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Abstract;

Three subjects are discussed in this paper. 1) The mechanism of (HI,α) reactions is briefly studied. 2) Possible excitation of molecular resonance states of ^{12}C-^{12}C in ^{24}Mg through the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction were investigated. A precise measurement of the level widths in ^{24}Mg did not support the previous report that the molecular states seen in ^{12}C + ^{12}C scattering had been excited in the transfer reaction $^{12}C(^{16}O,\alpha)^{24}Mg$. 3) Highly excited states in ^{28}Si, which have a large parentage of ^{12}C-^{16}O, were also studied via the $^{12}C(^{20}Ne,\alpha)^{28}Si$ reaction. An angular correlation measurement revealed the lowest 8^+ and 10^+ states at 14.00 and 15.97 MeV, respectively, which were selectively excited in the $^{12}C(^{20}Ne,\alpha)$ reaction. These results suggest a possible new band in ^{28}Si.

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I. Reaction mechanism of (HI,α) reactions

There have been many experimental works of (HI,α) reactions. This reaction has been used mainly for study of multi-particle multi-hole states, molecular resonance states, high spin states, and etc. One of the most crucial points for applying this reaction for the studies of the first two problems is the reaction mechanism, i.e., if the reaction proceeds directly. If the reaction proceeds via compound nuclear process, one could not expect the excitation of molecular states at all. Although many works have been made on the first two subjects with using (HI,α) reactions, there have been very little experimental works on the reaction mechanism, and thus it is not well understood. One could make some tests for the problem, as usual, with the excitation function, the angular distribution and also selectivity in excitation. It is also well known in heavy ion reactions that it is important to meet the kinematical matching condition to have a large cross section.[1] However, this condition simply implys that the reaction may be favored by the kinematical conditions, but does not necessarily imply that it goes through a direct process. Therefore, it must be worthwhile to overlook the reaction mechanism of the (HI,α) reactions before we discuss the possible excitation of molecular resonance states.

Fig.1 compares the α-spectra obtained from two reactions leading to the same residual nucleus ^{24}Mg with an α-particle emission. There is a tremendous difference in excitation of the residual states, i.e., discrete states are clearly excited in the $^{16}O(^{12}C,\alpha)$ reaction[2], whereas only a smooth continuum states are seen in the $^{14}N(^{14}N,\alpha)$ reaction[3]. This dramatic difference, however, is predominantly due to the difference of the Q-values[4]. Namely, since the latter reaction has a larger Q-value, the states with higher excitation energy and with smaller angular momenta would be more favored. The situation can be more clearly understood in Fig. 2, where the kinematically fovored regions are hatched. The $^{16}O(^{12}C,\alpha)^{24}Mg$ reaction at 36 MeV favors the states near the yrast line, thus the reaction excites a very small number of states. On the contrary, the $^{14}N(^{14}N,\alpha)^{24}Mg$ reaction at 28 MeV plunges into a region of states of high level density and of smaller spins, resulting in a kind of continuum spectrum. As was mentioned earlier, the reaction mechanism still is not clear much with such an investigation. One of the scarce example for the selectivity is the excitation of 2^+ states in ^{20}Ne via the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction.[5] The 2^+ state at 7.833 MeV is excited more strongly than the 2^+ state at 7.421 MeV by a factor of 10. Since these two states locate close each other, the difference is mainly due to that of nuclear structure of the states. This fact indicates that there is a non compound-nucleus process in the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction at 25 MeV, although it does not imply that the reaction is a direct (one-step) process. Further study is clearly required for the study of the (HI,α) reaction mechanism. This would be an essential problem for the subject in the next section.

II. Excitation of Molecular Resonance States via (HI,α) reactions

Since the pioneer work on molecular states in ^{24}Mg by Almqvist, Bromley and Kuehner[6] this has been one of the hottest subjects in heavy ion study. Many resonaces were observed in several exit channels in the $^{12}C + ^{12}C$ scattering, and are attributed to quasi-molecular states of two ^{12}C. A recent work suggested that such resonance states could

be excited by the massive transfer reaction $^{12}C(^{16}O,\alpha)^{24}Mg$. Lazzarini et al.[7] have measured the energy spectra of alphas for the excitation energy up to 45 MeV in ^{24}Mg, and pointed out a possible correspondence of the gross peaks to those seen in the exit channels of alpha particle and ^{8}Be emissions in the $^{12}C+^{12}C$ scattering. See Fig. 3. It was simply based on the correspondence in energies.

However, our recent measurement[8] of the level widths and the excitation energies of these states with high resolution shows completely different values from those[7,9] obtained by the $^{12}C + ^{12}C$ scattering. The level widths obtained by the two reactions are compared in Table 1. In the experiment we also observed all levels previously seen by Lazzarini et al. with a slight systematical energy shift which could be due to incorrect energy loss correction made in the previous experiment. The corresponding states claimed previously have completely different widths and much narrower widths for molecular resonance states, especially the state at 26.05 MeV. Therefore, the resonant states observed in the excitation function of the $^{12}C(^{12}C,^{8}Be)^{20}Ne$ reaction may not be the ones seen in the transfer reactions $^{12}C(^{16}O,\alpha)^{24}Mg$. A similar correspondence was claimed by Nagatani et al.[10] to a series of high spin states of up to 18^+ in ^{24}Mg found in the excitation function of the $^{12}C(^{12}C,^{12}C)$ reaction[11]. They found a series of gross peaks in the background subtracted α-spectra from the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction at 145 MeV, as shown in Fig.4. The excitation energies corresponded to those obtained by the $^{12}C + ^{12}C$ scattering. Further, they did not see such a gross bump in the $^{13}C(^{16}O,\alpha)$ reaction. Hence, they suggested that the gross structures were due to the molecular resonance states of ^{12}C-^{12}C. There arise at least two questions on this claim. First of all, why is there, in the higher excitation energy, no trace of peaks which correspond to higher spin states ($> 18^+$) ? As pointed out by Ichimura et al.[1], the kinematical matching condition may be important, but it is not resonable to have no trace of the excitation of the next spin state (20^+) just near the best matched kinematics. Secondly, why are the states at Ex $\geq$ 43 MeV not seen at 15^o in Fig. 4 ? One possible explanation could be as follows: The alphas for the gross bumps could be originated from the break up of the excited ^{16}O following the $^{12}C(^{16}O,^{16}O^*)$ reaction. Fig. 5 shows possible structurs[8] expected from this process through the excited states in ^{16}O denoted in the figure together with the experimental α-spectrum of Fig. 4. The dotted line is the expected line shape from the α-decay of the 16.29 MeV 6^+ state in ^{16}O. This explains the two problems mentioned above. Since there is no other α-decaying states below the 9.63 MeV 1^- state in ^{16}O which emitt an alpha particle of energy which corresponds to the excitation energy of Ex $\simeq$ 53 MeV in ^{24}Mg, there should not be any other peaks at excitation energy higher than 53 MeV. Further, the low-lying states of ^{16}O emit α-particles within small cones at forward angles, and thus the contributions of these processes disappear at lower alpha energy (which corresponds to higher excited states in ^{24}Mg) as the angles increases. This assumption agrees with a recent experimental result. Rae et al.[12] investigated the $^{12}C(^{16}O,\alpha)$ reaction with measuring ^{12}C and an alpha particle in coincidence. They concluded that the dominant process for the alpha particle production in the gross bump region was the inelastic breakup of ^{16}O from the

$^{12}C(^{16}O,^{16}O^*)$ reaction. This process, however, cannot give a satisfactory explanation for the target difference of the $(^{16}O,^{12}C)$ reaction as mentioned earlier. Another explanation was given by Szanto de Toledo et al.[13] They investigated the same reaction at low incident energies between 48.8 and 65 MeV, and found a series of gross bumps at low excitation energies in ^{24}Mg. They successfully explained the structure within a statistical model by taking account of the yrast states explicitly. However, this is in contradiction with a recent measurement[14] of the $^{14}N(^{14}N,\alpha)$ reaction, where no structure was found in the α spectrum at a high incident energy which meets the kinematical matching condition.

To summarize this section, it still seems an open question if the $^{12}C(^{16}O,\alpha)$ reaction really excites the molecular states of ^{12}C-^{12}C. A crucial test for the problem would be to compare absolute cross sections of the possible processes quantitatively. If they are the states of ^{24}Mg, it would be very important to determine next the level widths and the spins. So far no spins were assigned for these gross structures at high excitation energies.

III. Excitation of Highly Excited, High Spin States

Spin is one of the fundamental and important quantities in studying highly excited states including molecular resonance states especially in heavy-ion induced reactions. (HI,α) reactions between 4n-nuclei favor high spin states near the yrast line (see Figs. 1 and 2), where the level density is so small that one may observe a spectrum of discrete states. Fig. 6 shows the known yrast levels in the middle of the sd-shell nuclei[15]. Only up to

8^+ states the spins are known in ^{20}Ne and ^{24}Mg. The yrast 8^+ state had not been known in ^{28}Si. Recently, we have determined the first 8^+ and 10^+ states in ^{28}Si by utilizing the angular correlation method[16] for the reaction $^{12}C(^{20}Ne,\alpha_1)^{28}Si^*{}_J(\alpha_2)^{24}Mg(g.s.)$ at 52 MeV.[17] Fig. 7 shows a singles energy spectrum at 0^o taken with a magnetic spectrograph. There are some states excited selectively by the $^{12}C(^{20}Ne,\alpha)^{28}Si$ reaction. The three states at 14.00, 15.97 and 17.75 MeV were observed to decay with alpha emissions to the ground state and the first excited state in ^{24}Mg, and spins of 8^+, 10^+ and (8^+) were assigned to the three states, respectively. Fig. 8 summarizes the experimental results together with the states reported previously.[18,19] The 8^+ state expected for the ground state band locates between the two 8^+ states. The 10^+ state at 15.97 MeV seems too low in energy if it is the 10^+ member of the ground state band. Rather to say, it seems to form another band structure together with the 14.00 MeV 8^+ state, with the band head being the 0^+ state at 6.69 MeV[18]. The $(^{20}Ne,\alpha)$ reaction might favor a high spin state and a prolate shape since the primitive image of the reaction is the ^{16}O transfer on ^{12}C. From a nuclear structure point of view it would be very interesting to investigate if they form a new band, and if so the nature of the band.

IV. Summary

(HI,α) reactions are shown to be a good tool to study high spin states and band structures of nuclei. The possibility to excite molecular resonance states of $^{12}C-^{12}C$ in ^{24}Mg via the $^{12}C(^{16}O,\alpha)^{24}Mg$ reaction was discussed, and it seems at

this moment that the gross bumps seen in the singles alpha spectrum may not be due to the excitation of the molecular states. However, no consistent explanation so far has been obtained. This problem is also strongly correlated with the reaction mechanism of (HI,α). This is one of the most essential questions for the problem of molecular state excitations.

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Table 1 The excitation Energies and the level widths of ^{24}Mg observed in the $^{12}C(^{16}O,\alpha)$ reaction (ref. 8).

		Branching to ^{20}Ne states				Lazzarini et al.*	Fletcher et al.**
Ex (MeV)	Γ (keV)	0.0MeV (0^+)	1.63MeV (2^+)	4.25MeV (4^+)	8.78MeV (6^+)	Ex (MeV)	Γ (keV)
22.93	62±13		26 %	33 %		23.2	
23.23	35±13					23.5	
24.37	21± 7			63		24.7	
25.18	163± 6		24	15	31 %	25.5	200
26.05	<13			8	65	26.3	300
26.45	115±20				77	26.7	350

* from ref.9)
** from ref.10)

Figure Captions:

Fig. 1 α spectra from (a) the $^{16}O(^{12}C,\alpha)^{24}Mg$ reaction at 36 MeV and $\theta_L = 7.5^{\circ}$ (ref. 2) and (b) the $^{14}N(^{14}N,\alpha)^{24}Mg$ reaction at 28 MeV and $\theta_L = 7.5^{\circ}$ (ref. 3).

Fig. 2 Hatched areas are kinematically favored regions for the two reactions in Fig. 1. The dotted and dash-dot lines are the kinematically matched lines in angular and linear momenta, respectively.

Fig. 3 Comparison of structures in various $^{12}C + {}^{12}C$ exit channels (ref. 7).

Fig. 4 α spectra from the $^{12}C(^{16}O,\alpha)$ reaction at 145 MeV (ref. 10).

Fig. 5 Background subtracted α spectrum at 7° from the $^{12}C(^{16}O,\alpha)$ reaction (ref. 10). The dashed curve is a calculated line shape assuming ^{16}O inelastic scattering followed by α decay (ref. 8).

Fig. 6 Yrast levels of the sd shell nuclei denoted (ref. 15).

Fig. 7 A momentum spectrum of the $^{12}C(^{20}Ne,\alpha)$ reaction at 51.91 MeV and $\theta_L = 0^{\circ}$ (ref. 17).

Fig. 8 Possible two bands in ^{28}Si. The open circles are the present data (ref. 17) and the closed circles are from refs. 18 and 19).

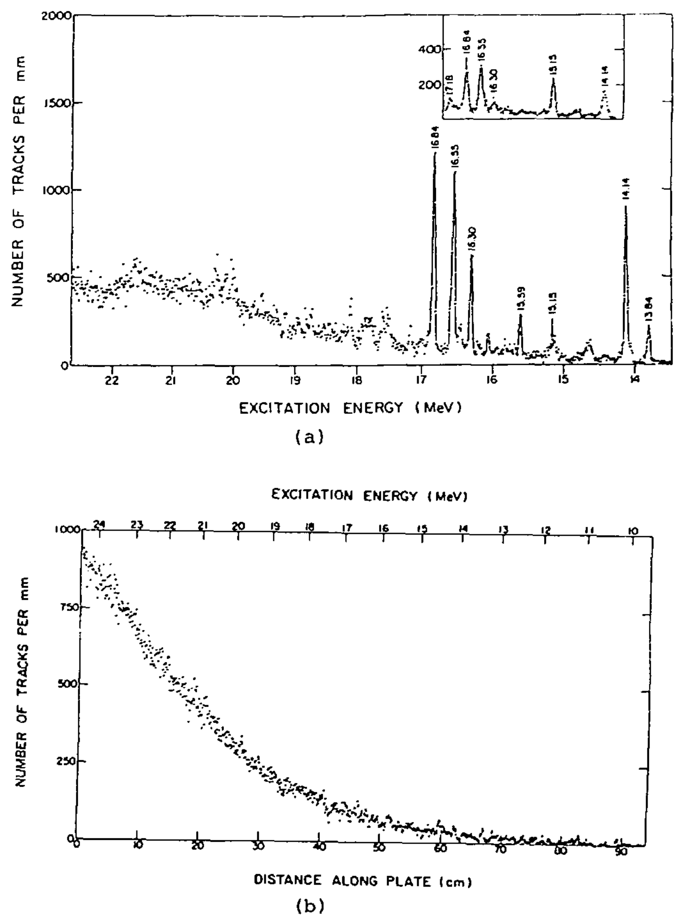

NUMBER OF TRACKS PER mm
EXCITATION ENERGY (MeV)
(a)
17.18
16.84
16.55
16.30
15.59
15.15
14.14
13.84
EXCITATION ENERGY (MeV)
NUMBER OF TRACKS PER mm
DISTANCE ALONG PLATE (cm)
(b)

Fig. 1

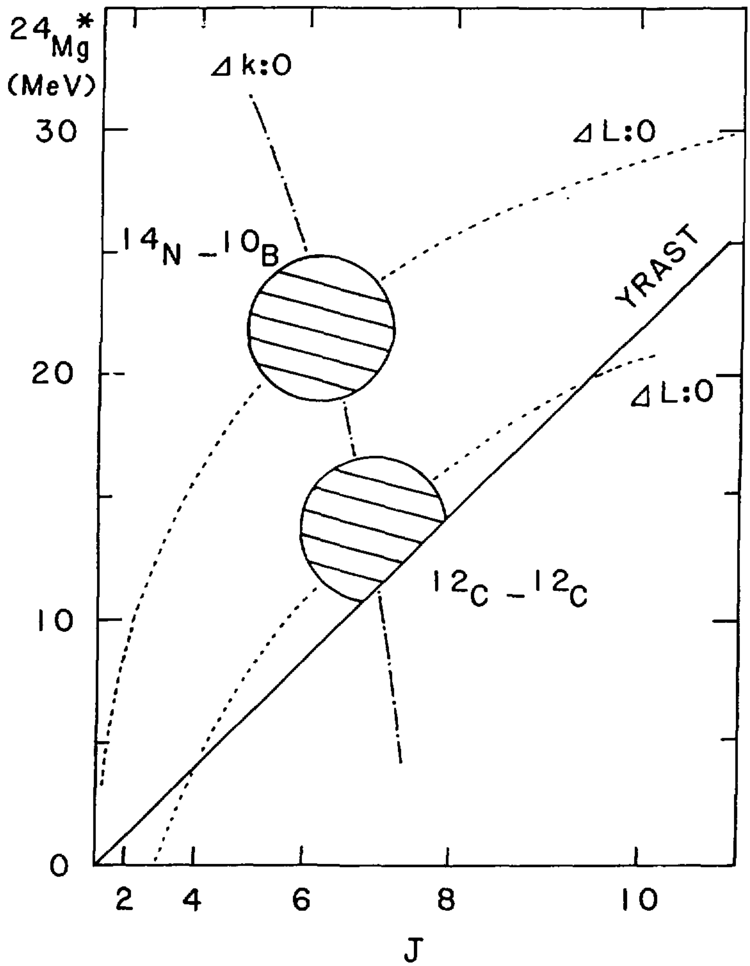


Fig. 2

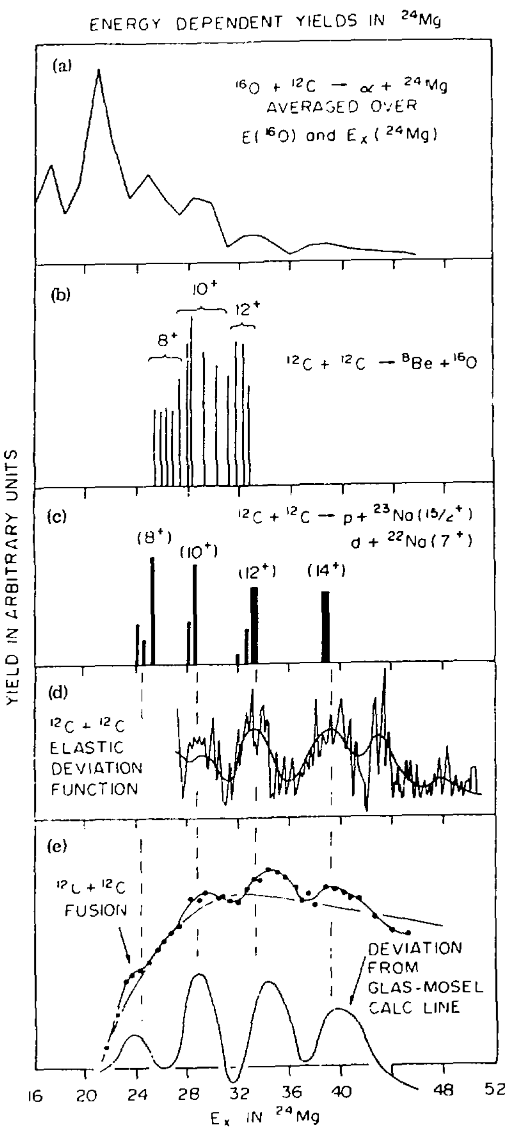

ENERGY DEPENDENT YIELDS IN 24Mg
(a)
16O + 12C → α + 24Mg
AVERAGED OVER
E(16O) and Ex(24Mg)
(b)
8+
10+
12+
12C + 12C → 8Be + 16O
(c)
12C + 12C → p + 23Na(15/2+)
d + 22Na(7+)
(8+)
(10+)
(12+)
(14+)
(d)
12C + 12C
ELASTIC
DEVIATION
FUNCTION
(e)
12C + 12C
FUSION
DEVIATION
FROM
GLAS-MOSEL
CALC LINE
YIELD IN ARBITRARY UNITS
16
20
24
28
32
36
40
48
52
Ex IN 24Mg

Fig. 3

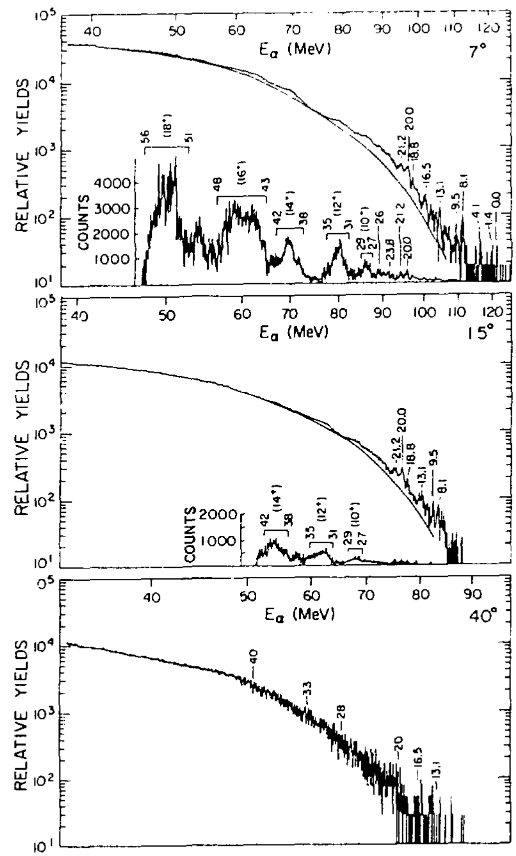

Eα (MeV)
7°
15°
40°
RELATIVE YIELDS
COUNTS
(18+)
(16+)
(14+)
(12+)
(10+)

Fig. 4

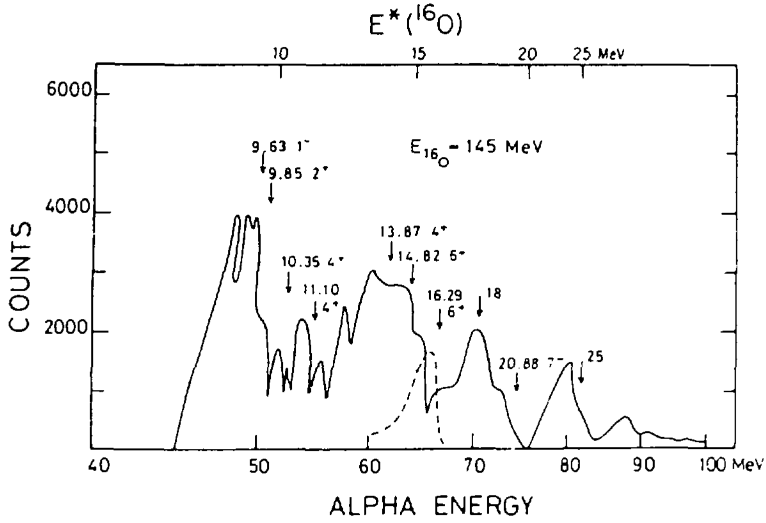

E*(16O)
10
15
20
25 MeV
6000
4000
2000
COUNTS
9.63 1⁻
9.85 2⁺
E16O = 145 MeV
10.35 4⁺
11.10
4⁺
13.87 4⁺
14.82 6⁺
16.29
6⁺
18
20.88 7⁻
25
40
50
60
70
80
90
100 MeV
ALPHA ENERGY

Fig. 5

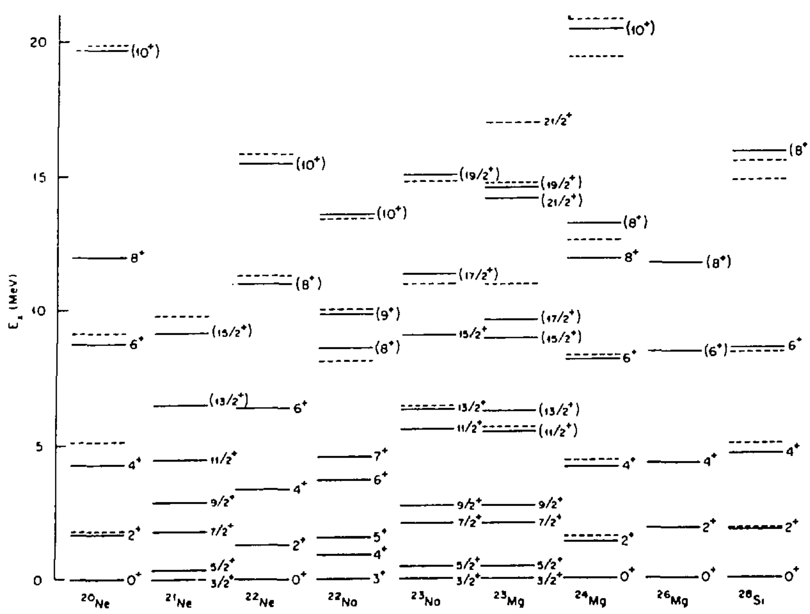
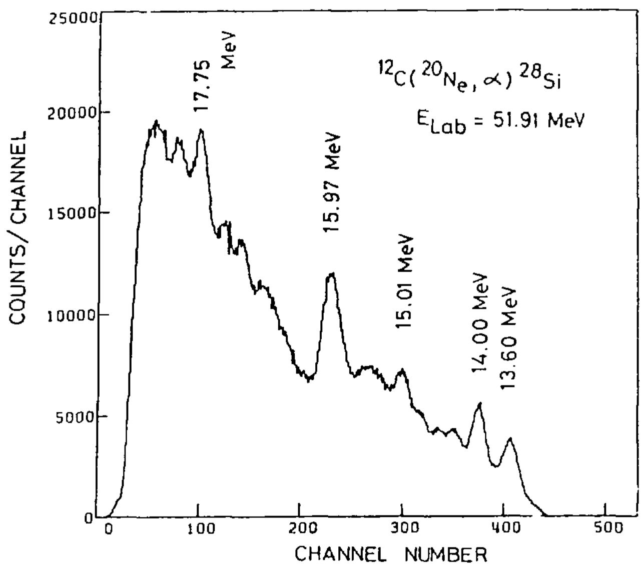
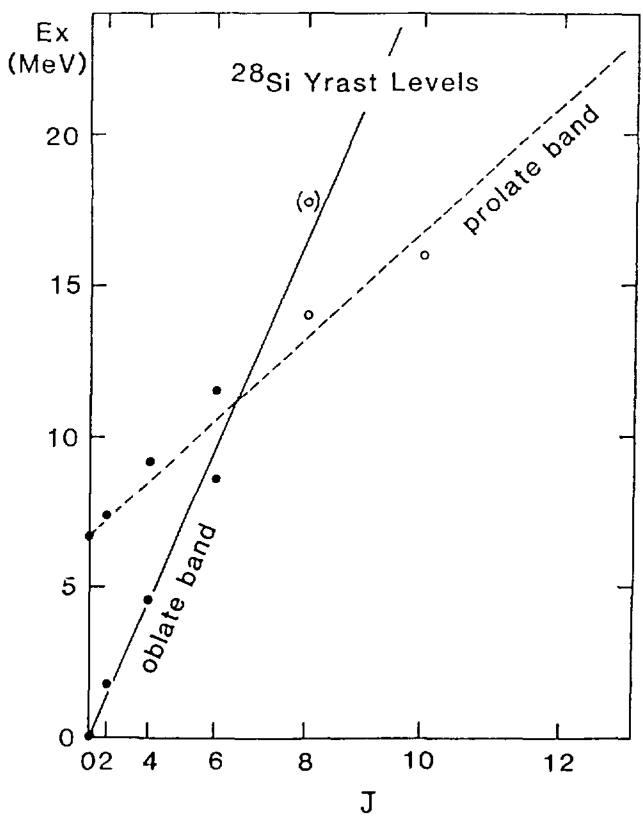

Ex (MeV)
20
15
10
5
0
20Ne
21Ne
22Ne
22Na
23Na
23Mg
24Mg
26Mg
28Si

Fig. 6



$^{12}C(^{20}Ne,\alpha)^{28}Si$
E_{Lab} = 51.91 MeV
17.75 MeV
15.97 MeV
15.01 MeV
14.00 MeV
13.60 MeV
COUNTS/CHANNEL
CHANNEL NUMBER

Fig. 7



Ex (MeV)
^{28}Si Yrast Levels
prolate band
oblate band
J

Fig. 8