Possible Quasimolecular Bands in ^{32}S

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Below the $^{16}O+^{16}O$ threshold, positive- and negative-parity bands at $E_x = 11$–17 MeV in ^{32}S are identified, whose moments of inertia and α reduced widths indicate possible quasimolecular bands of $^{16}O+^{16}O$ and of some asymmetric configuration.

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Quasimolecular states are one of the more interesting subjects in nuclear physics, especially in the study of the evolution of the nuclear shape as a function of excitation energy. Quasimolecular states, which have a large overlap with the dinucleus molecular configuration, are known to exist well above the threshold energy in some light nuclei. It is, however, expected that quasimolecular states will exist near or even below the threshold of their configuration, and play an important role in shape evolution. But there have been few studies of this energy region.[1,2] Thus, it is interesting to search for a quasimolecular state and the rotational band built on it near and below the threshold.

The nucleus ^{32}S has received much attention from several theoretical approaches,[3–9] which all predict quasimolecular states of $^{16}O+^{16}O$ configuration in the excitation energy region of 10–20 MeV, and it is also expected to have a well developed rotational band. However, little experimental study has been made of the high-lying states at this excitation energy region in ^{32}S. Although the ground state of ^{32}S is known to have a slight prolate deformation,[10] there is no rotational band found below the $^{16}O+^{16}O$ threshold, 16.539 MeV. High-spin states are known only up to spin 5^- (Ref. 11) in this region in ^{32}S, despite recent studies with the reaction[11] $^{29}Si(\alpha,n\gamma)^{32}S$ and the reaction[12] $^{28}Si(^{16}O,^{12}C\gamma)^{32}S$. Therefore, it is interesting to study highly excited high-spin states of ^{32}S specifically by use of the ^{16}O particle-transfer reaction $^{16}O(^{20}Ne,\alpha)^{32}S$, where the ground state of ^{20}Ne is known to have a large parentage of $^{16}O+\alpha$ configuration.[13] This reaction would excite high-spin states since the reaction brings a large angular momentum into the system, and could excite $^{16}O+^{16}O$ quasimolecular or highly deformed isomeric states by the ^{16}O transfer reaction.

We report here a part of the experimental results on spin assignments ranging from 4^+ to 8^+ and α-decay widths for the states at 11–17 MeV in ^{32}S from a particle-particle correlation method,[14] and suggest possible quasimolecular band structures in ^{32}S. Other experimental results including spin assignments from 3^- to 10^+ will be found elsewhere.[15]

A 51.9-MeV $^{20}Ne^{4+}$ beam was obtained from the sector-focused cyclotron of the Institute for Nuclear Study, University of Tokyo. The target was WO_3 of about 10 $\mu g/cm^2$ on a Au foil of 300 $\mu g/cm^2$. Singles α spectra were obtained at 0° by use of a quadrupole–double-dipole magnetic spectrograph[16] and a position-sensitive gas proportional counter.[17] The solid angle was set to 7.6 msr at the center of the focal plane counter. Figure 1 shows a typical α spectrum from the reaction $^{16}O(^{20}Ne,\alpha)^{32}S$ obtained at 0°. Although the spectrum contains some sharp peaks from the reaction $^{12}C(^{20}Ne,\alpha)^{28}Si$, this contamination does not harm the present experiment since the kinetic energies of decay α particles from ^{28}Si are much smaller than those from ^{32}S. Angular correlation functions were obtained for several states of ^{32}S excited through the reaction

$$^{16}O(^{20}Ne,\alpha_1)^{32}S^*(\alpha_2)^{28}Si(g.s.).$$

Here, the first α particle (α_1) was detected by the spectrograph at 0° and the second one (α_2) by a position-sensitive solid-state detector which subtended

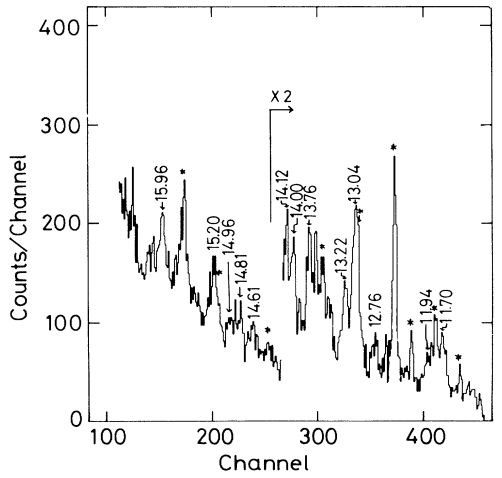

FIG. 1. A singles α spectrum from the reaction $^{16}O(^{20}Ne,\alpha)^{32}S^*$ obtained at 0° with $E_{lab}=51.88$ MeV. The peaks marked by asterisks are the states from the reaction $^{12}C(^{20}Ne,\alpha)^{28}Si^*$.

an angular range of about 40° in the laboratory system. A self-supporting Ta_2O_5 target of about 30 $\mu g/cm^2$, made by an anodical oxidation method,[18] was used for this measurement. A plastic scintillator placed behind the gas counter was used to obtain a fast timing signal for the coincidence measurement. The time resolution of the coincidence was typically 12 nsec. Spin determinations were made by the fitting of correlation functions with single $|P_L(\cos\theta)|^2$ functions, only natural parity being allowed for states in this geometry.[14] Decay particles were identified by kinematics and also by the energy losses in a thin Al foil which was placed on half of the solid-state detector. Correlation functions were also deduced for the continuum background. Figure 2(c) is a typical background correlation function at $E_x=15.0$ MeV, showing no significant structure with much smaller decay yields.

Total widths (Γ) of the states were determined by use of the thin WO_3 target, and by the mesaurement, separately, of the effect of the beam energy spread, the resolution of the spectrograph, the resolution of the focal-plane detector, and the energy loss in the target. They are 23, 13, 22, and 51 keV, respectively. The minimum measurable level width was 47 keV for this method. To check if these states were doublets or not, we compared two correlation functions made from the lower half and the higher half of each peak. There were no peaks which showed significant differences in the correlation patterns and the yields

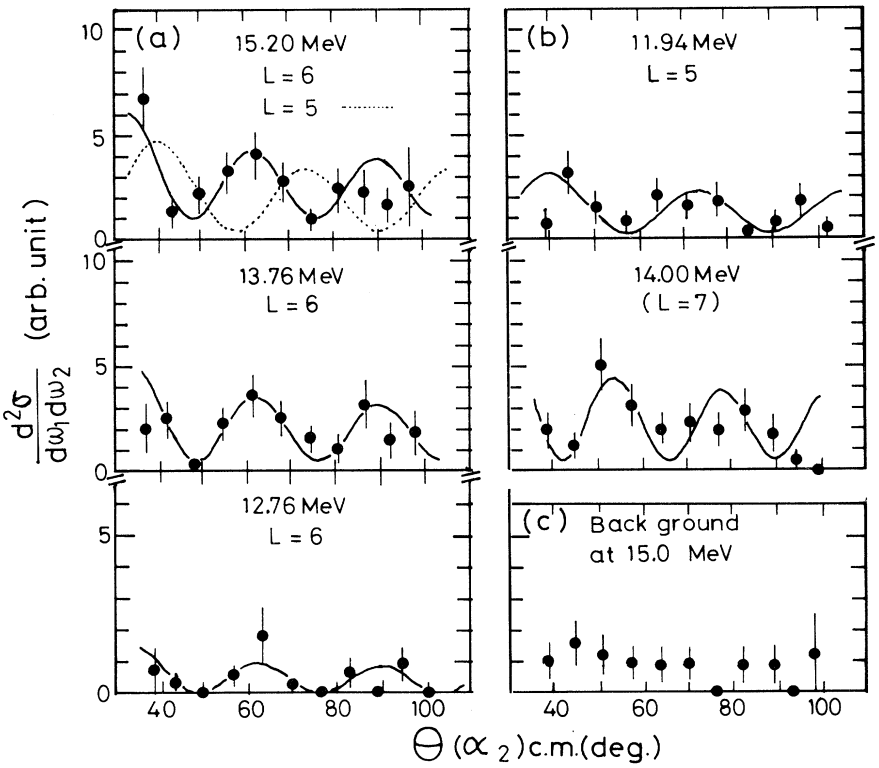

FIG. 2. α-α angular correlation functions for (a) the three 6^+ states, and (b) the odd-parity states. (c) The correlation function for the continuum background at $E_x=15.0$ MeV where an excitation energy bite equal to 60 keV is used. The solid lines are the best-fit curves with a function $a+bx|P_L(\cos\theta)|^2$. The L value in parentheses means that the spin assignment is tentative.

TABLE I. Excitation energies, the spins and parities, level widths, α-branching ratios, and α reduced widths (normalized to the Wigner limit) of the states observed in ^{32}S. The channel radius a_c is taken to be $1.40\times(28^{1/3}+4^{1/3})$ fm, and the Wigner limit $3\hbar^2/2\mu_c a_c^2$ is 428 keV, where μ_c denotes the reduced mass. The error in excitation energy is 20 keV except for the 15.20-MeV 6^+ state which has 100 keV for the error, and the error in level width is 24 keV.

E_x (MeV)	Spin, parity	Γ (keV)	Γ_{α_0}/Γ (%)	$\theta^2_{\alpha_0}$ (%)
11.70	(4^+)	55	$8.4^{+5.0}_{-5.1}$	$7.5^{+4.5}_{-4.6}$
11.94	5^-	86	$12.8^{+5.0}_{-5.1}$	43^{+17}_{-17}
12.76	6^+	84	$2.1^{+3.8}_{-1.3}$	$7.7^{+14.0}_{-4.7}$
13.04	(4^+)	<47	$9.9^{+3.4}_{-3.5}$	<2.5
13.76	6^+	50	$7.8^{+2.2}_{-2.2}$	$3.2^{+0.9}_{-0.9}$
14.00	(7^-)	50	$14.0^{+3.6}_{-3.7}$	19^{+5}_{-5}
14.81	(8^+)	91	$10.0^{+2.3}_{-2.3}$	40^{+9}_{-9}
15.20	6^6	119	$4.2^{+0.9}_{-0.9}$	$0.88^{+0.20}_{-0.20}$

between the two. Thus, these states would not be doublets, although a possible doublet of same spin states was not excluded. No proton decays were observed in the present experiment. Other experimental setups were the same as used previously for the study of ^{28}Si.[1,2]

There are about eighteen states excited through the reaction ^{16}O(^{20}Ne,α) in the excitation energy region from 11 to 17 MeV in ^{32}S, as shown in Fig. 1. The excitation energies of some states are denoted in the figure and listed in Table I. There are seven states observed for the first time, and eleven states which seem to correspond to those seen previously in the reaction[19] ^{28}Si(^{7}Li,t). The state observed at 11.70 MeV in the present experiment does not seem to be the 2^+ state observed at 11.75 MeV in some reactions[19-21] because of the spin assignment obtained here.

Some of the angular correlation functions obtained for the reaction

$$^{16}\mathrm{O}(^{20}\mathrm{Ne},\alpha_1)^{32}\mathrm{S}^*(\alpha_2)^{28}\mathrm{Si(g.s.)}$$

are shown in Fig. 2 together with the best-fit curves (solid lines). Here, 6^+ is assigned to the three states at 12.76, 13.76, and 15.20 MeV in the present excitation energy region, as shown in Fig. 2(a). Some other states of odd parity are also displayed in Fig. 2(b). The spin assignments made, for the first time, from the present experiment are listed in Table I together with the level widths (Γ), the α_0 branching ratios (Γ_{α_0}/Γ), and the α reduced widths normalized to the Wigner limit ($\theta^2_{\alpha_0}$). The channel radius was taken to be $a_c=1.4\times(28^{1/3}+4^{1/3})$ fm for the penetrability and the Wigner-limit calculations, where the value of 1.4 fm is found to be large enough for the radius parameter. In Table I errors in Γ_{α_0}/Γ and $\theta^2_{\alpha_0}$ include the errors from extrapolations of decay yields to all the solid angles, made by use of the best-fit curves.

The new states obtained here are plotted in Fig. 3 together with the dashed lines drawn through the data points as a guide to the α reduced width, since in a cluster model members of a rotational band should have the same α-spectroscopic factor. They seem to follow the $J(J+1)$ rule. The $\theta^2_{\alpha_0}$ values of the members of the positive-parity band at the highest excitation energy are around 1%, those at the second highest excitation energy are 3%–8%, and those at the lowest excitation energy are 10%–40%, whereas the $\theta^2_{\alpha_0}$ values of the members of the negative-parity band are 20%–40%. Therefore, there are three possible positive-parity bands with large moments of inertia, with the rotational constant $k=\hbar^2/2\mathcal{I}=91$–$109$ keV, but with different α-decay properties, which suggests quite different intrinsic states among these positive-parity bands. There is also a negative-parity band with a moment of inertia and α reduced widths similar to those of the lowest positive-parity band.

The experimental k values of the four bands are in good agreement with a simple prediction of $k=95$ keV obtained by the assumption of point masses for two ^{16}O nuclei, where a charge mean square radius, $1.04\times(16^{1/3}+16^{1/3})$ fm,[22] was taken for the separation of the two nuclei. These experimental rotational constants are also well reproduced by theoretical calcu-

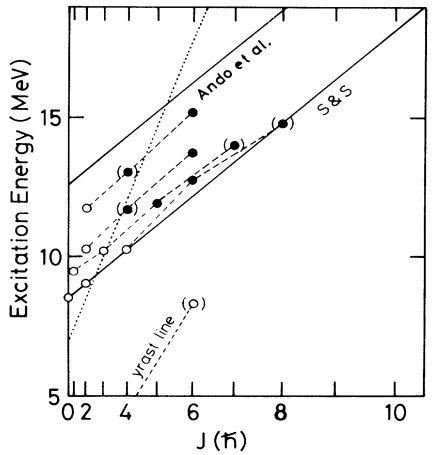

FIG. 3. Excitation energies and the spins determined in the present experiment (filled circles) together with the states known previously (open circles) (Refs. 8, 13, 20, and 21). The solid line of "S & S" is a microscopic α-cluster prediction (Ref. 7) and the solid line of "Ando *et al.*" is an RGM prediction (Ref. 3). A dotted line shows a rotational band of $\alpha + {}^{28}$Si(g.s.).

lations which predict an $^{16}O + {}^{16}O$ quasimolecular band of a dumbbell shape by the resonating-group method ($k = 60$–70 keV),[3] the Hartree-Fock calculation with the two-center shell model ($k = 121$ keV),[5] and the microscopic α-cluster model ($k = 91$ keV).[8] Although the experimental k values are different from $k = 48$ keV predicted originally by Ragnarsson, Åberg, and Sheline,[8] a reasonable value $k = 62$ keV can also be obtained[9] by inclusion of $\gamma = 5°$ for the calculation with $\epsilon = 0.6$ alone. This calculated band also has a large parentage of $^{16}O + {}^{16}O$ configuration since it has such a large prolate deformation.

However, they are quite different from $k = 259$ keV for an $\alpha + {}^{28}$Si configuration as shown by the dotted line in Fig. 3. One other possibility is the $\alpha + {}^{28}\mathrm{Si}^*(2_1^+)$ cluster states which would have $k = 110$ keV for the band of $J = L + 2$. However, the experimental branching ratios of the band members do not show dominant decays to the 2_1^+ state. Thus, the main configuration of these bands is not α-cluster configuration.

The highest positive-parity band could be the $^{16}O + {}^{16}O$ quasimolecular band since the moment of inertia is close to those predicted[3–7,9] for the $^{16}O + {}^{16}O$ quasimolecular state and the bandhead energy is also close to the $^{16}O + {}^{16}O$ threshold. The observed small α reduced widths of the band also support this assumption. On the other hand, the lowest positive- and negative-parity parallel bands have large and similar α reduced widths. Thus, these two bands may be considered to form an inversion doublet.[13] Since the energy difference of the doublet states is a good measure of clustering,[13] and it is only 0.9 MeV in this case, they are well developed molecular states of some asymmetric configuration, but not α cluster states as discussed above. Theoretical calculations for α widths would be very useful to study further structures of these bands.

In conclusion, high-spin states at 11–17 MeV in ^{32}S have been investigated via the reaction

$$^{16}\mathrm{O}(^{20}\mathrm{Ne},\alpha)^{32}\mathrm{S}(\alpha)^{28}\mathrm{Si(g.s.)}.$$

Possible band structures of quasimolecular configurations of $^{16}O + {}^{16}O$ and of some asymmetric configurations (but not α-cluster states) are suggested from the spin assignments and the α reduced widths.

Most analyses have been made at the main computer facility of the Institute for Nuclear Study, University of Tokyo.

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