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QUASI-MOLECULAR STATES IN sd-SHELL NUCLEI

S. Kubono, N. Ikeda, T. Nomura, M. Oyaizu, J. Tanaka, M. H. Tanaka, Y. Funatsu[1], H. Miyatake[2], S. Kato[3], T. Yamaya[4], and S. Ohami[4]

Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo, 188 Japan.
1) Department of Physics, Kyushu University, Fukuoka, 812 Japan.
2) College of General Education, Osaka University, Toyonaka, Osaka, 560 Japan.
3) College of General Education, Yamagata University, Yamagata, 990 Japan.
4) Department of Physics, Tohoku University, Sendai, 980 Japan.

Quasi-molecular states near and below the threshold of the molecular configuration in sd-shell nuclei are discussed using recent experimental data with particle-gamma coincidence method and particle-particle coincidence method. Possible quasi-molecular states have been identified in ^{24}Mg as well as in ^{28}Si and ^{32}S. The important role of quasi-molecular states are discussed, specifically for the shape evolution of nuclei as a function of excitation energy and angular momentum.

I. Introduction

One of the interesting subjects in the study of cluster dynamics is the cluster or molecular structure near or below the threshold energy of the configuration. This excitation energy region is just the place to learn about the shape evolution as a function of excitation energy and/or spin. One expects there a dumbbell shape structure, which we call here quasi-molecular states, rather than a well developed di-nuclear structure which is called molecular states. In the last few years, super deformed states have been well known at high excitation energies in some heavy nuclei, which have an axis ratio of about 2. The quasi-molecular states

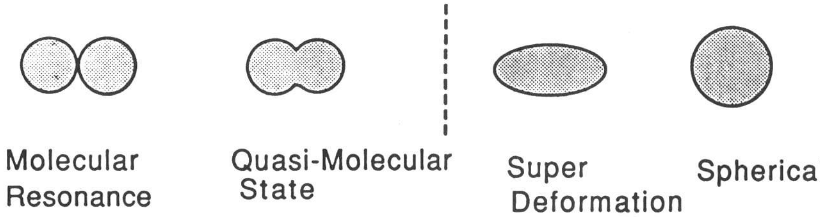

Fig. 1 Nuclear shape evolution.

should have a large overlap with the super deformed states, and be considered to be a state of further elongation from a super deformed state to a state with a neck. There are very few experiments made for this subject in this excitation energy region, although it should be an interesting region to approach from both higher and lower energy sides.

Figure 1 shows a possible shape change of nuclei. The quasi-molecular states have been long predicted in light sd-shell nuclei[1-5]. For example, there are several theoretical calculations[1-5] made for ^{32}S. Most calculations have predicted[1-4] a sort of dumbbell shape structure at certain excitation energies. Well developed rotational bands based on the shapes in fig. 1 are also expected except for the spherical shape.

Characteristics of the quasi-molecular states may be summarized as follows; they will have large quadruple moment, large moment of inertia, accurate J(J+1) spacing if there is a rotational band based on this structure, and they will have long gamma life time because of the shape. Therefore in experiment, one has to study the decay properties of these states, by either measuring particle decay or gamma decays. Particle-particle correlation method and particle-gamma coincidence method were utilized in the experiments discussed here.

II. Quasi-Molecular States in ^{28}Si and ^{32}S

Since the quasi-molecular states locate near and below the thresholds of the molecular configuration, they can not be investigated through a resonant scattering simply. Instead, other methods like particle-particle correlation method or gamma decay measurement should be used. Here, I will discuss on the study with particle correlation technique, which is useful[6,7] for the study of the states between the excitation energy

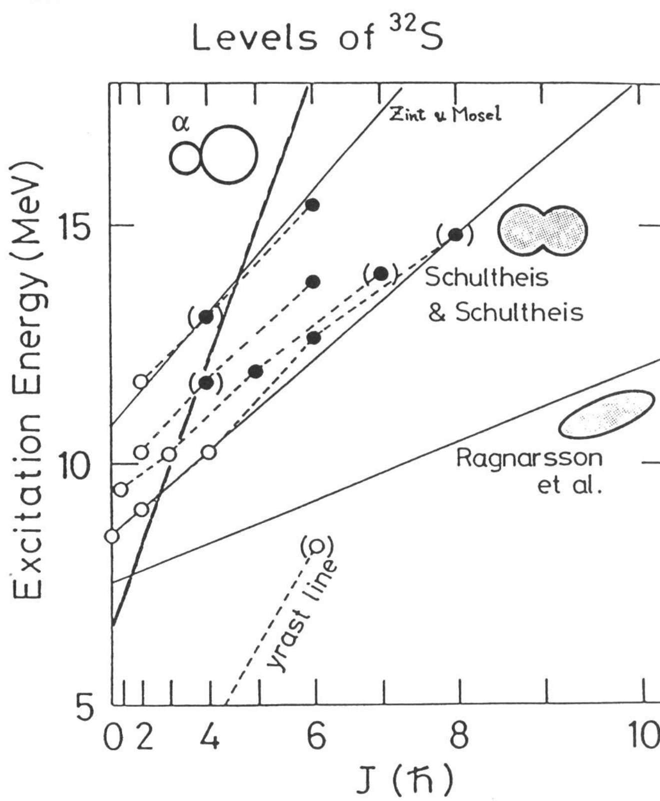

Fig. 2 Possible quasi-molecular states in ^{32}S together with some theoretical predictions[1,4,5].

region of the molecular threshold and the α threshold in even-even sd-shell nuclei, since the latter decay channels are the lowest in energy among the particle decay channels. This technique also is feasible because quasi-molecular states seem to have considerable parentage of α clustering.

An example of such study[6,7] is given in fig. 2, which shows possible quasi-molecular states of $^{16}O + ^{16}O$ in ^{32}S below the molecular threshold but above the α threshold. The particle decay widths measured suggest some rotational band structures. The experimental rotational constant and the band head energy are in good agreement with the microscopic α-cluster-model prediction by Schultheis and Schultheis[4]. Other theories[1-3,5] also predict similar rotational bands in this energy region.

The particle correlation measurement provides total level widths and particle decay reduced widths in addition. Of course, the former should be measured only when the experimental resolution is better than the level widths. These physical quantities should be very rich for nuclear structure study. Especially, the particle reduced widths will give a strong guide line for classifying the states into a band structure. Some states observed [6,7] in ^{32}S have a few tens of keV or less of α -reduced widths, and thus the reduced widths were actually measured with a high resolution spectrograph together with the decay particle detection. However, these states do not show any trace of proton decays.

This is quite contrary to those[8, 9] in ^{28}Si, shown in fig. 3, which were also

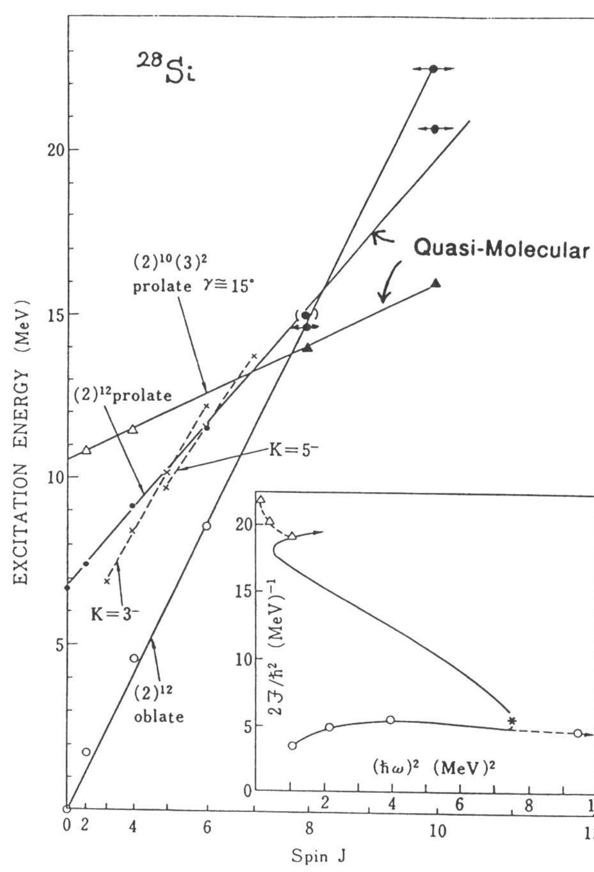

Fig. 3 Possible quasi-molecular states in ^{28}Si. Closed circles and triangles are the data by particle correlation measurement.[8, 9]

studied through the particle-particle correlation method. The states in ^{28}Si were also found to have a new rotational band structure. An interesting observation here is that there is no measurable total level widths, but they decay with protons by roughly the same rates as the αs'. Further, the branching ratios of the particle decays leading to different final states show quite different values state by state. Thus, theoretical calculations on particle decays are strongly desired to study further the quasi-molecular states. From the experimental point of view, measurement of gamma decays from and between these states should be very helpful.

III. $^{12}C + ^{12}C$ Capture Gamma Reaction

Recently, gamma rays of the capture reaction $^{12}C + ^{12}C \rightarrow \gamma + ^{24}Mg$ have been measured for the states at 0 - 10 MeV. High-energy gamma rays were measured in coincidence with the ^{24}Mg particle detection. The gamma rays were measured by using large NaI crystals[10] and the particles were separated out by a gas-filled isotope separator (GARIS)[11] which was installed recently at Institute for Nuclear Study (INS), University of Tokyo. The high energy gamma detector was surrounded by 8-cm thick plastic scintillators. The GARIS was used without gas. A $^{12}C^{2+}$ beam of 16 MeV was obtained from the INS Sector-Focussing Cyclotron, with a typical beam intensity of 1 μA.

The singles gamma spectra from the capture reaction in fig. 4 show clearly the transitions to the ground state and

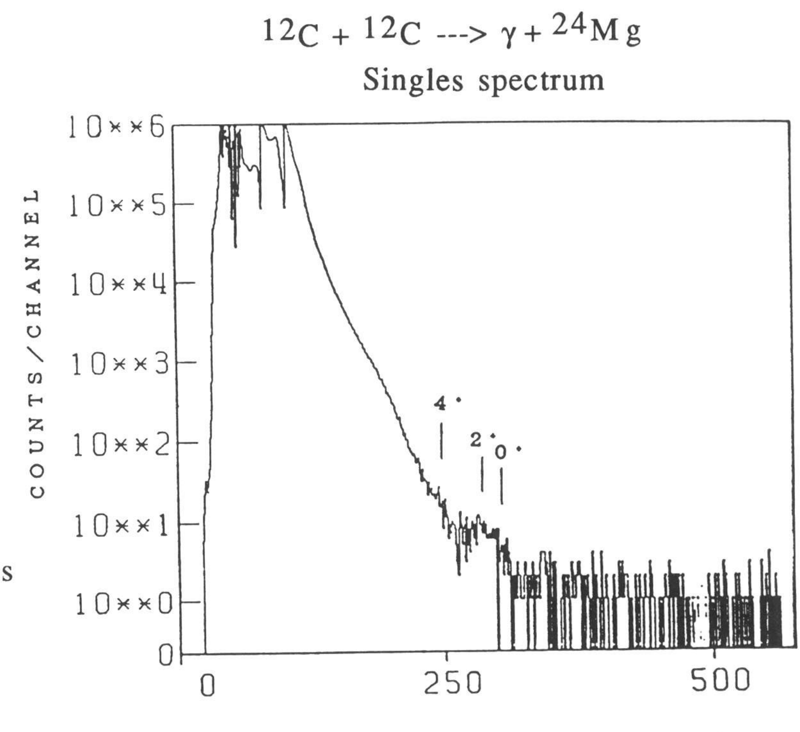

Fig. 4
A Singles spectrum of the gamma rays from the ^{12}C + ^{12}C scattering at 16 MeV.

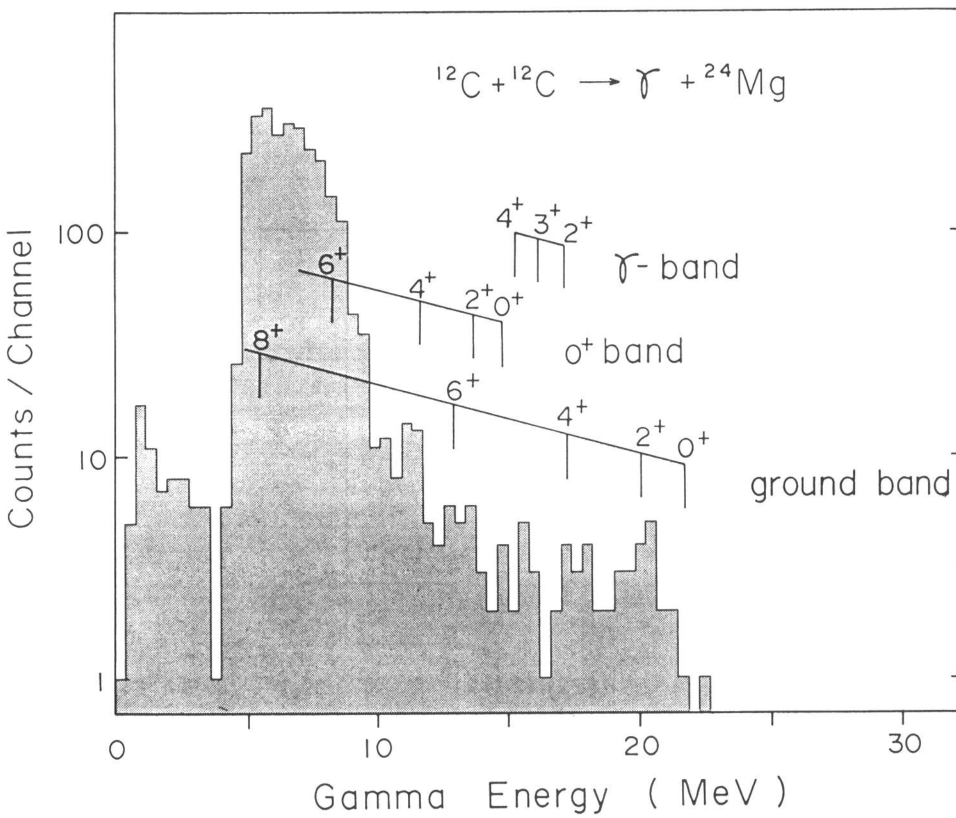

Fig. 5 Gamma ray spectrum from the ^{12}C + ^{12}C scattering measured in coincidence with ^{24}Mg particles.

the first excited state, and the transition to the $4_1{}^+$ state is barely seen. Thus, the gamma transitions to the excited states above the first 2^+ state can be hardly studied without particle coincidence measurement. Figure 4 shows a gamma ray spectrum obtained in coincidence with the ^{24}Mg particle detection, where ^{24}Mg were uniquely identified by energy, time-of-flight, and Bρ value. The coincidence rate is very low due to the present setup with the GARIS and the charge state fraction of ^{24}Mg, where 8^+ was chosen for detection to minimize the background with this separator. The spectrum observed includes several discrete transitions from the incident channel to some specific states in ^{24}Mg. One can easily see the excitation of the ground band members, i. e., the transitions to the ground state, the 1.37-MeV $2_1{}^+$ state, the $4_1{}^+$ + $2_2{}^+$ states and the 8.11-MeV $6_1{}^+$ state. The members of the excited 0^+ band with the band head energy of 6.43 MeV are excited with a much stronger intensity. Generally, the intensity within the same band members increases as the spin value of the final state increases. However, there is clearly a strong selectivity in transition, e.g., the members of the gamma band are not strongly excited, actually almost

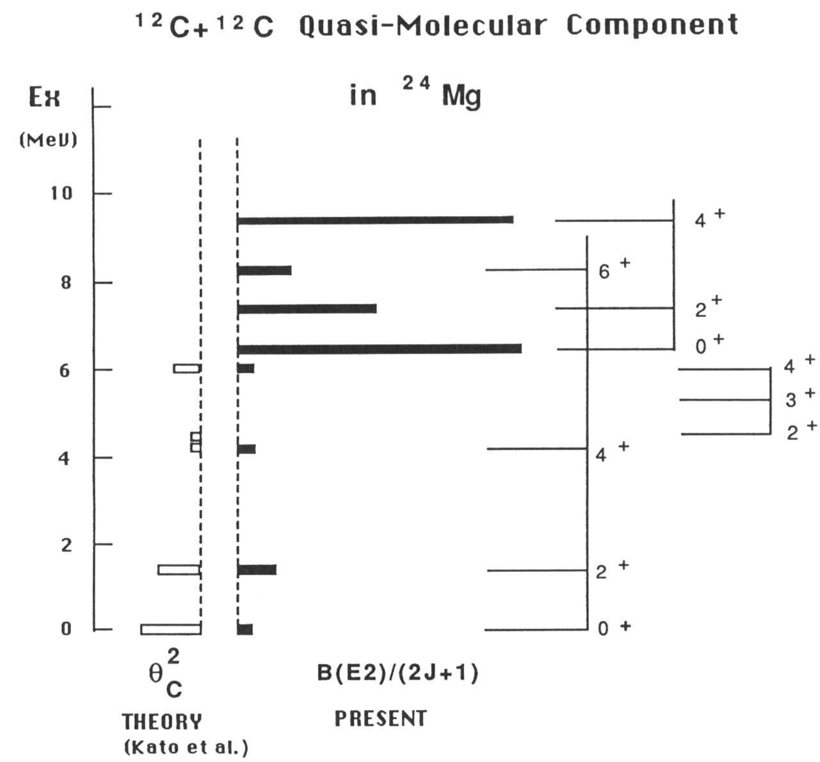

Fig. 6 Relative B(E2) values divided by (2J+1). The closed bars are the present results and the open bars are the theoretical predictions[12].

no yield for the 3^+ member of the band. More clearly, the intensities are compared schematically in fig. 5, where the gamma ray yields were divided by a factor of (2J + 1) with J being the final state spin, and also divided by $E\gamma^5$ assuming E2 transitions, since all transitions are for collective states and the incident channel has only even partial waves. The factor of (2J+1) would eliminate a part of the incident channel effect. On the left hand side in the figure, a theoretical prediction of ^{12}C + ^{12}C reduced widths by Kato[12] are plotted. The experimental strength of the $2_1{}^+$ state is normalized to that of the theory. The relative intensity seems to be consistent with the theory for the members of the ground band and the gamma band. However, there is no prediction for the members of the $K^\pi = 0^+$ band with the band head energy of 6.43 MeV, whereas the experiment show tremendous excitation of these states. A quasi-molecular band which has a dumbbell shape is suggested by Schultheis and Schultheis[4] to locate in this excitation energy region with the same rotational constant of 151 keV in ^{24}Mg. Some cluster states of α and ^8Be are predicted[13] at excitation energies of about 11 MeV and above. The present experimental results are clearly different from these states. Since the rotational constant is larger than that of the ground band (k = 193 keV) but smaller than those found in ^{28}Si and ^{32}S as discussed in the previous section, this band could have more squashed quasi-molecular like shape. Descouvemont and Baye[14] predicted three molecular bands of ^{12}C + ^{12}C, and the lowest band has a quasi-molecular shape of the separation of 3 fm and the rotational constant similar to the present band, although the excitation energies are close to the ground band. Thus, present band is a good candidate of quasi-molecular states.

IV. Summary

Experimental results with a particle correlation method were discussed in terms of quasi-molecular states. Although the usefulness of the technique is shown for this subject, further study in both theory and experiment is needed to establish quasi-molecular states. Application of particle-gamma coincidence measurement for the capture reaction of $^{12}C + ^{12}C \rightarrow \gamma + ^{24}Mg$ was also discussed for quasi-molecular state study. This reaction preferentially excites the members of the $K^{\pi} = 0^{+}$ band (the band head energy of 6.43 MeV), suggesting this band has a large fraction of ^{12}C + ^{12}C quasi-molecular configuration.

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