PHYSICAL REVIEW C VOLUME 33, NUMBER 4 APRIL 1986

$g_{9/2}$ single particle state in ^{28}Si

S. Kubono, K. Morita,* M. H. Tanaka, A. Sakaguchi,† and M. Sugitani
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo, 188 Japan

S. Kato
Yamagata University, Yamagata, 990 Japan

(Received 30 April 1985)

A direct evidence of $2\hbar$-high single particle component has been obtained for the first time in *sd*-shell nuclei from measurement of α_0 and p_0 decay from the 12.80-MeV state in ^{28}Si populated through the ^{12}C(^{20}Ne,α)^{28}Si reaction. This state is assigned $J^\pi = 6^+$ and has a $g_{9/2}$ single particle component of 20–30% in a nearly stretched proton configuration of $(g_{9/2}d_{5/2}^{-1})$.

It is of great importance to study single particle distributions of higher shell orbits more than 1 $\hbar$ in the high excitation energy region, e.g., the discussion on 1p-1h stretched states and also higher multipolarity giant resonances. In *sd*-shell nuclei there has yet been no clear evidence of a $g_{9/2}$ component which is 2 $\hbar$ higher than the *sd* shell, although there were extensive works[1,2] on $f_{7/2}$ component of 1 $\hbar$. Although single particle states can be studied through one-nucleon stripping reactions like the (α,t) reaction,[2] they are not free from multistep process contributions and further, the transferred angular momentum dependence is very small in the angular distributions. Thus, it is crucial for this kind of study to determine directly the single particle strength, as well as the multipolarity, experimentally. Measurement of the decay particles in coincidence provides unique determination of such quantities.

There are several works[2–4] reported which suggest a nonzero $g_{9/2}$ component in *sd*-shell nuclei. Theoretically, the centroid energy of $g_{9/2}$-shell single particle states is predicted to be higher than the $f_{7/2}$ centroid by 10–15 MeV.[5,6] The *g*-shell component of about 7% was suggested to distribute in the excitation energy region lower than 20 MeV from the fitting of the (α,t) angular distributions.[2] However, the suggestion is not conclusive at all, as mentioned above.

We have studied the *g*-shell component in the excitation energy region of 10–17 MeV in ^{28}Si by observing the decay particles from the highly excited states in ^{28}Si populated through the ^{12}C(^{20}Ne,α)^{28}Si reaction at 52 MeV. This angular correlation technique[7–9] is free from the effect of multistep processes. Further, the (^{20}Ne,α) reaction preferentially brings in a large angular momentum into the system, and thus this reaction is very useful to excite high spin states.[7–9]

We report in this paper the first direct observation of a *g*-shell component of a significant fraction of nearly stretched $(g_{9/2}d_{5/2}^{-1})_{6^+}$ configuration in *sd*-shell nuclei. Other spin-parity assignments will be found elsewhere.[10]

A 51.93-MeV ^{20}Ne^{4+} beam was obtained from the sector-focusing cyclotron of the Institute for Nuclear Study, University of Tokyo. Self-supporting natural carbon foils of 20–30 μg/cm^2 were used for the target in the correlation measurement. Singles α spectra from the ^{12}C(^{20}Ne,α)^{28}Si reaction were obtained at 0° by using a quadruple-quadruple-dipole magnetic spectrograph[11] and a position-sensitive gas proportional counter.[12] The solid angle was set to 7.6 msr. A thin plastic scintillator, which was placed just behind the proportional counter, was used for the fast timing for the coincidence measurement. Angular correlation functions were measured for several states of ^{28}Si excited strongly through the ^{12}C(^{20}Ne,α_1)^{28}Si reaction, where the decay particles α and p from the ^{28}Si states were measured by a position-sensitive solid state detector in the scattering chamber in coincidence with α_1. The particle identification of the decay particles was made in two ways; kinematics (energy versus angle), and energy loss of the particles, which was produced in a thin aluminum foil put on half of the detector at forward angles. This foil also prevents enormous elastic scattering events. Using a thin carbon target of 9 μg/cm^2, a measurement of level widths and the excitation energies of the ^{28}Si states was tried by separately determining the contributions of the beam energy spread, the resolution of the spectrograph, the resolution of the focal plane counter, and the energy loss in the target. All levels observed were found to have level widths smaller than 39 keV. The error in the excitation energies obtained is less than 30 keV. Other experimental setups are described elsewhere.[7,8]

Figure 1(a) shows an α-singles spectrum from the ^{12}C(^{20}Ne,α)^{28}Si reaction measured at 0° with the spectrograph. There are several sharp peaks of ^{28}Si excited in the reaction. Most peaks in the spectrum are found to decay both with α and p emissions. This conclusion is also supported by the fact that the kinetic energies of the decay particles are consistent within 50 keV, with an assumption that a single state decays with p and α emissions. The decay yields of α_0 and p_0 leading to the ground states of ^{24}Mg and ^{27}Al, respectively, are displayed in Fig. 1(b), which were obtained by extrapolating the experimental correlation functions using the best fit curve of Legendre functions to the whole solid angles.

Among the peaks seen[10] in Fig. 1 we discuss here specifically the state at 12.80 MeV, since clear evidence of $g_{9/2}$ single particle component is obtained for the first time. In this excitation energy region, there are some works[13] reported on the ^{27}Al(p,p) scattering. The nearest state of a significant proton width is the 12.741-MeV 3^- state ($E_p = 1.2008$ MeV in ^{27}Al+p scattering). In the high resolution spectrum, this 3^- state was expected on the tail of the 12.80-MeV state peak, but there was no peak seen at the energy.

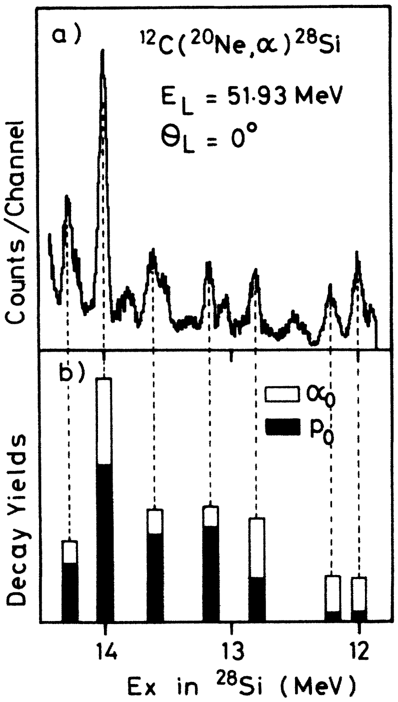

FIG. 1. (a) A singles α spectrum from the $^{12}C(^{20}Ne,\alpha)^{28}Si$ reaction obtained at 0° with 51.93 MeV, and (b) the coincident decay yields of alphas and protons to the ground states of ^{24}Mg and ^{27}Al, respectively.

The upper limit of the yield is less than 10% of the 12.80-MeV state peak. Since a peak of 10% cannot produce such a large p_0 decay yield as shown in Fig. 1(b), the main contribution of the proton decay is not from the 3^- state. The decay yields were also compared for the lower half and the upper half of the $(^{20}Ne,\alpha)$ peak at 12.80 MeV, resulting in almost identical correlation functions. Thus, there is little chance of a doublet.

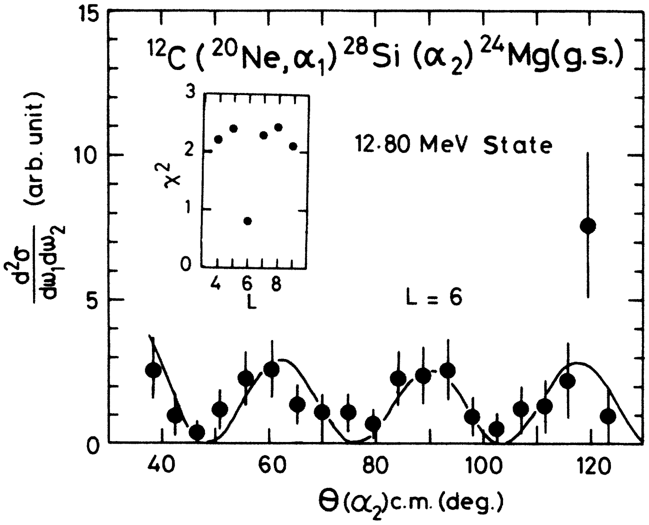

FIG. 2. An α-α angular correlation function obtained for the 12.80-MeV state. The solid line is the best fit curve with $|P_{L=6}(\cos\theta)|^2$. The inset is the χ^2/N values obtained in fitting for each L.

The branching ratios obtained for the 12.80-MeV state are $\Gamma_{p_0}/\Gamma=0.42$ and $\Gamma_{\alpha_0}/\Gamma=0.58$, where $\Gamma=\Gamma_{\alpha_0}+\Gamma_{p_0}$ was assumed since there was no particle decay observed to excited states and the sum of the decay yields of p_0 and α_0 estimated for all the solid angles is roughly equal to the peak yield at 12.80 MeV in the singles spectrum.

Figure 2 shows the experimental angular correlation function for the 12.80-MeV state together with the best fit curve of a single $|P_L(\cos\theta)|^2$, which gives a unique spin assignment of $J=L$ in the present geometry.[7-9] The inset in the figure is the χ^2/N values obtained in fitting the data. The data are unambiguously fitted with $L=6$ with the minimum χ^2 value. The correlation function for the proton emission does not have a clear pattern due to a mixing of different m components. Since only natural parity is allowed in the present experimental geometry,[7-9] 6^+ is assigned to this state. This state is found to decay simultaneously with a proton emission to the $\frac{5}{2}^+$ ground state of ^{27}Al. Thus, the proton decays with the angular momentum $L=4$, since the angular momenta larger than 4 are not allowed due to the very small penetrability. This fact indicates that the 12.80-MeV state has a proton single particle component of g shell, most probably in a configuration of $(g_{9/2}d_{5/2}^{-1})_{T=0,J=6^+}$ since the main component of the ground state in ^{27}Al is $d_{5/2}^{-1}$. This is the highest spin of the configuration observable in the present experimental setup as mentioned above.

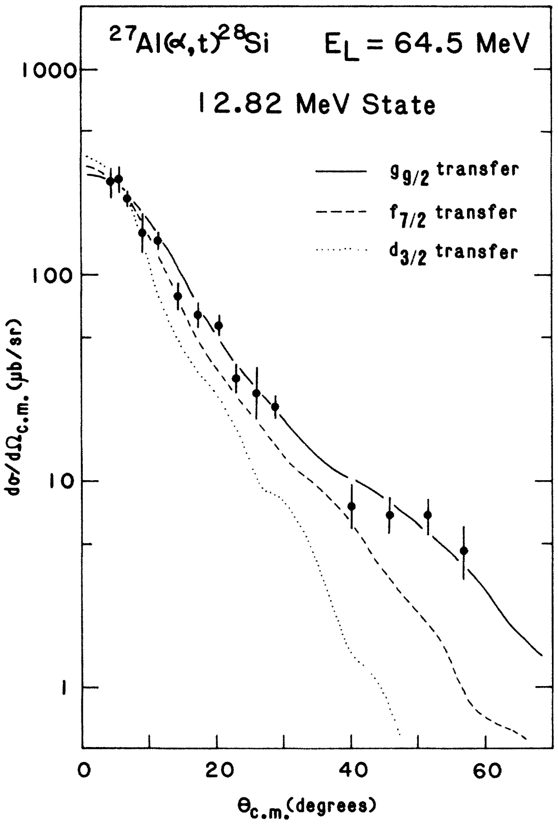

FIG. 3. Angular distribution of tritons from the $^{27}Al(\alpha,t)^{28}Si$ reaction leading to the 12.82-MeV state at 64.5 MeV. The data are taken from Ref. 2. The solid line is the DWBA result assuming a $g_{9/2}$ proton transfer, the dashed line is for a $f_{7/2}$ transfer, and the dotted line is for a $d_{3/2}$ transfer.

By correcting the branching ratio for the penetrability and the Wigner limit and assuming those mentioned above for the total width, the spectroscopic factor of $g_{9/2}$ may be roughly estimated to be $S = 0.3$, 30% of the single particle limit, where a parentage of $g_{9/2}$ shell from the α-decay component is not included. In this estimate the channel radius, which brings in the largest ambiguity, was taken to be $R_C = 1.4 \times (24^{1/3} + 4^{1/3})$ for α and $1.4 \times (27^{1/3} + 1^{1/3})$ for p in the calculations of penetrability and the Wigner limit, $W = 3\hbar^2/2\mu_C R_C^2$. The S factor derived varies as much as 35% when the channel radius is changed by 10%, although the conclusion would not be altered. Note that the decay particles are free from any two-step process contributions as mentioned earlier.

There is no 6^+ state observed in the ^{27}Al(p,p) nor ^{24}Mg(α,α) scattering[13,14] in this energy region. There is also no peak observed at this energy in the ^{27}Al(d,n)^{28}Si reaction at 25 MeV.[15] This may be understood that the angular momenta brought in are too small in these scatterings. However, the present 12.80-MeV state could be the same state observed at 12.82 MeV in the ^{27}Al(α,t)^{28}Si reaction[2] at $E_{\text{lab}} = 65$ MeV. The present 6^+ state is clearly different in nature from the first 6^+ state known at 8.54 MeV, which is a member of the ground rotational band,[17] and thus the (α,t) angular distribution for the 6_1^+ state is strongly distorted by multistep process effects. However, the present 6^+ state has a considerable direct $g_{9/2}$ transfer component as shown from the decay data. Once one knows that the state decays directly to ^{27}Al (g.s.) by a proton emission with the angular momentum $L = 4$, it is worthwhile to deduce S factor from the (α,t) reaction using the distorted-wave Born approximation (DWBA) calculation, even though the angular distribution is not clearly L dependent. The angular distribution was fitted previously by DWBA calculations with $L = 1 + 3$ in Ref. 2. The angular distribution is better fitted by assuming a $g_{9/2}(L = 4)$ transfer on ^{27}Al in our reanalysis, as shown by the solid line in Fig. 3. The S factor derived here is $S(g_{9/2}) = 0.2$, where the same parameters and coupling scheme[16] were used for the calculation (as in Ref. 2) for simplicity. In the DWBA analysis, the transferred proton was assumed to be bound slightly in a spherical nucleus, as was assumed in Ref. 2. These assumptions produce an ambiguity less than 50% in the analysis.[2] However, these would not alter the present conclusion. This S factor derived is consistent with the result obtained above from the decay measurement, although the two S-factor values obtained here contain a large ambiguity.

The $f_{7/2}$ single particle states in ^{28}Si are known at 11.58 MeV ($T = 0$) and 14.36 MeV ($T = 1$)[1] with a $(f_{7/2}d_{5/2}^{-1})_{6^-}$ configuration. The single particle limit of $f_{7/2}$ is not exhausted by the two levels, and the other fractions are expected to locate above these states.[2] In the present experiment other fractions of $g_{9/2}$ would scatter similarly at an excitation energy region higher than 12.80 MeV. However, the important fact here is that a state of considerable single particle amplitude of $g_{9/2}$ exists as low as at 12.80 MeV, which is much lower than the theoretical predictions that the $g_{9/2}$ centroid locates 10–15 MeV (Refs. 5 and 6) above the $f_{7/2}$ centroid. This should be an interesting subject. One possibility is that the state has a very large deformation since the present 6^+ state just follows the $J(J+1)$ rule for the possible excited prolate band proposed previously.[17]

The authors are indebted to M. Yasue and M. Igarashi for fruitful discussions.

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[*] Present address: Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, 351 Japan.

[†] Present address: Kyoto University, Kyoto, 606 Japan.

[1] H. Orihara *et al.*, Phys. Rev. Lett. **48**, 469 (1982), and references therein.

[2] M. Yasue, T. Tanabe, S. Kubono, J. Kokame, M. Sugitani, Y. Kadota, Y. Taniguchi, and M. Igarashi, Nucl. Phys. **A391**, 377 (1982).

[3] T. Suzuki, A. Arima, and K. -I. Kubo, Nucl. Phys **A288**, 493 (1977).

[4] U. Abbondanno *et al.*, Nuovo Cimento **13A**, 321 (1973).

[5] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. I.

[6] K. W. Schmid, Phys. Rev. C **24**, 1283 (1981).

[7] S. Kubono *et al.*, Phys. Lett. **103B**, 320 (1981).

[8] S. Kubono *et al.*, in *Proceedings of the INS International Symposium on Dynamics of Nuclear Collective Motions, Mt. Fuji, July 6–10, 1982*, edited by K. Ogawa and K. Tanabe (Bando Printing Co., Osaka, 1982), p. 509.

[9] K. Morita, S. Kubono, M. H. Tanaka, H. Utsunomiya, M. Sugitani, S. Kato, J. Schimizu, T. Tachikawa, and N. Takahashi, Phys. Rev. Lett. **55**, 185 (1985).

[10] S. Kubono *et al.* (unpublished).

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

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

[13] R. O. Nelson *et al.*, Phys. Rev. C **29**, 1656 (1984).

[14] J. Cseh *et al.*, Nucl. Phys. **A385**, 43 (1982).

[15] H. Orihara (private communication).

[16] H. Ohnuma, J. Kasagi, F. Kakimoto, S. Kubono, and K. Koyama, J. Phys. Soc. Jpn. **48**, 1812 (1980).

[17] R. K. Sheline, S. Kubono, K. Morita, and M. H. Tanaka, Phys. Lett. **119B**, 263 (1982).