C + ^{19}F reactions at E_{lab} = 25–72 MeV

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Thick targets of natural carbon were bombarded with ^{19}F ions at E_{lab} = 25–72 MeV. Residual activities were counted off-line with a Ge(Li) detector. γ rays from the decay of ^{7}Be, ^{22}Na, ^{24}Na, ^{27}Mg, ^{28}Mg, ^{28}Al, and ^{29}Al were observed, and yield curves were determined. Yield curves calculated with the Blann-Plasil statistical evaporation code were compared with the experimental results and found to agree well in most cases.

[NUCLEAR REACTIONS C + ^{19}F, E = 25–72 MeV; measured activation yields of ^{7}Be, ^{22}Na, ^{24}Na, ^{27}Mg, ^{28}Mg, ^{28}Al, and ^{29}Al. Natural targets, Ge(Li) detector.]

I. INTRODUCTION

In order to understand the mechanisms of heavy-ion nuclear reactions which can involve compound system formation, it is helpful to compare experimental cross sections for formation of many residual nuclei formed in a reaction with theoretical values. Cross sections for reactions induced by ^{16}O ions on targets in the nickel region have recently been measured by several groups[1–4] and compared with cross sections calculated with the Blann code, which is based on the statistical model.[5] ^{14}N and ^{16}O induced reactions on several nuclei in the A = 12 to 30 region have been studied in a similar manner.[6] In the present work, ^{19}F induced reactions on ^{12,13}C have been studied. Preliminary results of this work have been reported in Ref. 7.

II. EXPERIMENTAL TECHNIQUES

The target material used in the investigation was ultrahigh purity, natural carbon in the form of graphite discs ~2 mm thick, which is sufficient to stop all incident ions and residual nuclei formed in the bombardment. This technique enhanced the detection of low-yield products and reduced bombarding time. Targets were irradiated in a simple target assembly which also served as a Faraday cup.

Singly-charged fluorine ions were produced in a Heinicke direct extraction source[8] and accelerated in the Florida State University super FN tandem Van de Graaff accelerator. After stripping in a carbon foil, the positive particles in +4 to +7 charge states were analyzed and focused on target. Beam currents on target ranged from 100 nA to 2.5 μA, and total charges up to 2500 μC were collected. Fluctuations in beam intensity were recorded and used to calculate corrections in the yield of short-lived products.

Following irradiation, targets were removed to an off-line 20 cm^3 Ge(Li) detector having 2.3 keV resolution (at 1.33 MeV). Counting commenced 2.5 min after the end of bombardment and was continued for one month. As each count was completed, it was dumped into an EMR 6130 computer for analysis.

III. STATISTICAL MODEL CALCULATIONS

Statistical model (SM) calculations were made using the code developed by Blann and Plasil.[5] This code is based on the Weisskopf-Ewing (WE) formula,[9] which gives the probability for emitting a particle ν with channel energy between ϵ and $d\epsilon$,

$$P_\nu(\epsilon)d\epsilon = \frac{(2s+1)_\nu \mu_\nu \epsilon \sigma_\nu(\epsilon)\rho(E_f)d\epsilon}{\sum_{\nu=1}^{n}(2s+1)_\nu \mu_\nu \int_0^\infty \epsilon \sigma_\nu(\epsilon)\rho(E_f)d\epsilon} . \quad (1)$$

In Eq. (1), s is the channel spin, μ the mass, $\sigma_\nu(\epsilon)$ the inverse cross section, and $\rho(E_f)$ the level density of the residual nucleus. The summation extends over all channels n.

Entrance-channel cross sections and inverse cross sections were calculated by a standard optical model program[10] with parameters from Ref. 11. Experimental masses,[12] with pairing energies,[13] were used; a level density parameter of $A/8$ was used in all calculations. A more com-

TABLE I. Product nuclides and their decay characteristics.

Nuclide	$T_{1/2}$	E_γ (MeV) [a]	Branching ratio (%) or relative intensity	Reference	Complementary reaction products [b]
^{7}Be	53.5 day	0.477	10.3	15	^{24}Na(^{25}Na)
^{22}Na	2.62 yr	0.511(m_0c^2)	180	16	^{9}Be or $2\alpha n(2\alpha 2n)$
		1.275	90	16	
^{24}Na	15.0 h	1.369	99	16	^{7}Be or $\alpha 2pn(2\alpha)$
		2.754	99	16	
^{27}Mg	9.46 min	0.844	71	16	$3pn(\alpha p)$
		1.014	29	16	
^{28}Mg	21.07 h	0.95	35.9	16	$3p(3pn)$
		1.35	54	16	
		1.78	100	16	
^{28}Al	2.259 min	1.78	100	16	$2pn(\alpha)$
^{29}Al	6.52 min	1.28	90	16	$2p(2pn)$
		2.43	6.5	16	

[a] Only those γ rays that were used in calculating yields are listed.
[b] From ^{12}C + ^{19}F; ^{13}C + ^{19}F products are given in parentheses.

plete description of this type of calculation is given elsewhere.[1,5,6]

To compare the calculated results with the experimental ones, we converted the calculated cross sections to yields. The yield of a product is related to the cross section by

$$Y = \sum_{i=1}^{A} \sum_{j=E_t}^{E} a_i \sigma_{ij} R_j \ . \qquad (2)$$

The summation over i extends over all target isotopes A, while the summation over j extends from the threshold energy to the bombarding energy; σ_{ij} is the cross section in an energy interval, and R_j is the range[14] in the interval.

IV. RESULTS

The observed product nuclei, along with their decay characteristics, are listed in Table I. Yield curves for these nuclei are shown in Figs. 1 and 2. The solid lines are drawn through the data to show the shapes of the excitation functions. The dashed lines are SM calculations using $I = I_{rig}$ as the moment of inertia, and the dotted lines are SM calculations using $I = 0.5 I_{rig}$. It should be noted that these SM calculations are unnormalized and that I is the only parameter that was changed. In Fig. 1, no SM calculations for ^{7}Be or ^{28}Mg are shown. Since the program is set up to handle only n, p, and α emission, the cross section for ^{7}Be emission could not be calculated. Since ^{28}Mg results from the emission of three protons, the calculation of its yield was more sensitive to proton optical model parameters than the calculation of the other products shown. Even in the case of ^{27}Mg, the emission of a neutron in addition to the three protons makes the calculation less sensitive to the proton optical model parameters.

V. DISCUSSION

As is evident from Figs. 1 and 2, agreement between the measured and the calculated yields for ^{27}Mg and ^{28}Al is good, with the measured values indicating that the moment of inertia used in the calculation should be between $0.5 I_{rig}$ and I_{rig}. In the case of ^{29}Al, the experimental yields are below the calculated values even for $0.5 I_{rig}$, while for ^{22}Na and ^{24}Na the experimental yields are above the range of calculated values.

The WE formula used in these calculations is based on an s-wave assumption, with subtraction of rotational energy serving as an approximation for competition by γ ray deexcitation. It was, therefore, necessary to adjust one of the parameters in the calculation in order to reproduce the experimental data to within a factor of 10. Since the moment of inertia I was used for this purpose, I should be construed as a parameter that is indicative of the effects of angular momentum rather than as a physical quantity. The values assigned to I were, however, kept between $0.5 I_{rig}$ and I_{rig}, values which are physically meaningful and which have previously given good fits to high-yield products.[1-4,6]

The effects of angular momentum on multiple particle emission are simulated by lowering the value of I, which moves the yrast line towards lower partial wave interactions. Since this effect is cumulative for each emission, excitation curves for products formed by emission of three or four nucleons should be better fitted by the calculation than excitation curves for products

that are only one or two nucleons removed from the compound nucleus. The calculations for ^{27}Mg and ^{28}Al do indeed fit better than the calculations for ^{29}Al with a value of $0.5I_{rig}$. A comparable fit in that case can be achieved only by further reduction of I. The evaporation of α particles differs from nucleon evaporation in that it is the favored channel for removing angular momentum.[1,17-19] Reducing the population of these high-spin states by γ decay (i.e., with a small value of I) would result in low yields for products formed by emission of α particles.[17] Therefore better agreement for α emission products, such as ^{22}Na (emission of $2\alpha 2n$ from ^{12}C + ^{19}F) and ^{24}Na (emission of 2α from ^{13}C + ^{19}F), can be obtained by use of $I > I_{rig}$. It appears, then, that the discrepancies between experimental and calculated excitation functions can be removed by simulating the effects of angular momentum on the reaction processes through the appropriate adjustment of I in the calculations.

The possibility that other channels or mechanisms are involved in the formation of low-yield products such as ^{22}Na and ^{24}Na cannot be completely ruled out. The calculation for ^{24}Na assumed that it was formed by the reaction ^{13}C(^{19}F, 2α)^{24}Na throughout the incident energy range and, in addition, by ^{12}C(^{19}F, $\alpha 2pn$)^{24}Na at higher incident energies. The poorer fit at higher energies probably reflects the opening of additional exit channels, e.g., ^{12}C(^{19}F, ^{7}Be)^{24}Na. The evaporation of complex particles is not taken into account in the program. It has been shown that n, p, and α evaporations account for about 90% of the flux from the compound nucleus.[5] Thus the remaining 10% of the exit flux is probably due to evaporation of complex particles which could result in enough added yield to bring the calculations into better agreement with the data if it were included, since both ^{22}Na and ^{24}Na are low-yield products.

Another possible cause for the underestimation of the Na yields by the program could be the participation of more than one mechanism in the formation of these nuclei. The formation of ^{22}Na is the clearest case where a direct reaction is also a possibility; it can be formed if ^{19}F picks up a ^{3}He cluster from either ^{12}C or ^{13}C. This requires that ^{12}C can be represented as ^{9}Be + ^{3}He and ^{13}C as ^{10}Be + ^{3}He. In reactions on thin ^{13}C enriched targets, almost all the ^{22}Na has been shown to come from the ^{12}C component.[20] However, a similar reaction ^{26}Mg(^{12}C, ^{9}Be)^{29}Si has been found to have a very small cross section.[21] Formation

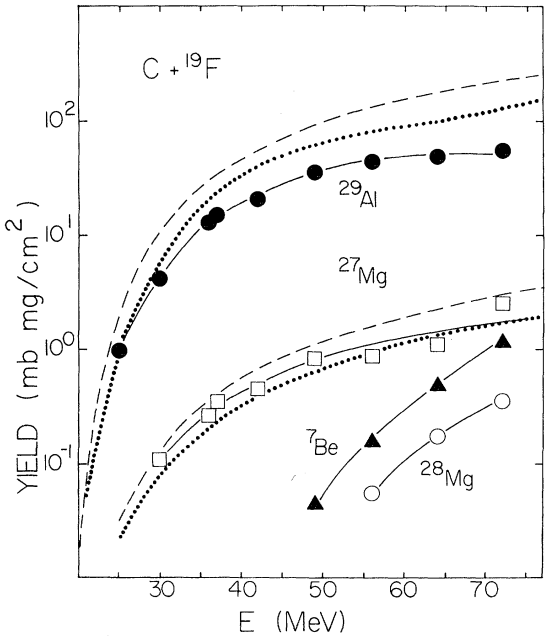

FIG. 1. C + ^{19}F thick target yields for ^{29}Al, ^{27}Mg, ^{7}Be, and ^{28}Mg. The solid line connecting data points is drawn to show the shape of the excitation function; (---) are SM calculations using $I = I_{rig}$; (...) are SM calculations with $I = 0.5I_{rig}$. Error bars representing counting statistics are smaller than the data points.

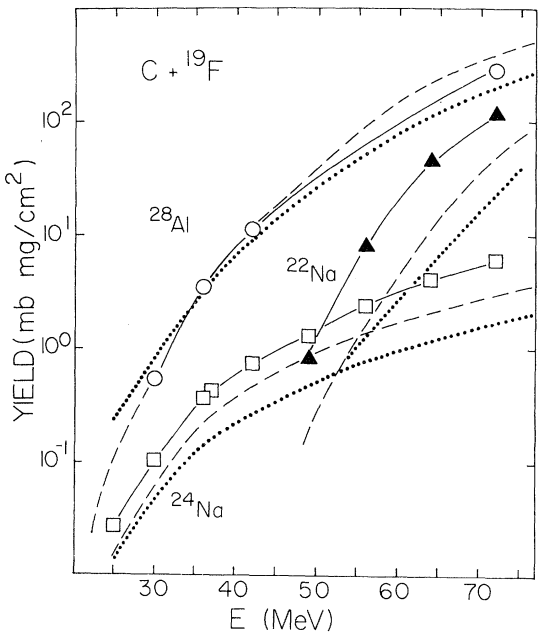

FIG. 2. C + ^{19}F thick target yields for ^{28}Al, ^{22}Na, and ^{24}Na. The solid line connecting data points is drawn to show the shape of the excitation function; (---) are SM calculations using $I = I_{rig}$; (...) are SM calculations with $I = 0.5I_{rig}$. Error bars representing counting statistics are smaller than the data points.

of ^{24}Na or ^{7}Be would require at least a five-particle transfer and is even less likely. Another possibility is a collective (fission) mechanism, i.e., a mechanism proceeding through a transition state. Because the effect of angular momentum is to increase the probability for emission of large particles that can carry away appreciable amounts of angular momentum, a collective-type process is enhanced in heavy ion reactions in the tail of the spin distribution in the compound nucleus.[6] Although the amount of these high spin states is small compared with the total reaction cross section if it proceeds through selected exit channels, inclusion of this contribution to the total yield might be sufficient to produce better agreement.

Because of the assumptions in the Blann-Plasil code, no definite conclusions about the mechanisms for formation of ^{22}Na and ^{24}Na can be made. Because adequate fits may be obtained for ^{28,29}Al, ^{27}Mg, and ^{22,24}Na by changing I, it is reasonable to conclude that these products are the result of simple evaporations from the compound nucleus. A similar conclusion has recently been reached by Pühlhofer *et al.* for C + F reactions in the $A = 21-30$ mass range at similar bombarding energies.[22]

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