Nonequilibrium Population of Magnetic Substates and Excitation-Energy Division in the Decay of an Orbiting Complex

A. Ray,[a] D. D. Leach, and R. Vandenbosch
Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195

K. T. Lesko[b]
Argonne National Laboratory, Argonne, Illinois 60439

and

D. Shapira
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 2 May 1986)

γ-ray angular correlations have been measured for the strongly damped reaction $^{12}C(^{28}Si,^{12}C)^{28}Si$ at $\theta_{c.m.} = 180°$ for $E_{c.m.} = 42.7$ and 33.7 MeV. The ^{12}C 4.44-MeV, $J^{\pi} = 2^+$ state is found to be produced almost exclusively in the $m = 0$ magnetic substate with respect to the beam axis. Comparison of singles and coincidence yields shows that the ^{12}C comes out in its ground state most of the time ($\approx 70\%$) resulting in the entire excitation energy ≈ 15–20 MeV appearing in ^{28}Si. These results can be reproduced by a constrained phase-space calculation.

PACS numbers: 25.70.Cd, 25.70.Lm

Recent backward-angle measurements of strongly damped reaction products from the $^{28}Si + {}^{12}C$,[1] $^{20}Ne + {}^{12}C$,[2] and $^{16}O + {}^{27}Al$[3] reactions have indicated the formation of a long-lived orbiting complex. A lifetime comparable to or larger than the rotation time is implied by the $1/\sin\theta$ angular distribution of these binary reaction products. Comparison of recent results[4] on the relative yields in different exit channels for the $^{24}Mg + {}^{16}O$ reaction and the $^{28}Si + {}^{12}C$ reactions demonstrates an entrance-channel effect in these reactions and confirms that a noncompound process is dominant in these reactions.

We have performed a new experiment aimed at clarifying the mechanism involved in these reactions and the nature of the intermediate state involved. We have studied the population of magnetic substates, the excitation-energy division, and the angular momentum partition for the strongly damped component of $^{28}Si + {}^{12}C$ inelastic scattering.

We report here on a particle-γ coincidence measurement to determine whether the magnetic substate population and the ratio of the yield of ^{12}C(g.s.) to that of ^{12}C(4.44 MeV) is determined by phase-space considerations or enhanced by the structure of the orbiting complex. We used reverse kinematics and measured the angular correlation of 4.44-MeV γ rays in coincidence with carbon particles detected at $\theta_{lab} = 0°$. We also recorded the carbon singles spectra. From this and the angle-integrated yields of 4.44-MeV γ rays we obtained the ratio of the ^{12}C(4.44 MeV) to ^{12}C(g.s.) yields.

A natural carbon target was bombarded by 112.3- and 142.7-MeV ^{28}Si beams from the Argonne National Laboratory superconducting linac. The beam was stopped by a tantalum foil mounted in front of a gas-ΔE, solid-state-E telescope placed at 0°. Particle identification techniques were used to identify carbon particles which were transmitted through the tantalum foil. An inch-thick lead shroud with openings at both ends was placed around the tantalum foil to absorb low-energy γ rays produced in the tantalum foil. An array of three 5-in. × 6-in. NaI detectors was placed in the backward hemisphere at laboratory angles of 140°, 123°, and 90°. The γ-ray, time-difference, and particle spectra were recorded event by event. The efficiencies of the NaI detectors at 4.44 MeV were obtained by bombardment of a carbon target with a proton beam and use of the measured target thickness and the integrated charge and known differential γ-ray cross sections[5] for production of 4.44-MeV γ rays.

Figure 1 shows the NaI spectra in coincidence with carbon particles at $E_{c.m.} = 42.7$ MeV for $-11.6 \leq Q \leq 0$ MeV. We observe the 1.78- and 2.84-MeV γ-ray lines from the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in ^{28}Si and the Doppler-shifted 4.44-MeV γ rays from ^{12}C at all angles. Figure 2 shows the angular correlation of 4.44-MeV γ rays in the rest frame of the ^{12}C nucleus for the region $-20.0 \leq Q \leq -11.6$ MeV. The errors were obtained by our adding in quadrature the statistical error and the error in the relative gamma detector efficiencies. We do not know if the bumps that we see around 4 MeV in the gamma-ray spectra are entirely due to Doppler-shifted 4.44-MeV γ rays which come from the $2^+ \rightarrow 0^+$ transition in ^{12}C. There are possible γ-ray transitions in ^{28}Si and ^{24}Mg in this energy region and the energy resolution was not good enough to

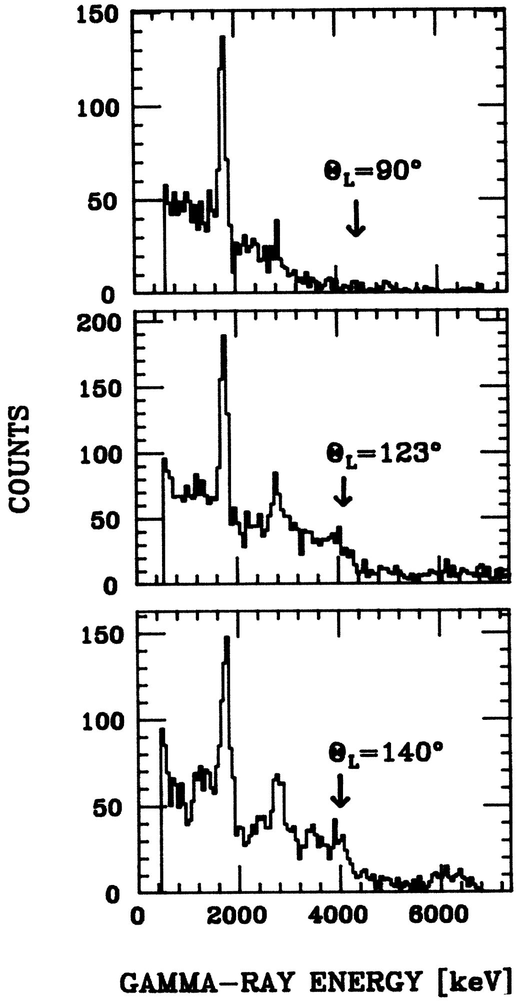

FIG. 1. Coincidence NaI spectrum obtained at 140°, 123°, and 90° for the reaction $^{28}\mathrm{Si}+{}^{12}\mathrm{C}$ at $E_{\mathrm{c.m.}}=42.7$ MeV and for $-11.6\leq Q\leq 0.0$ MeV.

separate them. However these are $6^+\rightarrow 4^+$ and $3^+\rightarrow 2^+$ transitions and not $2^+\rightarrow 0^+$ transitions. The expected angular distributions from $6^+\rightarrow 4^+$ and $3^+\rightarrow 2^+$ transitions are very different from the observed angular distribution and their contributions are estimated to be less than 10%. In Fig. 2 we show three possible γ-ray angular correlation curves. These angular correlation curves are for $2^+\rightarrow 0^+$ $m=0$, $2^+\rightarrow 0^+$ $m=\pm 1$, and $2^+\rightarrow 0^+$ $m=\pm 2$ transitions, where we have taken the beam axis as the quantization axis. We find that the observed angular correlation is very similar to the $m=0$ $2^+\rightarrow 0^+$ correlation[6] $[A(\theta)=\sin^2\theta\cos^2\theta]$. The contributions of $m=\pm 1$, ± 2 magnetic substates are not more than 5%. Figure 2 also shows the angular correlation of 1.78-MeV γ rays in the rest frame of the emitting nucleus. This angular correlation is consistent with the form $A(\theta)=1-\frac{3}{8}\sin^4\theta$, implying that the 1.78-MeV γ ray is emitted as result of the deexcitation of ^{28}Si nucleus

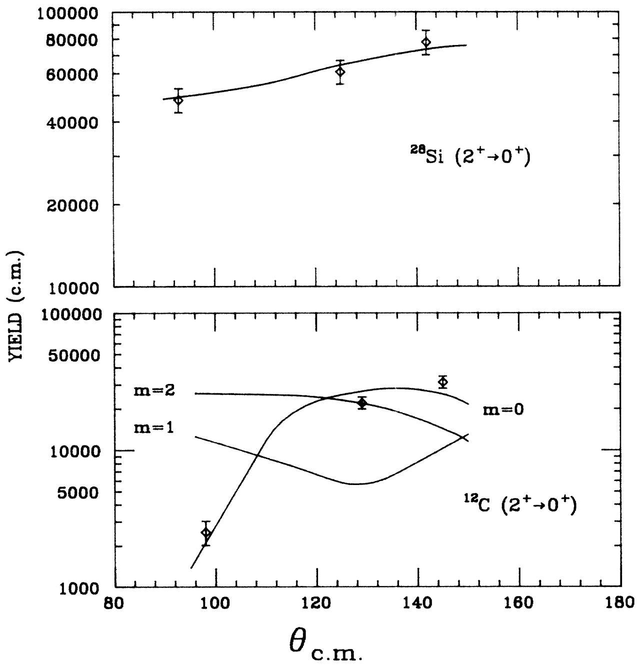

FIG. 2. The angular correlation of 1.78-MeV γ rays for $-20.0\leq Q\leq 0.0$ MeV and of 4.44-MeV γ rays for $-20.0\leq Q\leq -11.6$ MeV at $E_{\mathrm{c.m.}}=42.7$ MeV. The full curves are calculated angular correlations as explained in the text.

by a stretched $E2$ cascade.[6] We observed the same $^{12}\mathrm{C}(2^+\rightarrow 0^+)$ angular correlation at all Q-value bins and bombarding energies. The finite-solid-angle effects of the NaI detectors were also considered.

We have obtained information about the relative probabilities for formation of ^{12}C in its ground state and first excited state by the following procedure. The total number of angle-integrated 1.78-MeV γ-ray counts in the Q-value region -6.5 MeV $\leq Q\leq -2.0$ MeV was determined by the assumption that the multiplicity of the 1.78-MeV γ ray is unity in that Q-value region. Then the total number of counts in the carbon singles spectrum in the Q-value region -6.5 MeV$\leq Q\leq -2.0$ MeV was normalized to that of the total angle-integrated 1.78-MeV γ-ray counts in the same Q-value region. The same normalization factor was used at other Q-value bins at the same bombarding energy. In this way, we obtained an upper limit for the multiplicity of 4.44-MeV γ rays. We found that the upper limits of the average multiplicities of the 4.44-MeV γ rays integrated over all Q values are 0.26 and 0.20 for $E_{\mathrm{c.m.}}=42.7$ and 33.7 MeV, respectively.

The large suppression of $m\neq 0$ magnetic substates obtained from the angular correlations is very striking. The previously observed ^{12}C angular distribution implies that a long-lived intermediate is involved in this reaction. Some qualitative aspects of the reaction mechanism are fairly clear. During the reaction process, the kinetic energy of relative motion and the initial orbital angular momentum is converted into internal excitation energy of the reaction intermediate, by either collective excitation or particle exchange. Part of the initial orbital angular momentum is transferred into the internal rotational degrees of freedom. Let us consider two limiting cases regarding the nature of the reaction intermediate. If the rotational degrees of freedom are strongly coupled the reaction intermediate will rotate as a rigid body. This is the sticking limit in the terminology of deeply inelastic heavy-ion reactions. If only radial forces are present in the breakup the reaction products will come out in their $m=0$ magnetic substates, in agreement with our angular correlation results. The partition of the initial orbital angular momentum into intrinsic and final orbital components for a rigid rotation is simply proportional to the relevant moments of inertia for the dinuclear system. The initial orbital angular momenta contributing to orbiting reactions are expected to be between the l_{crit} value characterizing fusion and l_{graz} characterizing elastic scattering. An average orbiting angular momentum of about $23\hbar$ is expected at $E_{\text{c.m.}}=42.7$ MeV from the measured fusion cross section.[7] For a rigid dinuclear system approximated by spheres in contact, one expects the ^{12}C spin to be $\approx 1.6\hbar$ and the ^{28}Si to be $\approx 6.5\hbar$. The latter value is in reasonable agreement with the average value of $\approx (7-9)\hbar$ that we have deduced in a separate experiment.[8] The interpretation of the expected spin of $\approx 1.6\hbar$ (or perhaps 1.2 if a more extended dinuclear complex is assumed) is more difficult because our system is quantized. However, our qualitative expectation from this simple picture would be that ^{12}C should preferentially be formed in a 2^+ state. This is in contrast to the observation that ^{12}C is preferentially formed in its ground state.

The other limiting case we consider is that of a dinuclear system in statistical equilibrium. Such a model is actually very similar to the compound-nucleus model. We considered a dinuclear system consisting of two touching spheres in thermal equilibrium. We calculated the rotational energies of the system for all possible angular momentum couplings and from those obtained the relevant phase-space factors. The probability of population of a particular magnetic substate was obtained by multiplication of the phase-space factor by the square of the appropriate Clebsch-Gordan coefficients. We found that the ratio of the yields of the $m=\pm 1$ magnetic substates to that of the $m=0$ magnetic substate is ≈ 1.4 and the ratio of the yields of $m=\pm 2$ to that of the $m=0$ magnetic substate is ≈ 0.4. So our observation that the contributions of $m=\pm 1$, $m=\pm 2$ magnetic substates of ^{12}C are less than 5% of the $m=0$ contribution is completely in disagreement with the statistical calculation. The dinuclear statistical-model calculations or the compound-nucleus-model calculations predict a 4.44-MeV γ ray multiplicity of about 0.5 at both $E_{\text{c.m.}}=42.7$ and 33.7 MeV. The observed multiplicities are appreciably lower than these predictions.

We now consider a constrained statistical model where all the degrees of freedom are not decoupled. The ^{12}C(g.s.) to ^{12}C(4.43 MeV) cross-section ratio, integrated over various Q-value bins, is calculated with the restriction that only $m=0$ substates can be populated. The rate $R_x\,d\epsilon_x$ for emitting a particle x from an excited-state nucleus 1 (excitation energy E_1, spin J_1, parity π_1, $m_1=0$) to form a product nucleus 2 (at E_2, J_2, π_2, $m_2=0$), is given by

$$\frac{\rho_2(E_2,J_2,\pi_2)}{2\pi\hbar\,\rho_1(E_1,J_1,\pi_1)}\sum_{S=J_2-s_x}^{J_2+s_x}\sum_{l=J_1-S}[(J_2,s_x,0,0,S,0)(S,l,0,0,J_1,0)]^2T_l^x(\epsilon_x)\,d\epsilon_x.$$

In the above expression ϵ_x is the kinetic energy of particle x, s_x is its spin, l is the orbital angular momentum, and T_l^x are the transmission coefficients for the scattering of particle x on nucleus 2. The spin distribution was obtained from a distribution with l_{crit} values of 21.4 and 23.7 at $E_{\text{c.m.}}=33.7$ and 42.7 and with a diffuseness of 2 units. The

TABLE I. Comparison of experimental results with constrained-statistical-model calculations.

	Experimental results		Statistical model
$E_{\text{c.m.}}$ (MeV)	Q value (MeV)	Upper limits (1σ) of $Y_{4.44}/Y_{\text{g.s.}}$ (%)	$m=0$ constraint calculations $Y_{4.44}/Y_{\text{g.s.}}$ (%)
42.7	$-11.6\leq Q\leq 0$	30.9	22
42.7	$-20.0\leq Q\leq -11.6$	40	27
42.7	≤ -20.0	28.5	20
33.7	$-11.6\leq Q\leq 0$	22.5	14
33.7	≤ -11.6	30.8	23

summation was performed for conserved parity. In Table I, we tabulate the ratios of cross sections of ^{12}C(g.s.) to first excited state integrated over various Q-value regions as obtained from this restricted statistical model and compare these ratios with those obtained experimentally. We conclude that the statistical-model calculation with an $m=0$ restriction can give a reasonable reproduction of the experimental results. The dinuclear statistical model with an $m=0$ restriction predicts that the average ratio of ^{12}C(4.44 MeV) to ^{12}C(g.s.) is ≈ 0.25, which is in agreement with the measured upper limit (0.34) of the above mentioned ratio. We do not want to leave the impression that all features of the orbiting process can be described by a statistical model with only an $m=0$ magnetic substate restriction. We certainly need different dynamical constraint(s) to reproduce the observed entrance-channel dependence of mass division.

We do not have a clear understanding of the origin of the dynamical restraint which allows us to account for the excited-state to ground-state population ratio by suppressing the contribution of $m\neq 0$ final states. Such a constraint does not arise naturally if one assumes that the primary mechanism for energy dissipation in the entrance channel is nucleon exchange, as is indicated for strongly damped reactions in much heavier systems. In the nucleon-exchange model the Fermi motion of the transferred nucleons leads to sizable $m\neq 0$ excitations. This effect could be suppressed if alpha exchange were important, or might also arise if collective excitations were important and favored $m=0$ excitations. Alternatively the $m\neq 0$ suppression may be a result of the dynamics of the breakup of the dinuclear complex. The relative importance of entrance-channel and exit-channel effects is not clear. Further work is required to clarify the situation.

We thank the staff of the Argonne linac for providing the Si beam. We thank M. Vineyard for assistance in data collection. This work was supported in part by the U. S. Department of Energy.

(a)Present address: Cyclotron Laboratory, Texas A&M University, College Station, TX 77843.

(b)Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720.

[1] D. Shapira *et al.*, Phys. Lett. **114B**, 111 (1982).

[2] D. Shapira, J. L. C. Ford, Jr., and J. Gomez del Campo, Phys. Rev. C **26**, 2470 (1982).

[3] D. Shapira, J. L. C. Ford, Jr., J. Gomez del Campo, and P. H. Stelson, Phys. Rev. C **21**, 1824 (1980).

[4] A. Ray *et al.*, Phys. Rev. C **31**, 1573 (1985).

[5] P. Dyer *et al.*, Phys. Rev. C **23**, 1865 (1981).

[6] R. D. Gil, *Gamma-Ray Angular Correlation* (Academic, London, 1975).

[7] B. A. Harmon *et al.*, to be published.

[8] A. Ray, Ph.D. thesis, University of Washington, 1986 (unpublished).