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Molecular Resonances in Sub-Coulomb Energy Region (^{12}C-^{12}C, ^{12}C-^{24}Mg, ^{12}C-^{9}Be systems)

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Molecular resonance in sub-Coulomb energy region was studied on ^{12}C-^{12}C, ^{12}C-^{24}Mg and ^{12}C-^{9}Be systems. The excitation functions and the angular distributions were measured on the reactions ^{12}C(^{12}C, ^{8}Be$_{g.s.}$)^{16}O$_{g.s.}$, ^{24}Mg(^{12}C, α)^{32}S and ^{9}Be(^{12}C, ^{8}Be$_{g.s.}$)^{13}C$_{g.s.}$. Sub-Coulomb resonances were observed in all systems and the contribution of the ^{12}C$^{*}_{2nd}$(0^{+}, 7.65 MeV) state is proposed.

1. INTRODUCTION

Nuclear molecular resonoances were firstly found on ^{12}C-^{12}C system in 1960.$^{1)}$ Thereafter, many experimental and theoretical investigations were performed about this problem. Investigations on various nuclear systems and various energy regions were performed. Especially, nuclear resonances were found at high energy region on ^{12}C-^{16}O system.$^{2)}$ This fact developed the area of the existence of molecular state. Much works were done about various systems.$^{3)}$ Now, the molecular resonance at high energy is clearly explained with the band-crossing model.$^{4)}$ However, the molecular resonance at sub-Coulomb energy region, which is the start point of the problem of the molecular resonance, is not explained theoretically. In this energy region, the level density of the compound nucleus is large and the number of the open channel is large, so that the existence of the discrete state is impossible.

The existence of the molecular resonance at sub-Coulomb energy region has been measured in a few system; ^{12}C-^{12}C,$^{1)}$ ^{12}C-^{16}O$^{5)}$ system and probably ^{12}C-^{13}C,$^{6)}$ ^{12}C-^{14}C$^{7)}$ system. In this energy region, differing from that of high energy region, the characteristic nature of the related nucleus are considered to relate the phenomena. All of the observed systems contain the ^{12}C nucleus as a member of the pair. This fact suggests the effect of the special nature of the ^{12}C nucleus. The structure of the ^{12}C nucleus is interpleted with the alpha-cluster model; the ground band is 3α state and the 2nd excited state (7.65 MeV; 0^{+}) is the α-^{8}Be cluster state. We used the nature of this state as a probe to see the origin of the molecular resonace. This state has large ^{8}Be decay width. The experimental studies were mainly performed by measuring the ^{8}Be-decay channel which was scarcely measured because of the difficulty of the experimental technique. Firstly, we studied the ^{12}C+^{12}C system which is the most famous system. Secondly, ^{12}C+^{24}Mg system was studied. Both nuclei of this system are 4N-nucleus, but the level density of the

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compound nucleus and the number of the open channel are large, so that the molecular resonance is not expected. Thirdly, $^{12}C+^{9}Be$ system was investigated. In this system the level density of the compound nucleus is small but the ^{9}Be nucleus has a loosely bound neutron which causes the strong absorption nature, thus the existence of the molecular resonance is not expected.

As the result, in all of the three systems, which have typical different nature and only one common nature is that the one-nucleus of the system is the ^{12}C nucleus, however the molecular-resonance-like structures were observed at sub-Coulomb energy region.

2. ^{12}C-^{12}C SYSTEM

In this system, much experimental works have been done on the elastic and inelastic scatterlng, γ, p, α, n, d-emitted reaction and many resonances were found.[8] However, on the ^{8}Be-emitted channel, which has small Q-value (0.2 MeV) and also the angular momentum matching is good, only a few work has been reported. Fletcher *et al.*[9] studied at $E_{CM}=9\sim20$ MeV. Recently our group[10] studied at $E_{CM}=6\sim10$ MeV. In this work we measured the excitation functions and the angular distributions of $^{12}C(^{12}C, {}^{8}Be_{g.s.})^{16}O_{g.s.}$ reaction at sub-Coulomb energy region. ^{12}C beam from the Kyoto University

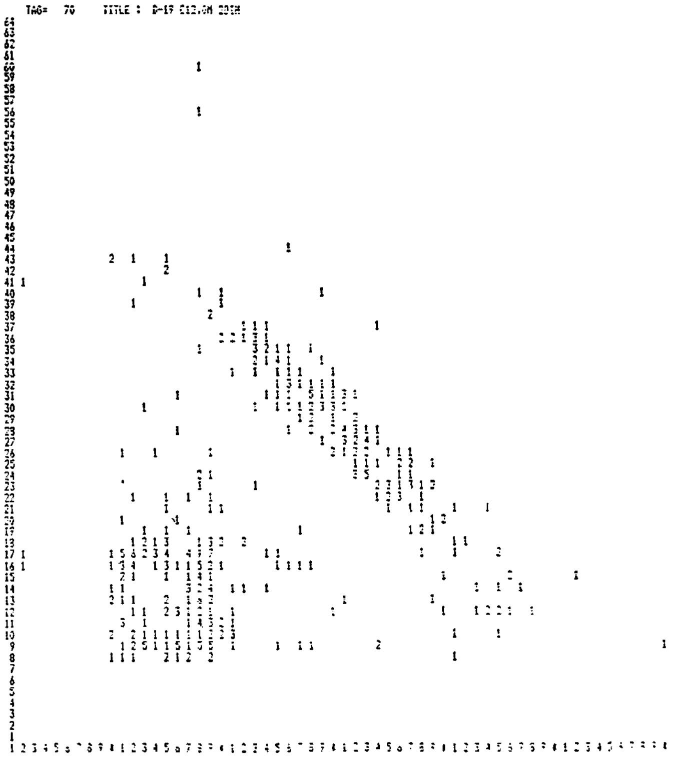

Fig. 1. Two dimensional energy spectrum of the reaction $^{12}C(^{12}C, {}^{8}Be)^{16}O$ at $\theta_L=0°$, and $E_{lab}=12.0$ MeV.

tandem Van de Graaff accelerator was used. The emitted ^{8}Be ions were measured with a pair of large area (800 mm^{2}) SSD. The effective solid angle of ^{8}Be detection was more than 1 mstr. in most case. A typical spectrum is given in Fig. 1. The excitation functions measured are shown in Fig. 2. There are sharp peaks corresponding to three resonances which were firstly discovered by Bromley *et al.*[1] (E_{CM}=5.6, 6.0 and 6.3 MeV). The angular distributions were measured at the energies of these peaks and the intermediate of the peaks. The measured angular distributions are shown in Fig. 3.

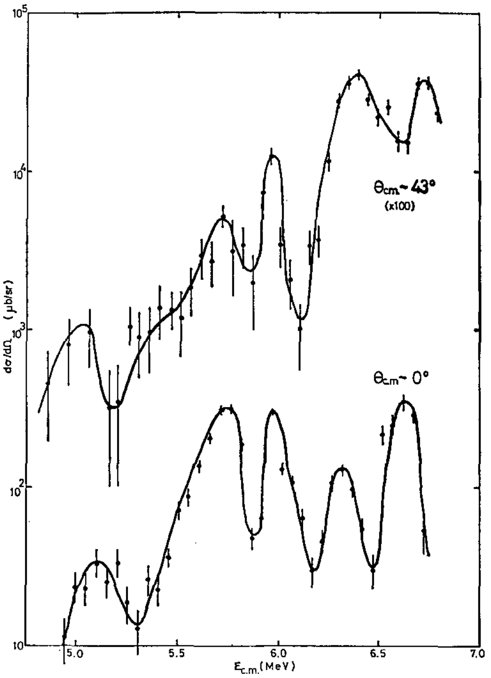

Fig. 2. Excitation functions of the ^{12}C(^{12}C, ^{8}Be$_{g.s.}$)^{16}O$_{g.s.}$ reaction. The solid lines in the figures are shown for the guide to the eye.

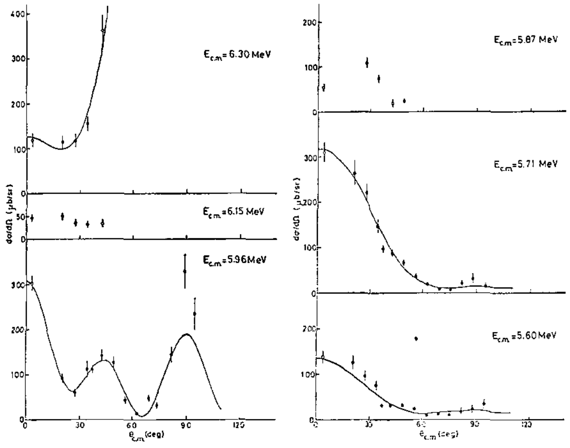

Fig. 3. Angular distributions of the ^{12}C(^{12}C, ^{8}Be$_{g.s.}$)^{16}O$_{g.s.}$ reaction. The soild lines in the figures are the calculated values.

Assuming these peaks were isolated resonance, the data were analysed with the sum of two Legendre functions. The formula used in the analysis are as follows:

$$\frac{d\sigma}{d\Omega}(\theta) = A|P_J(\cos\theta) + ae^{i\phi}P_{J'}(\cos\theta)|^2 \tag{1}$$

$$\frac{d\sigma}{d\Omega}(E) = \frac{1}{2k_c^2}\left|(2J+1)\cdot\frac{\sqrt{\Gamma_c\Gamma_o}}{E-E_\lambda+\frac{i}{2}\Gamma_t}\cdot P_J(\cos\theta) + (2J'+1)\,\mathrm{B}e^{i\alpha}P_{J'}(\cos\theta)\right|^2 \tag{2}$$

$$A = \frac{2}{k_c^2}(2J+1)^2\cdot\frac{\Gamma_c\Gamma_o}{\Gamma_t^2} \tag{3}$$

The results of the analysis are shown in Fig. 3 and Table I. It is clearly seen that the main part of the spin of the resonance is $J^\pi=2^+$ at $E_{CM}=5.71$ MeV, $J^\pi=4^+$ at $E_{CM}=5.96$ MeV and $J^\pi=2^+$ at $E_{CM}=6.30$ MeV, respectively. In table II, the values of the partial width and the total width of each resonances, derived from the values of table I, are shown. As the values of Γ_c, those of Erb *et al.*[11] were used.

On these three resonances, the value of the reduced width can be compared. These have relation that are roughly $\langle\theta_c^2\rangle\sim4\langle\theta_{o-Be}{}^2\rangle$ and $\langle\theta_{o-Be}{}^2\rangle\sim4\langle\theta_\alpha^2\rangle$ (per channel). This fact suggests that the $^{16}O+{}^8Be$ decay channel has large effect on the nature of the resonance.

From these experimental results, various models proposed to the structure of the molecular resonance of the ^{12}C-^{12}C system at sub-Coulomb energy region can be tested. Firstly, the $^{12}C_{g.s.}$-$^{12}C_{g.s.}$ potential resonance model[12] is not true. Nextly, the double resonance model

Table I. Results of the resonance analysis. Equation (1) in the text was used.

$E_{c.m.}$ (MeV)	J	J'	A	a	ϕ (deg)
5.71	2	0	162.3	.459	59.6
5.96	4	2	488.8	.636	127.7
6.30	2	0	892.2	.886	158.0
5.60	2	0	82.2	.432	33.7

Table II. Derived resonance parameters. Equations (2) and (3) in the text were used.

	present work			Wada *et al.*		
E_{CM} (MeV)	5.71	5.96	6.30	6.68	8.37	8.88
J^π	2^+	4^+	2^+	2^+	4^+	6^+
$\frac{\sqrt{\Gamma_c\Gamma_o}}{\Gamma_t}$ (%)	2.3	2.3	5.7	16.9	11.2	8.3
Γ_t (keV)	200	80	150	150	150	150
Γ_c (keV)	10	4	16	15	39	8.5
Γ_o (keV)	2.1	0.8	4.6	42.8	7.2	18.2
$\langle\gamma_o\rangle^2$ (keV) ($r_o=1.5$)	3.1	2.5	3.6			
Wigner limit ratio (%) $(\langle\gamma_o\rangle^2/(3\hbar^2/2\mu a^2))=\langle\theta_o^2\rangle$	1.2	1.0	1.4			

of the coupling with the $^{12}C_{g.s.}$-$^{12}C^*$ state[13] has possibility. Coupling with $^{12}C_{g.s.}$-$^{12}C^*_{1st}$ (4.44 MeV; 0^+) cannot be considered but coupling with $^{12}C_{g.s.}$-$^{12}C^*_{2nd}$ (7.65 MeV; 0^+) may be a candidate. Also, the model that the one of the ^{12}C nuclei excited to three alpha state[14] has a possibility. As a result, these three resonances may be a molecular structure constructed with a $^{12}C_{g.s.}$ nucleus and a $^{12}C^*_{2nd}$ (0^+; 7.65 MeV) nucleus or three alpha state.

3. ^{12}C-^{24}Mg SYSTEM

Excitation functions of the reaction $^{24}Mg(^{12}C, \alpha)^{32}S$ leading to the ground and the first excited state of the residual nucleus were measured. The results are shown in Fig. 4. The angular distributions were measured at the energy of the peaks of the excitation function. The results are shown in Fig. 5. The measured angular distributions were compared with $|P_L(\cos\theta)|^2$ and J^π value was assigned. The derived values are $J^\pi = 5^-$, 7^- and 6^+ at $E_{CM} = 12.4$, 13.1 and 14.3 MeV, respectively. Because the Coulomb barrier of ^{12}C-^{24}Mg system is 13 MeV, these results suggest the existence of the sub-Coulomb molecular resonance.

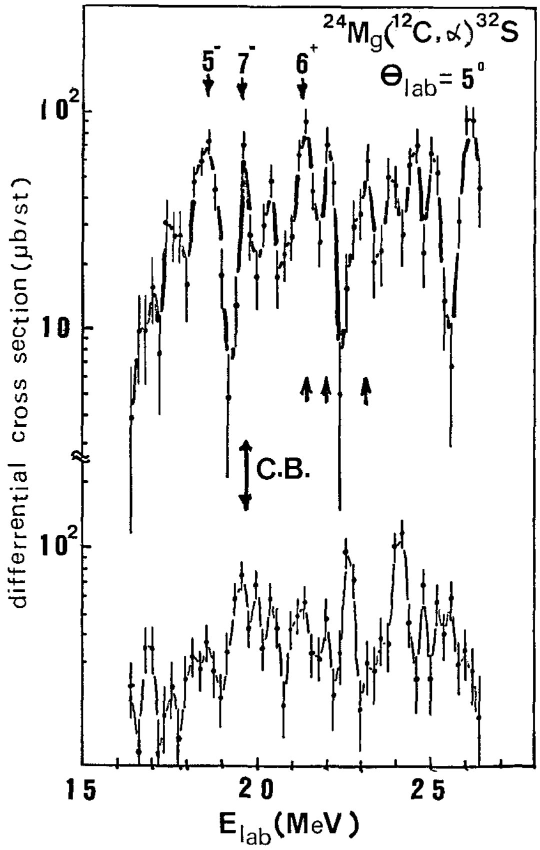

Fig. 4. Excitation functions of the reaction $^{24}Mg(^{12}C, \alpha)^{32}S$ leading to the ground and the first excited state of the residual nucleus. The solid lines in the figures are shown for the guide to the eye.

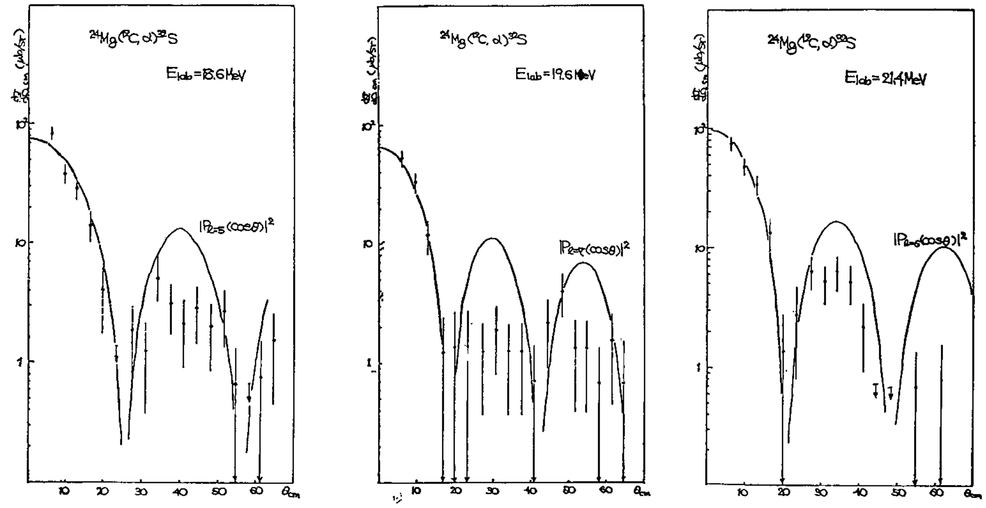

Fig. 5. Angular distributions of the reaction ^{24}Mg(^{12}C, α)^{32}S$_{g.s.}$. Solid lines in the figures are the fitting of $|P_L(\cos\theta)|^2$.

4. ^{12}C-^{9}Be SYSTEM

Excitation functions of the reaction ^{9}Be(^{12}C, ^{8}Be$_{g.s.}$)^{13}C$_{g.s.}$ were measured at three angles ($\theta_{Lab}=0°$, 20°, 40°). The emitted ^{8}Be ions were detected with a pair of large area SSD's. The results of the excitation funcions are shown in Fig. 6. At $\theta_{Lab}=0°$, a resonance-like structure is seen about $E_{CM}=5.15$ MeV. The angular distributions were measured at $E_{CM}=4.50$, 5.14 and 5.79 MeV. The experimental results are shown in Fig. 7. All of three energies, the cross section become larger at backward angles but at forward angles the cross sections rise only at $E_{CM}=5.14$ MeV. In ^{9}Be nucleus, the last neutron is loosely bound and also in ^{13}C nucleus, the last neutron is loosely bound. Such loosely bound neutron can easily transfer from ^{9}Be to ^{13}C. To see the effect of the direct neutron transfer process, the measured angular distributions were compared with the exact finite range DWBA calculation. The code SATURN-MARS was used. The results are shown in Fig. 8. The angular distributions of $\theta_{Lab}\geq 40°$ are fitted well by this

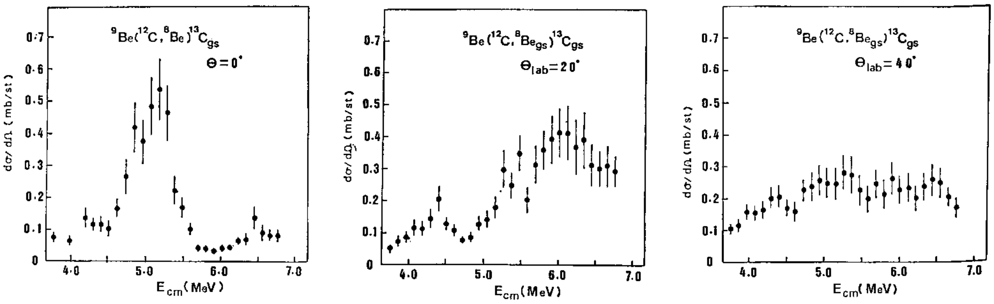

Fig. 6. Excitation funtion of the reaction ^{9}Be(^{12}C, ^{8}Be$_{g.s.}$)^{13}C$_{g.s.}$.

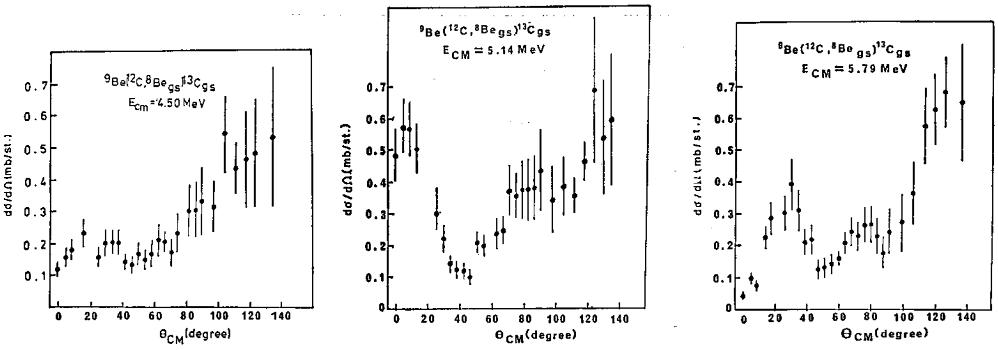

Fig. 7. Angular distributions of the reaction ^{9}Be(^{12}C, ^{8}Be$_{g.s.}$)^{13}C$_{g.s.}$.

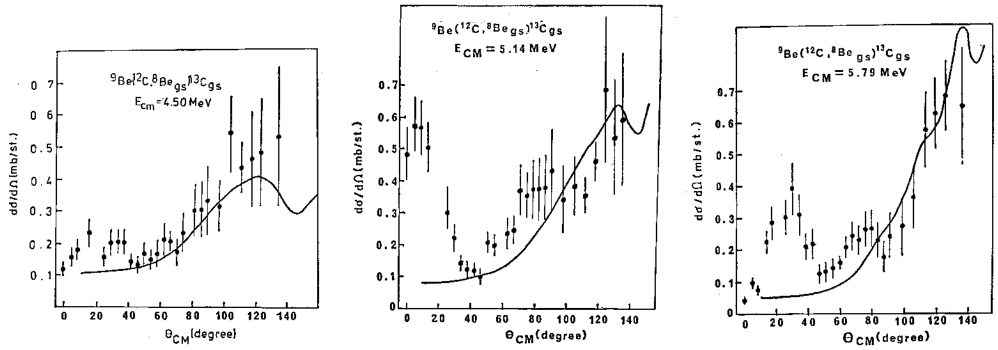

Fig. 8. Direct neutron transfer calculation of the ^{9}Be(^{12}C, ^{8}Be$_{g.s.}$)^{13}C$_{g.s.}$ reaction. Exact finite range DWBA calculation code was used.

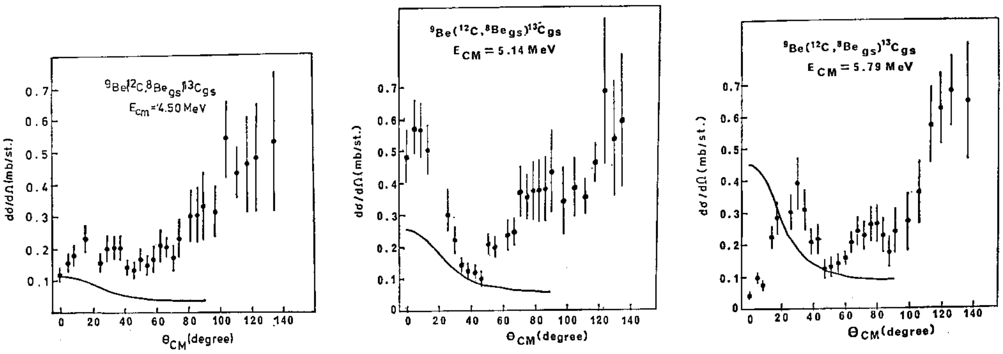

Fig. 9. Comparing with Hauser-Feschbach calculation.

calculation. At the backward angle, direct neutron transfer reaction process may play impotrant role. The direct alpha transfer reaction can be considered to have negligible effect on this system.[15]

As the reaction process related to this reaction, the possibility of the statistical compound nucleus formation process was also considered. The experimental angular distributions were compared with Hauser-Feshbach calculation.[16] The results are shown in Fig. 9. The rise of the cross section at forward angle at E_{CM}=5. 14 MeV cannot be

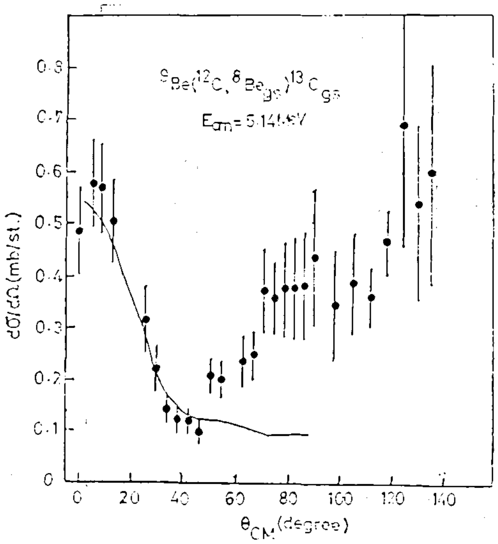

Fig. 10. Resonance analysis of the angular distribution of the $^{9}Be(^{12}C, ^{8}Be_{g.s.})^{13}C_{g.s.}$ reaction at E_{CM}=5.14 MeV.

explained by this proccess.

After the various types of analysis described above, the existence of a molecular resonance was considered to be the fact which can explain the phenemenon. The angular distribution was analysed with single level resonance formula. The result is shown in Fig. 10. Considering the χ^2-value and the transmission coefficient of the entrance channel, $J^{\pi}=11/2^-$ is the most reasonable J^{π}-value. Energy of this resonance is clearly under the Coulomb barrier. This fact increases the knowledge on the nuclear molecular resonance.

5. RESULTS AND DISCUSSION

In this work, typical three nucleus-nucleus systems were investigated. The common character is the ^{12}C nucleus, which is in all cases, a partner of the system. The condition related to the existency of the molecular resonance is various. In the systems investigated in this work, only the ^{12}C-^{12}C system was expected to detect the molecular resonances, but through the investigation on the other systems the molecular resonances were observed. In the usual criterion on the possibility of the existence of the sub-Coulomb molecular resonance,[17] $^{12}C+^{24}Mg$ system and $^{12}C+^{9}Be$ system are thought to have no resonance. Contrary to this expectation, sub Coulomb resonances were observed in both systems. The origin of the existence of the resonance is considered to come from the special structure of the ^{12}C nucleus which is in all systems, a partner nucleus. Moreover, in $^{12}C+^{12}C$ and $^{12}C+^{9}Be$ systems, resonances were strongly observed in the ^{8}Be emitted channel. One of the interpretation is the role of the $^{12}C^{*}_{2nd}$ (0^+; 7.65 MeV) state. This state is interpreted as the $\alpha+^{8}Be$ cluster structure and has large $\alpha+^{8}Be$ decay width. The measurement of ^{8}Be decay channel on the various systems in which one of the nuclei is ^{12}C may clearify the problem of the sub-Coulomb molecular resonance.

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