complicated processes such as core excitation are negligible in the $(\alpha,d)$ transition to these states. The 8.14-MeV state was previously assigned at $7^+$ by other authors[8,9] from the $^{24}Mg(\alpha,d)^{26}Al$ reaction. The other states in Table I are newly proposed in the present work. The enhancement factors for these states are also listed in Table I.

Among the six states shown in Fig. 2, only the 11.806-MeV state was observed in the $(^3He,d)$ reaction. The

TABLE I. Spectroscopic strengths for the $7^+$ states in $^{26}Al$ observed via $(\alpha,d)$ and $(^3He,d)$ reactions. Spectroscopic information on the 6.88-MeV $6^-$ state cited from Ref. 1 is shown for comparison. Integrated $(\alpha,d)$ cross sections $\sigma_\int$ are also given. Abbreviated notations for the two-nucleon configurations are used: For instance, $f7f7$ means $(f_{7/2})^2$.

| $E_x$ (MeV) | $J^\pi$ | Conf. | $NLJ$ | $\sigma_\int$ in $(\alpha,d)$ (mb) | Enhancement Factor in $(\alpha,d)$ | Spectroscopic Factor in $(^3He,d)$ |
|---|---|---|---|---|---|---|
| 6.88 | $6^-$ | $d5f7$ | 056 | 1.67 | 0.33 | 0.13 |
| 7.89 | $7^+$ | $f7f7$ | 067 | 0.31 | 0.05 | |
| 8.14 | $7^+$ | $f7f7$ | 067 | 1.10 | 0.17 | |
| 8.98 | $7^+$ | $f7f7$ | 067 | 0.12 | 0.02 | |
| 10.61 | $7^+$ | $f7f7$ | 067 | 0.09 | 0.01 | |
| 11.81 | $7^+$ | $d5g9$ | 067 | 0.70 | 0.11 | 0.047 |
| 12.00 | $7^+$ | $f7f7$ | 067 | 0.11 | 0.03 | |

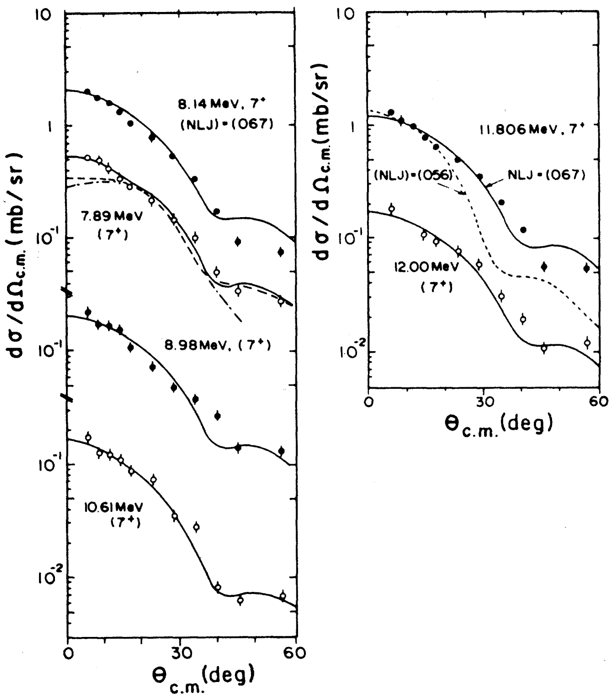


FIG. 2. Angular distributions for the $7^+$ states observed in the $^{24}$Mg($\alpha$,$d$)$^{26}$Al reaction at $E_\alpha$=63.7 MeV. The solid, dashed, dot-dashed, and dotted curves are DWBA calculations with ($NLJ$)=(067), (066), (065), and (056), respectively.

($^3$He,$d$) angular distribution for this state can be described by a $0g_{9/2}$ transfer as shown in Fig. 3. The curves in Fig. 3 are DWBA results calculated with the program DWUCK4,[17] using a resonance form factor. Therefore, this state must contain at least some of the $(d_{5/2}g_{9/2})$ component. The other $7^+$ states are considered to be excited only through the $(f_{7/2})^2$ configuration in the ($\alpha$,$d$) reaction.

Microscopic DWBA calculations for the ($\alpha$,$d$) reaction were made to further investigate the configuration of the 11.806-MeV state. Since no reliable and established method exists to obtain absolute DWBA cross sections for two-nucleon transfer reactions, we used the strongest $6^-$ state to scale the DWBA cross sections for the ($\alpha$,$d$) reaction. Namely, first we calculated the ($\alpha$,$d$) cross section to the 6.88-MeV $6^-$, $T=0$ state taking the pure $(d_{5/2}f_{7/2})$ configuration, and then multiplied the result by 0.13, which is the $f_{7/2}$ spectroscopic factor obtained in the ($^3$He,$d$) study.[1] Then we normalized the absolute scale of the ($\alpha$,$d$) cross section thus obtained to the data for the 6.88-MeV state. Using this scaling and the ($\alpha$,$d$) cross section calculated for the 11.806-MeV state with pure $(d_{5/2}g_{9/2})$ configuration, we expect that the $g_{9/2}$ spectroscopic factor of 0.047 for the 11.806-MeV state (see Table I) should give an ($\alpha$,$d$) cross section of about 1.2 mb/sr at forward angles. This is in excellent agreement with the measured value. Therefore we conclude that the 11.086-MeV state was excited mostly through the $(d_{5/2}g_{9/2})$ component of the wave function both in the ($\alpha$,$d$) and ($^3$He,$d$) reactions.

The $(f_{7/2})^2_{7^+}$ strength distribution is somewhat different from the $6^-$ strength distribution, although summed ($\alpha$,$d$) strength of 0.3 for the states with the $(f_{7/2})^2_{7^+}$ configuration is comparable to the $6^-$ strength with the $(d^{-1}_{5/2}f_{7/2})_{6^-}$ configuration. The total spreading width of the ($\alpha$,$d$) strength distribution for the $(f_{7/2})^2_{7^+}$ configuration is 4 MeV, which cannot be ascribed to the mixing of the $(f_{7/2})^2$ and $(d_{5/2}g_{9/2})$ configurations as the ($^3$He,$d$) reaction did not sense such mixing. However, the width is close to the calculated value of 4.6 MeV for the binding-energy difference between the $0f_{7/2}$ and $1f_{7/2}$ protons. On the other hand, the binding-energy difference of 8.1 MeV is predicted between the $0f_{7/2}$ and $1f_{7/2}$ neutrons. Therefore, if the spreading of the $7^+$ strength is due to the $1f_{7/2}$ mixture, the $1f_{7/2}$ proton is more likely to be mixed in the predominant $(0f_{7/2})^2$ configuration. If this is the case, these states may not be good eigenstates of isospin. The $(0f_{7/2}\text{-}1f_{7/2})^2$ configuration can generate only three $7^+$ states with $T=0$, while five $(f_{7/2})^2_{7^+}$ states are observed in the present experiment. Either some of the high-lying states have isospin mixture, or the observed fragmentation is due to the coupling with the excited core.

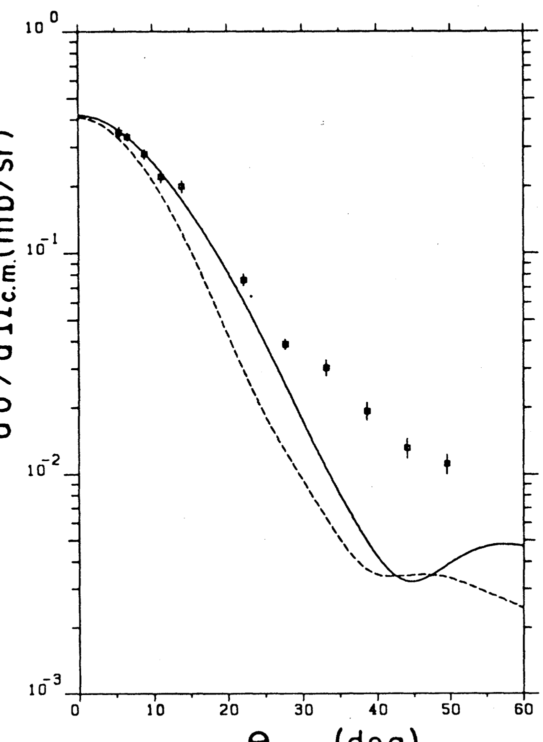


FIG. 3. Angular distribution for the 11.81-MeV $7^+$ state observed in the $^{25}$Mg($^3$He,$d$)$^{26}$Al reaction at $E_h$=55.2 MeV. The solid and dashed curves are the DWBA results for the $0g_{9/2}$ and $0f_{7/2}$ transfers, respectively, calculated with resonance form factors.

Several $7^+$ states are expected within the $sd$ shell. They have high seniorities and cannot be excited in direct one-step transfer reactions. However, they can carry a small fraction of the $(f_{7/2})^2$ or $(d_{5/2}g_{9/2})$ component through higher-order configuration mixing. A full $sd$-shell shell calculation using the Wildenthal interaction[18] predicts the lowest $7^+$ state at $E_x = 3.746$ MeV, close to the known $7^+(5^+)$ state at 3.922 MeV. The experimental $(\alpha,d)$ cross section for this state is of the order of 0.01 mb/sr, and its angular distribution is rather flat. Therefore this state is not excited in a direct process, and considered to have pure $(sd)^{10}$ configurations. The calculation predicts additional $7^+$ states at $E_x = 6.246$, 7.714, 8.857, 9.282, and 9.357 MeV. These energies are remarkably close to the energies of the $7^+$ states identified in the present work. It is very likely that these states carry fractions of the $(f_{7/2})^2$ or $(d_{5/2}g_{9/2})$ component and are observed in the $(\alpha,d)$ and $(^3\mathrm{He},d)$ reactions. No negative-parity states can be constructed within the $(sd)^{10}$ configuration to mix with the $(d_{5/2}f_{7/2})_{6^-}$ states.

We have not seen much $(d_{5/2}g_{9/2})_{7^+}$ strength below 14 MeV. The only state observed with the $(d_{5/2}g_{9/2})_{7^+}$ strength is the 11.81-MeV state. The enhancement factor for this state is 0.1. This state carries only a small fraction of the $g_{9/2}$ single-particle strength, and is located 3.7 MeV above the 8.14-MeV $7^+$ state, which has the largest $(\alpha,d)$ strength of the $(f_{7/2})^2$ configuration. This energy difference is consistent with the average separation of 5 MeV between the $(f_{7/2})^2$ and the $(d_{5/2}g_{9/2})$ configuration predicted by the DDHF calculation, considering that the 11.81-MeV state has only a small fraction of the $(d_{5/2}g_{9/2})$ strength.

In conclusion, five $7^+$ states in $^{26}$Al have been found in addition to the known $7^+$ state at 8.14 MeV. From a comparison of the $^{24}\mathrm{Mg}(\alpha,d)^{26}\mathrm{Al}$ and $^{25}\mathrm{Mg}(^3\mathrm{He},d)^{26}\mathrm{Al}$ cross sections, we have identified five of them that contain the $(f_{7/2})^2$ configuration and one state that contains the $(d_{5/2}g_{9/2})$ configuration. There seems to be no significant mixture of these two configurations. The energy separation between the $7^+$ states with these two configurations is in qualitative agreement with the DDHF calculation. The $(f_{7/2})^2_{7^+}$ strength distribution is different from that of the $(d^{-1}_{5/2}f_{7/2})_{6^-}$ observed in the $(\alpha,d)$ reaction. One of the possible origins of the spreading of the $(f_{7/2})^2_{7^+}$ states is the coupling between the unbound proton in the $0f_{7/2}$ and $1f_{7/2}$ shells. However, a good agreement between the energies of the observed $7^+$ states and those calculated in the full $sd$-shell model space suggests that these $7^+$ states are basically of the $(sd)^{10}$ nature mixed with a small fraction of the $(f_{7/2})^2$ or the $(d^{-1}_{5/2}g_{9/2})$ components into which two particles are transferred.

We are grateful to Professor T. Suzuki for critical reading of this manuscript. Numerical calculations were carried out with the central computers at the Institute for Nuclear Study (INS) and at Kanto Gakuin University.

---

*Present address: Research Center of Nuclear Physics, Osaka University, Ibaraki, Osaka, Japan.

†Present address: Faculty of Engineering, Miyazaki University, Miyazaki, Japan.

‡Present address: Miyagi University of Education, Sendai, Japan.

§Present address: Faculty of Liberal Arts, Yamagata University, Yamagata, Japan.

**Present address: Department of Physics, Rikkyo University, Toshima, Tokyo, Japan.

[1]R. J. Peterson *et al.*, Phys. Rev. C **38**, 1130 (1988).

[2]J. J. Kraushaar, M. Fujiwara, K. Hosono, M. Ito, M. Kondo, H. Sakai, M. Tosaki, M. Yasue, S. I. Hayakawa, and R. J. Peterson, Phys. Rev. C **34**, 1530 (1986).

[3]R. J. Peterson, B. L. Clausen, J. J. Kraushaar, H. Nann, W. W. Jacobs, R. A. Lindgren, and M. A. Plum, Phys. Rev. C **33**, 31 (1986).

[4]M. Yasue, H. Sato, M. H. Tanaka, T. Hasegawa, T. Tanabe, K. Nisimura, H. Ohnuma, H. Shimizu, K. Ieki, H. Toyokawa, S. I. Hayakawa, and R. J. Peterson (submitted to Phys. Rev. C).

[5]R. J. Peterson *et al.*, Phys. Rev. C **38**, 2026 (1988).

[6]K. I. Pearce *et al.*, Nucl. Phys. **A467**, 215 (1987).

[7]C. Lebo, B. D. Anderson, T. Chittrakarn, A. R. Baldwin, R. Madey, J. W. Watson, and C. C. Foster, Phys. Rev. C **38**, 1099 (1988).

[8]Y. Kadota, K. Ogino, K. Obori, Y. Taniguchi, T. Tanabe, M. Yasue, and J. Schimizu, Nucl. Phys. **A458**, 523 (1986).

[9]E. Rivet, R. H. Pehl, J. Cerny, and B. G. Harvey, Phys. Rev. **141**, 1021 (1966); K. Dong-Kyok, Jpn. J. Phys. **21**, 2445 (1966).

[10]K. Yazaki, Nucl. Phys. **A277**, 189 (1977); H. Sato and Y. Okuhara, Phys. Rev. C **34**, 2171 (1986).

[11]S. Kato, M. H. Tanaka, and T. Hasegawa, Nucl. Instrum. **154**, 19 (1978).

[12]M. H. Tanaka, S. Kubono, and S. Kato, Nucl. Instrum. **195**, 509 (1982).

[13]R. J. deMeijer, L. W. Put, J. J. Akkerman, J. C. Vermeulen, and C. R. Bingham, Nucl. Phys. **A386**, 200 (1982).

[14]M. Igarashi (unpublished).

[15]J. D. Cossair, W. S. Burns, and R. A. Kenefick, Nucl. Phys. **A287**, 13 (1977).

[16]M. Yasue, J. J. Hamill, H. C. Bhang, M. A. Rumore, and R. J. Peterson, Phys. Rev. C **30**, 770 (1984).

[17]P. D. Kunz (unpublished).

[18]B. H. Wildenthal, Prog. Part. Nucl. Phys. **11**, 5 (1984).