Q-value dependence of inelastic scattering and multinucleon transfer reactions $^{27}Al + ^{16}O$ at 88 MeV: Optimum Q values and Q-value dependence of angular distributions of reaction products

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$^{27}Al(^{16}O,X)$ reactions are studied at 88 MeV. The A and Z of reaction products $X = ^{16}O$, $^{15,14,13}N$, $^{13,12}C$, $^{11,10}B$, $^{9,7}Be$, and $^{7,6}Li$ are identified. Despite the low bombarding energy, the general features of (i) energy spectra, (ii) the optimum Q values $Q^m_{\rm eff}$, and (iii) angular distributions in 5 MeV intervals in Q are very similar to those of much higher energy data of heavier systems: i.e., (i) dominance of deep inelastic reactions, (ii) $Q^m_{\rm eff}$ values well reproduced by the "universal" relations previously found for deep inelastic reactions, and (iii) $\sigma(\theta,Q)$ of a form $A\exp[-\mu(Q)\theta]/\sin\theta$. The variations of $Q^m_{\rm eff}$ with θ, and of μ with Q and n, the number of transferred nucleons, are discussed in connection with the gradual evolution in reaction mechanisms from quasielastic to deep inelastic to complete fusion.

[NUCLEAR REACTIONS $^{27}Al(^{16}O,X)$, E=88 MeV, $X=^{16}O$, $^{15,14,13}N$, $^{13,12}C$, $^{11,10}B$, $^{9,7}Be$, and $^{7,6}Li$, measured energy spectra, optimum Q values, σ, $\sigma(\theta)$, and $\sigma(\theta,Q)$.]

I. INTRODUCTION

Many investigations have been made of the systematics of the optimum or the most probable "effective" Q values, $Q^m_{\rm eff}$, in multinucleon transfer reactions induced by heavy ions of the type $A+a\to b+B$: The optimum effective Q value is defined by

$$Q^m_{\rm eff}=(E^m_f-V^f_C)-(E_i-V^i_C)$$
$$=Q_{gg}-E^m_x+\Delta V_C\,, \quad (1)$$

where E_i, E^m_f, V^i_C, V^f_C, ΔV_C, Q_{gg}, and E^m_x are the incident c.m. energy, the most probable outgoing c.m. energy, the Coulomb barriers in the incident and outgoing channels, their difference, the Q value in a reaction leaving both the final products b and B in their ground states, and the most probable excitation energy in the final channel, respectively. Hereafter, the radius parameter r_0 will be taken to be 1.4 fm.

A very thorough study of $Q^m_{\rm eff}$ was reported by Mikumo *et al.*,[1] who obtained a very simple empirical relation between $Q^m_{\rm eff}$ and the number of transferred nucleons n (cf. Fig. 9 of Ref. 1 and Fig. 5 of this paper),

$$Q^m_{\rm eff}=\alpha n+\beta,\quad \text{for } n\leq 4 \quad (2)$$

with

$$\alpha\simeq -0.1(E_i-V^i_C)-0.9\ \text{(MeV)} \quad (3)$$

and β scattered around

$$\beta\simeq -3\ \text{(MeV)}. \quad (4)$$

These relations [(2)–(4)] hold for all the data available at that time identifying both A and Z, i.e., $^{52,53}Cr + ^{14}N$ at $E_{\rm lab}$ between 64 and 95 MeV, $^{A}Mo + ^{14}N$ (A = 92–100) at $E_{\rm lab}$ = 97 MeV,[1] and other reactions (quoted in Ref. 1) with a variety of incident variables, $E_i - V^i_C$, ranging between 20 and 60 MeV. (See Fig. 5.)

Moreover, by examining the available data for larger n, i.e., $5\leq n\leq 10$, Mikumo pointed out further empirical relations between $Q^m_{\rm eff}$ and n,[2]

$$Q^m_{\rm eff}=\alpha' n+\beta'\,, \quad (5)$$

with

$$\alpha'\simeq -0.06(E_i-V^i_C)+0.1\ \text{(MeV)}, \quad (6)$$

$$\beta'\simeq -0.4(E_i-V^i_C)-0.5\ \text{(MeV)}. \quad (7)$$

(See Fig. 5 of this paper.)

The quantities α and α' are interpreted as energy losses per nucleon transfer, which are proportional to the net incident energy, $E_i - V^i_C$. On the other hand, β and β' correspond to the energy losses due to the internal excitation of target nuclei in the inelastic channels, presumably corresponding to quasielastic (QE), i.e., $E^m_f\approx E_i$, and deep inelastic (DI), i.e., $E^m_f\ll E_i$ collisions, respectively.

It is often pointed out that multinucleon transfer (e.g., $n\geq 5$) reactions can only occur in DI collisions,[3] and as β' is obtained through the extrapolation from data for $n\gtrsim 5$ to $n=0$, it should be compared with $Q^m_{\rm eff}$ in the inelastic scattering.

In recent years several data of DI collisions were reported in the energy region of tandem accelerators, e.g., Ni(^{16}O, ^{16}O′) at 96 MeV by Albrecht *et al.*,[4] and an extensive study of ^{27}Al + ^{16}O at 90 and 100 MeV by Cormier *et al.*[5] These data gave a value of $|Q_{\rm eff}^m|$ larger than the value predicted by Eq. (7) by a factor of 1.5 to 2.

On the other hand, it is pointed out that from the systematics of angular distributions of cross sections of reaction products the reaction mechanism is classified by the so-called "modified Sommerfeld parameter" η'[6,7]

$$\eta' = \frac{Z_A Z_a e^2}{\hbar v'} \text{ with } v' = \left[\frac{2(E_i - V_i)}{\mu'}\right]^{1/2}, \qquad (8)$$

where $Z_A e$ and $Z_a e$ are the charges of the target and projectile, v' and μ' are their relative velocity and reduced mass, respectively. For simplicity we take V_i for the Coulomb potential V_C^i only, with radius parameter $r_0 = 1.4$ fm as above. If this classification is valid, even with low bombarding energy, ^{27}Al + ^{16}O at 88 MeV would correspond to much higher energy reactions of much heavier target-projectile systems.

The aims of the present study are the following: (i) to see if the systematics of $Q_{\rm eff}^m$ mentioned above are valid for incident variables different from those quoted above, i.e., ^{27}Al + ^{16}O at 88 MeV, and especially to obtain β' in the inelastic channel, (ii) to obtain systematics of energy spectra of emitted particles, (iii) relative yields of isotope productions $d\sigma/d\Omega$, and (iv) dependence on Q values of angular distributions of emitted particles $d^2\sigma/d\Omega\, dQ$ vs $\theta_{\rm c.m.}$.

II. EXPERIMENTAL PROCEDURE

The beam of 88 MeV $^{16}O^{7+}$ ions was produced by the 12 UD Pelletron at the Tandem Accelerator Center of the University of Tsukuba. Targets of aluminum foil 90–120 μg/cm^2 thick were irradiated by the ^{16}O beam with the intensity of 30 to 150 nA.

In the course of the irradiation, accumulation of carbon soot was observed at the beam spot on the target. In order to avoid this carbon accumulation, the target foil was moved bit by bit several times during the irradiation. Further, a liquid nitrogen trap was placed near the target to reduce the vapor pressure of hydrocarbons in the scattering chamber. These precautions assured us that the background in the energy spectra of emitted particles due to the carbon contamination was very small. This fact was confirmed by comparing the energy spectra obtained from the aluminum targets with those from a carbon target.

The reaction products were detected and identified by using conventional counter telescopes consisting of Si surface barrier E counters 300 μm thick and Si surface barrier ΔE counters of various thicknesses. The identification in A as well as Z of the reaction products was satisfactory with 29.5 μm thick ΔE counters, for $2 \le Z \le 8$, in the angular range $10° \le \theta_{\rm lab} \le 35°$. Thinner ΔE counters (6.7 and 16.9 μm thickness) were used to detect lower energy reaction products at backward angles of $22° \le \theta_{\rm lab} \le 75°$ at the expense of good identification in A. The data at backward angles were normalized to those at forward angles (as mentioned in Sec. III E).

The solid angles subtended by the detectors were 0.5 msr at forward angles and 1.0 msr at larger angles. The total energy resolution as measured for elastic peak was 500 keV full width at half maximum (FWHM), at $\theta_{\rm lab} = 22°$, including an important kinematical effect.

Energy signals from each counter telescope were sent to the memory of the PDP 11/40 computer system, and then sent to the PDP 11/50 system and were recorded event by event on a magnetic disk and a magnetic tape. Particle identification was executed using graphic display equipment.

III. RESULTS AND DISCUSSION

In the following, the data obtained in the present experiment are summarized and a discussion of the results is presented. In general, the present results are consistent with those of Cormier *et al.*[5] for ^{27}Al + ^{16}O at 90 and 100 MeV, although they identified either Z or A, but not both.

A. Energy spectrum

As an example, energy spectra of emitted particles ^{16}O, ^{15}N, ^{14}N, ^{13}C, ^{12}C, ^{11}B, ^{10}B, ^{9}Be, ^{7}Be, ^{7}Li, and ^{6}Li observed at $\theta_{\rm lab} = 26°$ are shown in Fig. 1.

The energy spectra of emitted particles, except for ^{16}O revealed only one component (a bump) at $\theta_{\rm lab} > \theta_{\rm gr} = 17°$

In the case of ^{16}O, in the QE region, some peaks at $E_x \simeq 2$ MeV and $E_x \simeq 6$–7 MeV were observed, giving $\beta \simeq -5$ MeV. Some selective peaks were also observed in the case of ^{15}N ($n = 1$) at the most forward angles, which are not shown in the figure.

Except for these peaks for $n = 0$ and for $n = 1$, at forward angles, for emitted particles corresponding to transfer of more nucleons (e.g., $n \ge 2$) no selective peaks were revealed and only a broad bump was observed, the peak of which corresponds to high excitation energies, $E_x = 15$–35 MeV, i.e., $E_f^m \ll E_i$. Thus the major part of the energy spectra corresponds to DI reactions, despite the low bombarding energy in the present experiment.

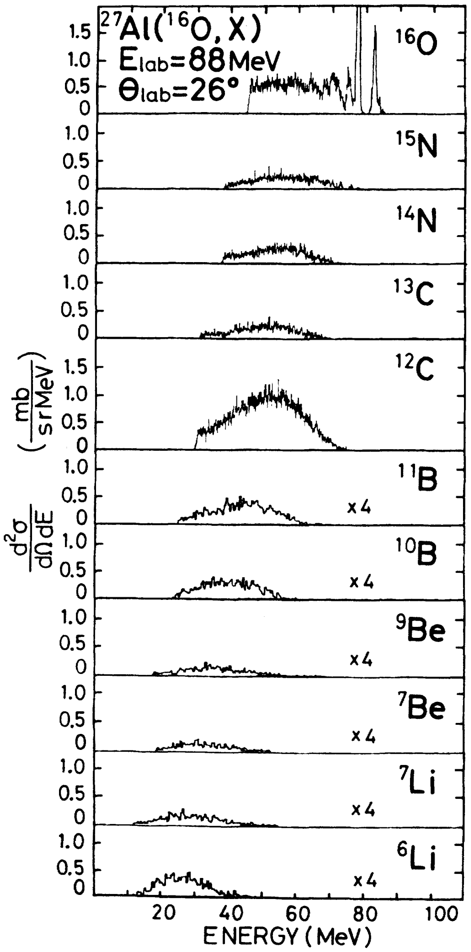

FIG. 1. Energy spectra of products in the reactions $^{27}Al(^{16}O,X)$. The abscissa and the ordinate show the energy (MeV) of products and the yields $d^2\sigma/d\Omega dE$ (mb/sr MeV).

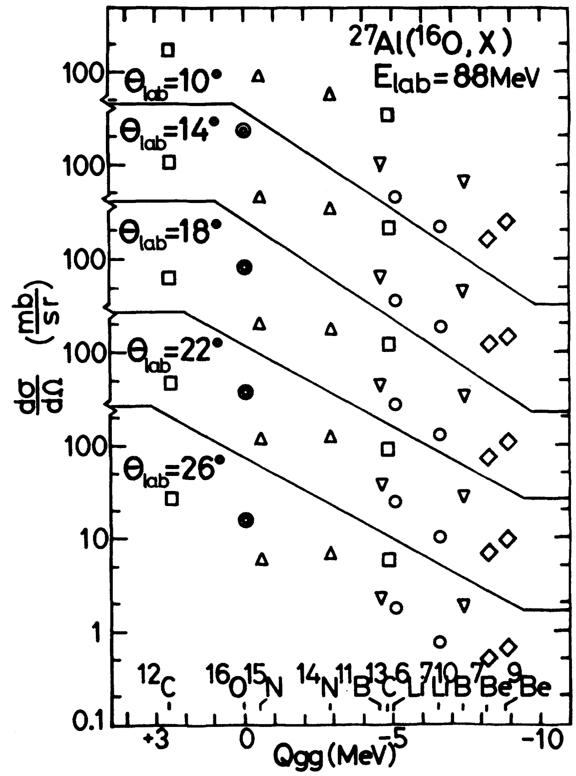

FIG. 2. Energy integrated production cross sections (mb/sr) of emitted particles in the reaction $^{27}Al(^{16}O,X)$ vs Q_{gg}, Q values for the reaction leaving both products in their ground states. The statistical errors are within the scales of points.

B. Energy integrated cross sections $d\sigma/d\Omega$

The cross sections vs Q_{gg} of production of isotopes of $3 \leq Z \leq 8$ at $\theta_{lab} = 10°$, 14°, 18°, 22°, and 26° are shown in Fig. 2. For ^{16}O, the elastic part is excluded. The yield of ^{12}C is extremely large and shows a smooth increase of $d\sigma/d\Omega$ with Q_{gg}. However, no simple Q_{gg} dependence with an equal gradient among the yields of all isotopes, as shown by Dubna group,[3] was obtained.

Due to the precautions to avoid carbon contamination on the target, the fraction of yields from carbon is considered to be negligibly small compared with that from aluminum itself. A very large yield of products with $A = 12$ was also observed by Cormier *et al.*[5] in the same system $^{27}Al + ^{16}O$ at 100 MeV.

The large carbon yield cannot be attributed merely to the effect of the separation energy of ^{12}C from ^{16}O: In the system $^{90}Zr + ^{16}O$, $^{197}Au + ^{16}O$, and $^{208}Pb + ^{16}O$ (Ref. 8) the yield of ^{12}C is not extremely large compared with those of ^{15}N and ^{13}C.

C. The relation of Q^m_{eff} vs θ_{lab}

The values of Q^m_{eff} were obtained from the Q values corresponding to the maximum yield. The uncertainties of these values are estimated, in most cases, to be within ±2 MeV. For reactions with large n, or even with small n in the case of comparable importance of QE and DI processes, the shapes of energy spectra often flatten, and the determination of Q^m_{eff} becomes more difficult. In some cases, the values of Q^m_{eff} could not be determined.

The values of Q^m_{eff} are presented as a function of θ_{lab} in Fig. 3. (A slight influence on Q^m_{eff} values by changing the lab system to a c.m. system was investigated. For instance, for ^{12}C the values of Q^m_{eff} differ by about 1 MeV at the most forward angles and are almost equal at larger angles.) Unlike in the work of $^{53}Cr + ^{14}N$ at 90 MeV with

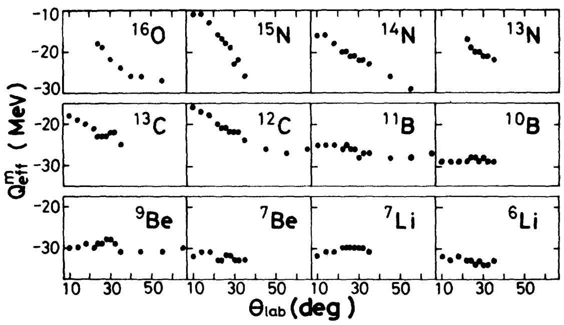

FIG. 3. The values of Q^m_{eff} (MeV) vs θ_{lab} (deg) of products in the reactions $^{27}Al(^{16}O,X)$ at 88 MeV.

$n \leqslant 5$, and with $\theta_{lab} < \theta_{gr}$,[1] where $Q^m_{eff} \simeq$ const throughout a wide range of θ_{lab}, $|Q^m_{eff}|$ increases strongly with the increase of θ_{lab} for the isotopes of O and N, is less angle dependent for isotopes of C and ^{11}B, and changes little with θ_{lab} for $10 \geqslant n \geqslant 6$. At angles $\theta_{lab} > \theta_{gr} \simeq 17°$, even for small n, Q^m_{eff} of each product tends to become constant. (The angle θ_{gr} is the grazing angle.)

These features reflect the fact that the greater the number of transferred nucleons n the more the energy becomes equilibrated, on the average, and attains a saturation for light products (e.g., $n \geqslant 5$), as is illustrated in the picture by Wilczyński.[9] On the contrary, for smaller n values, the strong variation of Q^m_{eff} with θ_{lab} in the region $\theta_{lab} \sim \theta_{gr}$ shows that the equilibration is still incomplete.

D. The relation of Q^m_{eff} vs n

The values of Q^m_{eff} are plotted as a function of n and θ_{lab} in Fig. 4. The variation of Q^m_{eff} with θ_{lab} mentioned in Sec. III C is indicated by the vertical bars.

The dotted straight line in Fig. 4 gives the values

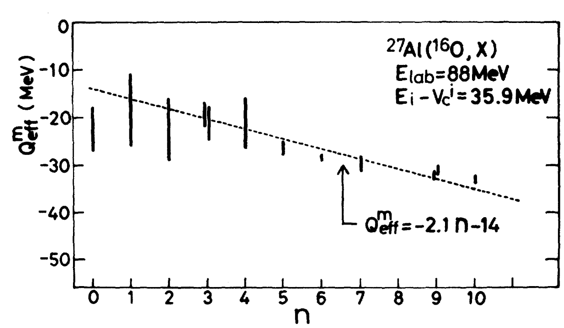

FIG. 4. The values of Q^m_{eff} (MeV) vs the number of transferred nucleons n. The dotted straight line was obtained from the predictions of Eqs. (5)–(7). The vertical bars indicate the variation of Q^m_{eff} vs θ_{lab}. (See the text.)

of Q^m_{eff} predicted by Eqs. (5), (6), and (7) for the present case: $E_i - V^i_C = 35.9$ MeV ($r_0 = 1.4$ fm). The overall trend of the experimental Q^m_{eff} values is quite well reproduced by the predicted values obtained with the other incident variables quoted above. On the contrary, Eqs. (2)–(4) do not reproduce the observed Q^m_{eff}'s. Equations (5)–(7) are thus shown to be useful in estimating the Q^m_{eff} values of unknown reactions.

The mean values of Q^m_{eff} for $n \leqslant 4$ change little with n, but much with θ_{lab} and a deviation from the straight line to both sides is observed. Because of the presence of the QE part, one should be careful in determining Q^m_{eff} at forward angles. An important deviation towards larger $|\beta'|$ was previously observed in the case of inelastic scattering, $n=0$, as in the case of Ni + ^{16}O at 96 MeV (Ref. 4) and $^{27}Al + ^{16}O$ at 100 MeV (Ref. 5), but their angular dependence was not so widely studied.

Our Eqs. (2)–(4) for QE reactions and (5)–(7) for DI reactions were obtained experimentally under

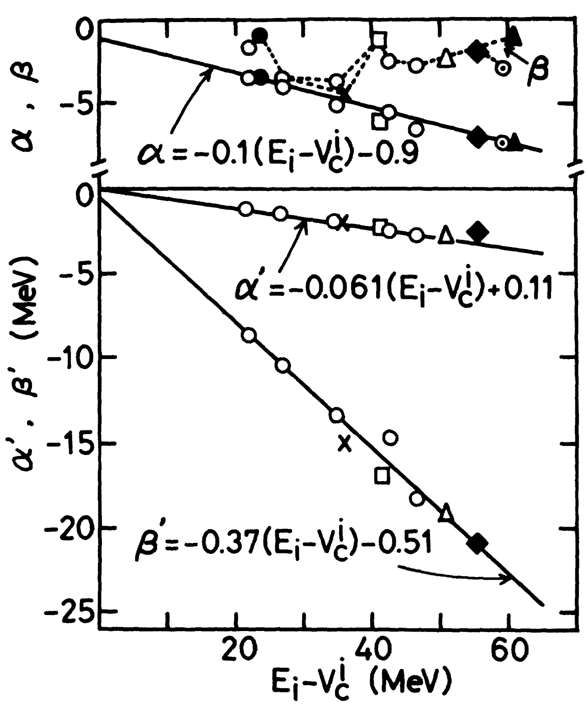

FIG. 5. The coefficients α, β, α', and β' (MeV) in Eqs. (2)–(7) for various reactions vs the effective incident energy, $E_i - V^i_C$ (MeV). The data shown are the results of reactions at various energies. O: $^{52,53}Cr + ^{14}N$ (Ref. 1), □: $^{92-100}Mo + ^{14}N$ (Ref. 1), ●: $^{90}Zr + ^{14}N$ (Ref. 1), ◆: $^{232}Th + ^{22}Ne$ (Ref. 11), ▲: $^{232}Th + ^{15}N$ (Ref. 11), ⊙: $^{26}Mg + ^{16}O$ (Ref. 12), Δ: $^{208}Pb + ^{16}O$ (Ref. 8) and present results. In the present results, data marked × are obtained to fit the mean data for transfer reactions $n > 0$.

the assumptions that (i) reactions proceed via the two-body reaction process $A+a \to b+B^*$ so that Eq. (1) holds, and (ii) heavy residual nuclei are highly excited and emit light particles successively, whereas light products are not excited. The available data giving rise to Eqs. (2)–(7) were found in the energy range $20 \leq E_i - V_C^i \leq 60$ (MeV). As the bombarding energy becomes high, i.e., as these conditions break down, there should be the limit of validity of our "universal" relations.

Gelbke *et al.*[8] compared their values of $Q_{\rm eff}^m$ of ^{208}Pb + ^{16}O at 140 MeV ($E_i - V_C^i = 50.1$ MeV) with Eqs. (2)–(4) and concluded that their data deviate from our predicted values. However, including Eqs. (5)–(7), the majority of their data were reproduced, except those of ^{13}N and ^{11}C (see Fig. 5).

Comparing with $Q_{\rm eff}^m$ the data of the reactions ^{208}Pb + ^{16}O at 315 MeV ($E_i - V_C^i$) = 213 MeV) by the same authors,[8] they claim that the general trend of isotopes of N and C ($1 \leq n \leq 4$) is rather better

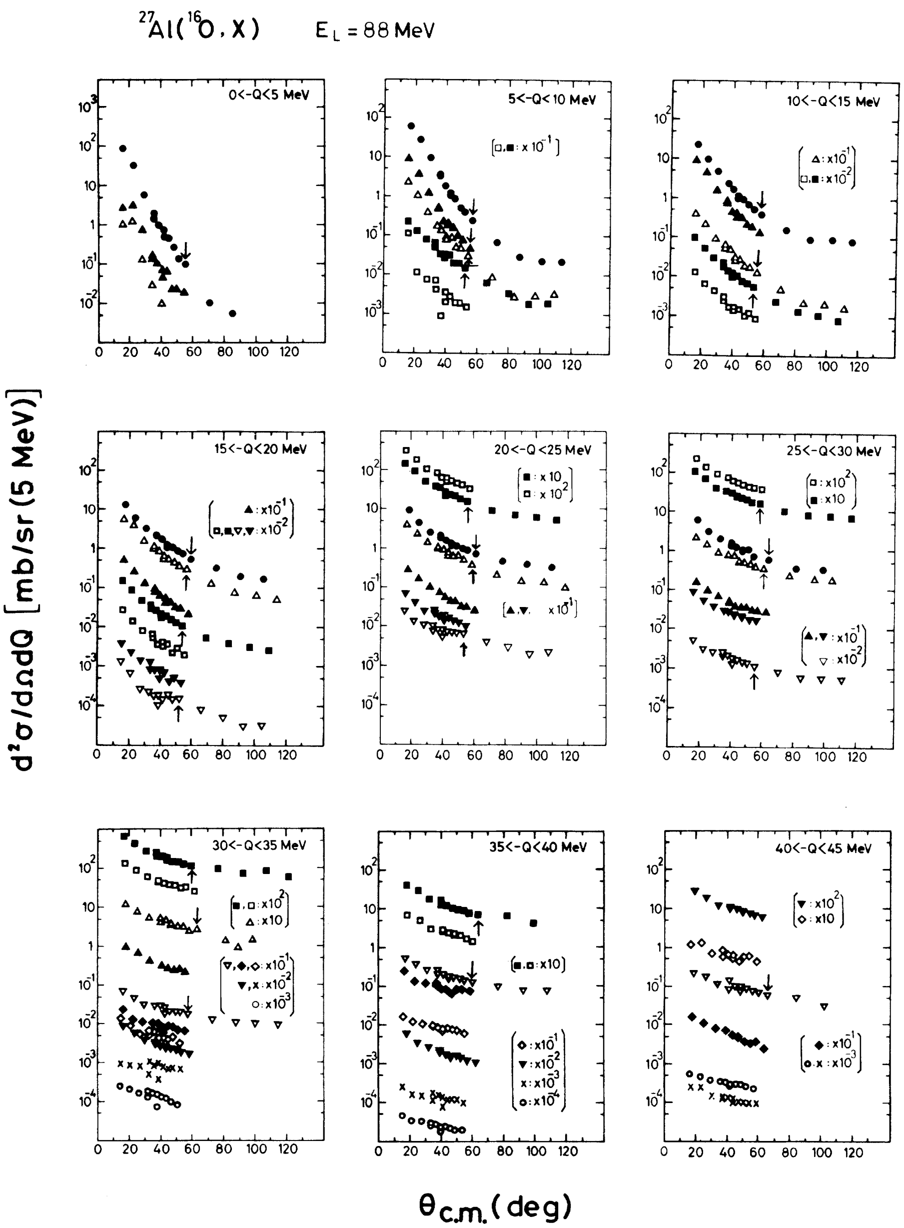

FIG. 6. Angular distribution $d^2\sigma/d\Omega dQ$ of products from the reactions ^{27}Al(^{16}O,X) at 88 MeV in the 5 MeV intervals of Q values [mb/sr 5 (MeV)]. ●: ^{16}O, ▲: ^{15}N, △: ^{14}N, □: ^{13}C, ■: ^{12}C, ▼: ^{11}B, ▽: ^{10}B, ◆: ^{9}Be, ◇: ^{7}Be, ×: ^{7}Li, ○: ^{6}Li.

reproduced by another simple relation,

$$Q_{\rm eff}^{m} = -\frac{nm}{M_a}(E_i - V_C^i)\,, \qquad (9)$$

which is valid for the case of $M_A \gg M_a$ and $M_a \gg\gg nm$, where m is the mass of the nucleon.[2] The data at extremely high energies seem to be reproduced by this *a priori* comprehensive relation. However, the majority of Gelbke's data deviate from Eq. (9) and are still better fitted with our Eqs. (2)–(4).

In a recent experiment of Fukuda *et al.*[10] on ^{93}Nb + ^{14}N at 159 MeV ($E_i - V_C^i = 93.0$ MeV), the data for $n \leq 5$ are well fitted using QE Eqs. (2)–(4). Also at 209 MeV ($E_i - V_C^i = 136.7$ MeV), some of their data for $1 \leq n \leq 4$ are rather well fitted by QE Eqs. (2)–(4); however, the data with $n \geq 5$ are not well fitted with DI Eqs. (5)–(7) at 209 MeV.

We can conclude that Eqs. (2)–(4) and (5)–(7) are valid for reactions at least in the range $20 \leq E_i - V_C^i \leq 60$ (MeV) and probably up to higher energies.

In Fig. 5 the relations of α, β, α', and β' vs $E_i - V_C^i$ are shown,[2] including the present and some old and recent data.[1,8,11,12] The value of β' of the present results with $n \leq 4$ was obtained from the mean values shown in Fig. 4.

E. Angular distribution $d^2\sigma/d\Omega dQ$ of reaction products as a function of Q values

Angular distributions $d^2\sigma/d\Omega\, dQ$ of isotopes of O, N, C, B, Be, and Li are shown in Fig. 6 in energy intervals of 5 MeV in Q values, from $0 < -Q < 5$ to $45 < -Q < 50$ MeV. At large angles, i.e., $\theta_{\rm lab} > 35°$, the identification of A being incomplete, the data beyond the angles indicated by arrows in each figure are obtained assuming that O, N, C, and B data be attributed to ^{16}O, ^{14}N, ^{12}C, and ^{10}B, respectively, and normalized at the points of the arrows.

Almost all the angular distributions are well reproduced by a form

$$\sigma(\theta, Q) = A(Q)\exp[-\mu(Q)\theta]/\sin\theta \qquad (10)$$

where θ are c.m. angles. Also in Fig. 7, some examples of $d\sigma/d\theta$ are given showing clearly their exponential form.

It is pointed out by Galin[6] and by Lefort and Ngô[7] that for reactions with small modified Sommerfeld parameters η', many reactions show the relation $d\sigma/d\theta \propto \exp(-\mu\theta)$ [e.g., Ni+Ar(280 MeV), $\eta' = 39$]. The value of $\eta' = 8.7$ in the present study.

An overall feature of angular distributions similar to the present case is shown in the same reactions, ^{27}Al + ^{16}O at 90 ($\eta' = 8.5$) and 100($\eta' = 7.9$) MeV, by Cormier *et al.*,[5] although no detailed discussions are made about the coefficients of exponential forms.

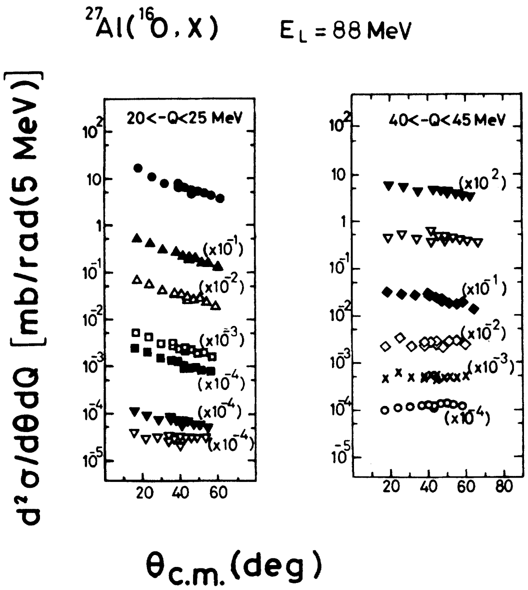

FIG. 7. Some examples of angular distributions $d^2\sigma/d\theta dQ$ [mb/rad 5 (MeV)] of products from the reaction ^{27}Al(^{16}O,X) at 88 MeV in the 5 MeV intervals of Q values. ●: ^{16}O, ▲: ^{15}N, △: ^{14}N, □: ^{13}C, ■: ^{12}C, ▼: ^{11}B, ▽: ^{10}B, ◆: ^{9}Be, ◇: ^{7}Be, ×: ^{7}Li, O: ^{6}Li.

Comparing the form of the present angular distributions with other data, the overall energy-integrated data of ^{208}Pb + ^{16}O at 315 MeV ($\eta' = 27$) (Ref. 8) resemble our angular distributions of exponential forms. On the contrary, for the data of the same reactions at lower energy, 140 MeV ($\eta' = 55$), the form of angular distributions is different, showing bell-shaped types, for products of N, C, and B.

The angular distributions of energy integrated cross sections in the present study reveal no bell-shaped form, but have a shape similar to that given by Eq. (10).

The values of A and μ are shown in Table I. For small $|Q|$, e.g., $|Q| < 15$ MeV, the values of μ are larger for smaller n and smaller for larger n. However, for larger $|Q|$, e.g., $|Q| \geq 15$ MeV, the values of μ are almost the same throughout a wide range of n, at least $0 \leq n \leq 5$. With the further increase of n, e.g., $n \geq 6$ and $|Q|$, e.g., $|Q| > 40$ MeV, the form of the angular distribution tends gradually to ~$1/\sin\theta$. Indeed, for $\mu < 0.5$, say, the form of Eq. (10) cannot be well distinguished from that of ~$1/\sin\theta$, characteristic of angular distributions of products in complete fusion (CF) reactions. Although the angular range of the angular distribution does not attain sufficient backward angles, $d\sigma/d\theta$ as shown in Fig. 7 is quite flat for large $|Q|$, whereas it is of exponential form for small $|Q|$.

These remarkable features reflect the fact that,

TABLE I. Coefficients A (mb/sr) and μ (rad^{-1}) of the angular distributions $\sigma(\theta,Q)=A\exp(-\mu\theta)/\sin\theta$ for various reaction products, in energy intervals of 5 MeV in Q values, and θ_d (deg), the decay angle of dinuclear systems with lifetimes τ (10^{-23} sec) rotating with angular velocity $\omega=\theta_d/\tau=3.4\times10^{21}$ (sec^{-1}). (See the text.)

$-Q$ (MeV)		^{16}O	^{15}N	^{14}N	^{13}C	^{12}C	^{11}B	^{10}B	^{9}Be	^{7}Be	^{7}Li	^{6}Li
0–5	μ	8.7										
	θ_d	6.6										
	A	250										
	τ	3.4										
5–10	μ	6.7	6.3	4.9	4.0	2.6						
	θ_d	8.6	9.1	12	14	22						
	A	130	13	2.1	0.30	1.2						
	τ	4.4	4.7	6.0	7.4	11						
10–15	μ	4.3	4.7	3.5	2.4	2.8						
	θ_d	13	12	16	24	20						
	A	21	9.0	2.9	0.63	5.3						
	τ	6.8	6.3	8.4	12	11						
15–20	μ	2.8	2.9	2.7	2.1	2.3	1.8	1.6				
	θ_d	20	20	21	27	25	32	36				
	A	8.2	3.2	3.2	1.2	7.5	1.6×10^{-1}	3.6×10^{-2}				
	τ	11	10	11	14	13	16	18				
20–25	μ	1.8	1.9	1.7	1.4	1.6	1.1	<0.5				
	θ_d	32	30	34	41	36	52					
	A	3.9	1.4	1.7	1.1	6.1	2.3×10^{-1}	5.7×10^{-2}				
	τ	16	15	17	21	18	27					
25–30	μ	1.6	9.3×10^{-1}	1.1	1.2	1.1	8.2×10^{-1}	5.0×10^{-1}				
	θ_d	36	62	52	48	52	70	110				
	A	2.9	5.9×10^{-1}	8.9×10^{-1}	1.0	4.0	2.9×10^{-1}	1.6×10^{-1}				
	τ	18	32	27	25	27	36	59				
30–35	μ		9.1×10^{-1}	7.0×10^{-1}	7.4×10^{-1}	9.2×10^{-1}	8.1×10^{-1}	<0.5	<0.5	<0.5		
	θ_d		63	82	77	62	71					
	A		4.2×10^{-1}	4.7×10^{-1}	4.9×10^{-1}	2.6	3.0×10^{-1}	2.0×10^{-1}	5.4×10^{-2}	3.5×10^{-2}		
	τ		32	42	40	32	36					
35–40	μ				6.8×10^{-1}	1.1	7.7×10^{-1}	<0.5	<0.5	<0.5		<0.5
	θ_d				84	52	74					
	A				2.8×10^{-1}	1.9	2.3×10^{-1}	1.9×10^{-1}	6.4×10^{-2}	4.4×10^{-2}		1.3×10^{-1}
	τ				43	27	38					
40–45	μ						1.0	<0.5	9.6×10^{-1}	<0.5	<0.5	<0.5
	θ_d						57		60			
	A						1.5×10^{-1}	9.0×10^{-2}	7.5×10^{-2}	4.0×10^{-2}	8.4×10^{-2}	1.5×10^{-1}
	τ						29		31			
45–50	μ										<0.5	<0.5
	θ_d											
	A										4.0×10^{-2}	1.1×10^{-1}
	τ											

for small $|Q|$, i.e., in QE collisions, the behavior of heavier and lighter products is different. For larger $|Q|$, i.e., in DI collisions, all the relevant products are equally relaxed, although incomplete, or suffer an equal frictional force[13] and behave in the same fashion, despite the difference of Z and A. For still larger $|Q|$ and n, the energy relaxation and equilibration of the system become more complete and as the angular distribution $\sim 1/\sin\theta$ shows, the reaction proceeds via the CF process.

Thus the results of angular distribution as a function of Q, $d^2\sigma/d\Omega\, dQ$, in the present study reveal clearly a continuous evolution QE $\to$ DI $\to$ CF as functions of n and Q.

F. Estimation of lifetimes of intermediate systems

Several models are presented predicting the angular distributions of the form of Eq. (10), e.g., either in terms of nuclear friction[13] or by a simple classical model of a rotating dinuclear system,[8,14] with a mean lifetime τ and an angular velocity ω.

According to the latter model, the angular distribution of a decaying product from such a system is given by

$$\frac{d\sigma}{d\Omega} = \text{const} \times \frac{1}{\sin\theta}\{\exp(-\theta/\omega\tau) + \exp[-(2\pi - \theta)/\omega\tau]\} . \tag{11}$$

In Eq. (11), if τ is very large, i.e., $\tau \gg 2\pi/\omega$, the angular distribution has the form

$$\frac{d\sigma}{d\Omega} = \text{const} \times \frac{1}{\sin\theta} , \tag{12}$$

which is expected for a complete fusion reaction.

On the contrary, if τ is very small, i.e., $\tau \ll 2\pi/\omega$, the angular distribution is strongly forward peaked and has a form of

$$\frac{d\sigma}{d\Omega} = \text{const} \times \frac{1}{\sin\theta} \exp(-\theta/\theta_d) , \tag{13}$$

where $\theta_d = \omega\tau$ is called a "decay angle." The angular distributions given by Eq. (10) correspond to the latter case.

In order to get the lifetime for each decaying product, at certain Q values, their angular velocities are estimated by

$$\omega = v_i/R_i , \tag{14}$$

$$E_i - V_C^i = \tfrac{1}{2}\mu_i v_i^2 , \tag{15}$$

where μ_i and v_i are the reduced mass and the relative velocity in the incident channels. We assume here a grazing collision between two spherical balls with distance of closest approach R_i. In the present case, using $R_i = R_A + R_a = 7.7$ fm, one obtains $\omega = 3.4 \times 10^{21}$ sec^{-1}. The values of θ_d and τ are shown in Table I, together with those of μ and A mentioned above. Lifetimes thus obtained are in the range $\tau = (0.3-4) \times 10^{-22}$ sec.

These values are roughly compatible with the results of the case of ^{208}Pb + ^{16}O at 315 MeV,[8] but seem to be short compared with the "transit time" of the projectile $T = 2R_i/v_i = 6 \times 10^{-22}$ sec. In actual grazing reactions, the interaction length will be much less than $2R_i$.

Moreover, ω in Eq. (14) is given by v_i and R_i, which should be modified in the course of realistic collisions. If

$$\omega_f^m \simeq v_f^m/R_f \tag{16}$$

is used,[1] instead of ω, where v_f^m and R_f are the most probable velocity and the distance of closest approach in the exit channel, respectively, the lifetime increases by 50–200%.

Although the estimate of lifetimes given above is very rough, the values obtained for small n and $|Q|$ are comparable to the interaction time of direct reactions, while they are much longer for large n and $|Q|$.

IV. CONCLUSION

The emitted particles from the reactions ^{27}Al + ^{16}O at 88 MeV are identified both in Z and A. Although the bombarding energy is low, the overall features of the products resemble that of much heavier systems at much higher energies, showing dominance of DI to QE and the exponential angular distributions.

The most probable effective Q values, Q_{eff}^m, for wide ranges of n are well reproduced by the empirical "universal equations" (5)–(7) predicted for DI collisions, despite some variations for $n \le 4$. Therefore Eqs. (2)–(4) and (5)–(7) are useful to predict the Q_{eff}^m values as far as two body reactions play the main role, at least in the energy range $20 \le E_i - V_C^i \le 60$ (MeV) and probably up to higher energies.

The angular distribution in Q-value intervals of 5 MeV shows the shape of $\sigma(\theta, Q) \propto \exp(-\mu\,\theta)/\sin\theta$, the form observed in much higher energy data. The variation of μ as a function of n and Q reveals clearly a gradual evolution of reaction mechanisms QE $\to$ DI $\to$ CF.

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