Direct γ transitions in $^{12}C+^{12}C$

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(Received 15 July 1981)

Preliminary results of an experiment to detect γ transitions between the high energy particle unstable structures known in the $^{12}C+^{12}C$ system are reported. The specific process investigated is $(^{12}C+^{12}C)$ 25.8 MeV (c.m.) $\rightarrow\gamma+(^{12}C+^{12}C)$ 19.3 MeV (c.m.) $\rightarrow\gamma+^{12}C+^{12}C$ (g.s. or 2^+). The initial energy is near the center of the gross structure thought to have $J^\pi=14^+$, and 19.3 MeV is the energy of the 12^+ intermediate width resonance. An upper limit (one standard deviation) is found $(\Gamma_\gamma/\Gamma)_{25.8\text{ MeV}}\lesssim(2\text{ to }8)\times10^{-6}$, depending on the analysis procedure. This result shows there is no collective γ decay between the intermediate width resonances at the energies studied here, and is comparable in size and consistent with resonance-fragmentation models but does not exclude nonresonant ones.

[NUCLEAR REACTIONS Compared $^{12}C+^{12}C\rightarrow\gamma+(^{12}C+^{12}C)$ and $^{12}C(2^+)+^{12}C(2^+)$ σ's; $E_{lab}=25.8$ MeV; deduced Γ_γ/Γ upper limit.]

The prominent structures in $^{12}C+^{12}C$ excitation functions have been investigated extensively. At energies considerably above the Coulomb barrier pronounced gross structures with widths about 2 or 3 MeV exist containing intermediate structures with few hundred keV widths.[1] One interpretation associates the structure with "single particle" resonances which are fragmented via coupling with inelastic or reaction channels.[2] The band crossing[3] and double resonance models[4] are examples of such mechanisms. The sharp contrast, inherently nonresonant mechanisms may also yield gross structures (at least in inelastic reactions) as a consequence of angular momentum matching together with the narrow partial wave windows associated with some optical potentials.[5] In this paper we report preliminary results of an experiment aimed at testing the reaction mechanism differently than has been done to date.

The idea is to use the electromagnetic decay time from the C+C system to clock the reaction time. The rotational-like spacing of the gross structure centroids suggests that there can be very large quadrupole decay widths between structures differing by two spin units. Specifically, the well-known $K=0$ rotational band formula

$$B(E2)=\frac{5}{16\pi}e^2Q_0^2|\langle J_f0|J_i020\rangle|^2$$

gives 180 W.u. (Weisskopf unit) for $J_i=14$, $J_f=12$ and a static quadrupole moment $Q_0=160\text{ fm}^2$ calculated for the C−C molecular state by Chandra and Mosel.[6] [Two touching uniformly charged ^{12}C spheres with radius constant 1.25 fm have the comparable moment $Q_0=200\text{ fm}^2$.] For 6.5 MeV γ rays (see below) this gives $\Gamma_\gamma=8.5$ eV. Thus, resonant pictures suggest that the branching ratio Γ_γ/Γ lies in the range $\sim2\times10^{-5}$ to $\sim3\times10^{-6}$ corresponding to representative intermediate or gross structure widths, respectively.

Nonresonant, direct processes should have shorter reaction times with commensurately smaller branching ratios. A given S matrix $S_l=\eta_le^{2i\delta_l}$ corresponds to the reaction time $\tau_r(l)=\hbar/2(d\delta_l/dE)$. We find $\tau_r(l=14)\sim\hbar/10$ MeV from the parametrized potential used by Phillips *et al.*[5] Similar reaction times can be found classically for grazing partial waves l_g where $\tau_r(l_g)=\Delta\theta/\omega=\Delta\theta\sqrt{2}/\sqrt{2(E-V_c)}$ and $\Delta\theta$ is a "sticking angle," I is the moment of inertia, and V_C is the Coulomb barrier. These estimates lead to the expectation $\Gamma_\gamma/\Gamma\lesssim1\times10^{-6}$ for nonresonant processes. Obviously, special techniques are required to find such small branching ratios no matter what the reaction mechanism.

In our experiment the 25.8 MeV (c.m.) incident energy is chosen near the center of the gross structure thought[1] to be characterized by $J^\pi=14^+$. Events are sought corresponding to γ decay to the well studied[7,8] 19.3 MeV intermediate width resonance with $\Gamma\lesssim0.5$ MeV and $J^\pi=12^+$. The sequence of interest is $(^{12}C+^{12}C)_{25.8\text{ MeV}}\rightarrow\gamma+(^{12}C+^{12}C)_{19.3\text{ MeV}}$ where the 19.3 MeV resonance decays into elastic or particle-stable ^{12}C excited states. Because the γ-ray momentum is only of order 1% of the ^{12}C momenta, $\sum\vec{p}_{12_C}\sim\vec{p}_{beam}$. In the experiment the momenta of coincident heavy particles are measured and spurious background events which normally obscure such rare processes are rejected on the basis of apparent momentum nonconservation.

The technique reported here was developed during the course of several runs using beams from the tandem[5] at both SUNY Stony Brook and Brookhaven National Laboratory. An enriched (99.90%) 50 $\mu g/cm^2$

^{12}C foil was used which was surrounded by a liquid nitrogen cooled jacket. Particles were detected in two position sensitive telescopes consisting of ionization chambers and 100 μm thick 1 cm $\times$ 5 cm silicon position sensitive detectors (PSD's) positioned 19 cm from the target and centered at 40.8° (lab). The intrinsic telescope energy resolution for ^{12}C ions was about 240 keV [full width at half maximum (FWHM)], the angular resolution of individual detectors was limited by the beam emittance to about 0.5°.

A major background source was expected to come from pulse-height deficient signals associated with inelastic scattering events caused by incomplete charge collection in detectors, or by "slit" scattering of the beam or reactions products. To alleviate the latter effect, electropolished 0.8 $\times$ 4.5 cm masks were placed in front of the PSD's, and two electropolished collimators were used in the beam line of large enough diameter (0.5 cm) so that less than 0.1% of the beam impinged on them.

Conventional electronics were used which included pileup inspection circuits for the ΔE signals and analog divider and multiplier circuits to derive position and atomic number (Z) information. The position, Z, and $\Delta E + E$ signals from both telescopes as well as the relative event time signal from a time-to-amplitude converter were stored on magnetic tape for subsequent analysis.

C + C events where tested kinematically by computing the apparent net momentum perpendicular and parallel to the beam direction assuming both C's had mass 12 amu. Figure 1 shows the momentum distribution of events collected in a short run with Q values ~ -8.86 MeV corresponding to the double inelastic ^{12}C(2$^+$) + ^{12}C(2$^+$) reaction. The observed distribution is consistent with Monte Carlo simulations based on beam spot size, target thickness, and recoil of the excited ^{12}C nuclei following emission of the 4.43 MeV γ rays (assumed to be emitted isotropically in the reaction plane). The figure also shows the momentum distribution of C + C events collected in a short run on a ^{13}C target. Events were selected which have apparent Q values around -6.5 MeV, and it is clear that such contaminant events can be readily distinguished from ^{12}C + ^{12}C events. Anomalous inelastic events where one or both telescopes give an abnormally small energy signal would be distributed on the right of the momentum plane. In the actual data processing, valid ^{12}C + ^{12}C events were defined to have net momentum values within the observed full width of the double inelastic distribution indicated by the rectangle in Fig. 1.

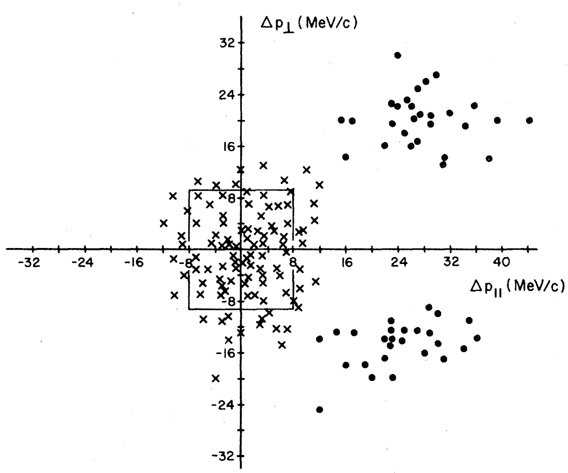

FIG. 1. Momentum distribution of some events from the ^{12}C + ^{12}C double inelastic reaction with -8.86 MeV Q value ($\times$ symbol) and from the ^{12}C + ^{13}C inelastic reactions with apparent Q values in the interval -6.5 ± 0.5 MeV (● symbol). $\Delta p_\perp$ is the net momentum perpendicular to the beam and $\Delta p_\parallel$ is the difference between the beam and reaction product momenta parallel to the beam direction. Momenta are derived from energy and position signals assuming particles have mass 12 amu.

The ratio, R, of the number of γ-decay events where the 19.3 MeV resonance breaks up into ^{12}C + ^{12}C or the ^{12}C + ^{12}C (2$^+$) inelastic channel to the number of double inelastic events from the parent structure is

$$R = \frac{\Gamma_\gamma}{\Gamma}\bigg]_P \left[\frac{\Gamma_{(2^+,2^+)}}{\Gamma}\right]_P^{-1} \left\{ G_{\rm el}\frac{\Gamma_{\rm el}}{\Gamma}\bigg]_{19.3\ {\rm MeV}} + G_{2^+}\frac{\Gamma_{2^+}}{\Gamma}\bigg]_{19.3\ {\rm MeV}} \right\} F ,$$

where P refers to the parent structure, the G factors are the geometrical coincidence detection efficiencies compared to the double inelastic reaction (see Table I below), and F is the fraction of the total γ-decay strength contained in the Q-value intervals viewed in the experiment. This expression assumes the angular distributions of the double inelastic reaction and the breakup processes are the same. Indeed, singles measurements show that the double inelastic distribution is rather featureless, roughly varying like the $(\sin\theta)^{-1}$ distribution calculated for sequential breakup following emission of an (unobserved) γ ray.

Figure 2(a) shows a Q-value spectrum using one telescope operated in "singles" mode. Clearly the background in the region where γ decay to the 19.3 MeV resonance followed by elastic breakup ($Q \approx -6.5$ MeV) or inelastic breakup ($Q \approx -10.9$ MeV) would appear is several orders of magnitude larger than the anticipated effect. Figure 2(b) shows the spectrum of all coincidence events which satisfy the momentum constraint. These data were collected in about 80 h. This spectrum is constructed by averaging Q values computed separately from the signals in each telescope since this procedure minimizes peak broadening caused by the beam spot size and target thickness. The peak associated with inelastic scattering to the 0$^+$ 7.65 MeV state of ^{12}C indicates the spectrum quality. This particle unstable state has

TABLE I. Number of events with momentum constraint. The coincidence efficiency is Q-value dependent. The relative efficiencies (based on the c.m. angular interval subtended by telescopes) are 0.7, 1.0, 0.85, 0.7, and 0.5, respectively.

	Final state Q value				
Incident energy (MeV)	4.43 MeV peak	6.5 ± 0.5 MeV	7.65 MeV peak	8.86 MeV peak	10.9 ± 0.5 MeV
25.8	1.15×10^6	8	85	4.48×10^6	8
28.8	0.67×10^6	2	31	1.14×10^6	2

the small radiation branching ratio $\Gamma_\gamma + \Gamma_\pi/\Gamma = (4.1 \pm 0.1) \times 10^{-4}$ according to Markham *et al.*[9] Furthermore, we find the singles cross section for this state is only $(19 \pm 2)\%$ of the cross section for the inelastic $^{12}C + ^{12}C(2^+)$ reaction. Thus, the ratio of coincidence 0^+ events to single inelastic 2^+ events

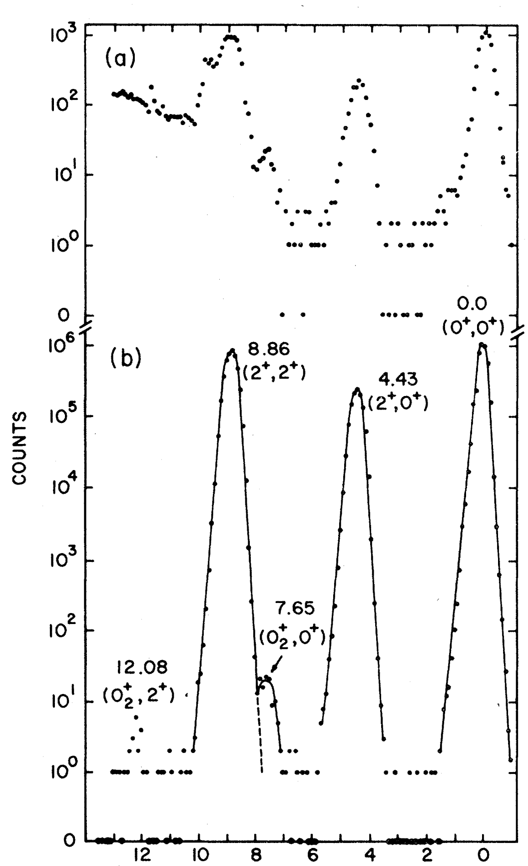

FIG. 2. Singles Q-value spectrum from one telescope is shown in part (a). A coincidence spectrum is shown in part (b). Peaks are labeled by reaction Q value and the spin parities of the ^{12}C states. The γ-decay events investigated here would lie in the 1 MeV regions centered at -6.5 and -10.9 MeV.

($Q = -4.4$ MeV) should be only $(7.9 \pm 0.8) \times 10^{-5}$. The data shown in Fig. 2(b) are in reasonable agreement giving the ratio $(6.1 \pm 0.7) \times 10^{-5}$.

From the spectrum it appears that 1 MeV intervals centered at the elastic and inelastic breakup Q values are free of the tails of the strong direct inelastic peaks. It remains to test whether the events in these intervals are due to the γ-decay process or to residual experimental background. This was done by collecting data at 28.8 MeV, an "off-resonance" incident energy.[1] The results are tabulated in Table I. Considering that the "off-resonance" data set has only one-third as many events as the "on-resonance" set, there seems to be no evidence for true γ-decay events. Multiplying the "off-resonance" number of events by 3 and subtracting from the "on-resonance" data, the net yield is 2 ± 5 in both 1 MeV intervals. Taking the one standard deviation limit, an upper limit on R is $(4+7)/(2.3 \times 10^6) = 4.8 \times 10^{-6}$ assuming half the double inelastic events come from the parent structure (see Ref. 8). From the literature,[8]

$$(\Gamma_{(2^+,2^+)}/\Gamma)_P \sim 20\% \sim (\Gamma_{el}/\Gamma)_{19.3\ \mathrm{MeV}} \sim 1/2(\Gamma_{2^+}/\Gamma)_{19.3\ \mathrm{MeV}} \ .$$

Using these width ratios and the geometrical factors listed in Table I,

$$\left(\frac{\Gamma_\gamma}{\Gamma}\right)_P \lesssim (1.6 \times 10^{-6})/F \ .$$

We obtain the factor $F = (2/\pi)\tan^{-1}(\Delta E/\Gamma)$ by approximating the γ-decay line shape as Lorentzian characterized by width Γ. Here $\Delta E = 1$ MeV. Then F ranges from 0.7 to 0.2 for $\Gamma = 0.5$ to 3 MeV, yielding an upper limit on $(\Gamma_\gamma/\Gamma)_P$ from 2 to 8×10^{-6}, respectively.

This range of upper limits allows the following conclusions:

(i) There is no fully collective γ decay between intermediate width resonances centered at 25.8 and 19.3 MeV since the measured limit is only about one-tenth the expected branching ratio.

(ii) The upper limit 8×10^{-6}, found if the γ-decay strength is assumed distributed over the gross structure width, is comparable in size and consistent with fragmentation resonant pictures.

Unfortunately, the present limit is not low enough to distinguish resonant from nonresonant mechanisms. Nonetheless, we have shown the technique discussed here has close to the requisite sensitivity. For the future, we are constructing an efficient γ-ray detector to be operated in coincidence mode with the particle telescopes. This should reduce the background while maintaining tolerable overall efficiency. In step with future γ-decay observations theoretical treatments of expected cross sections for resonant heavy ion capture reactions leading to unbound final states and for more generalized types of bremmstrahlung processes will be important.

This work was partially supported by the National Science Foundation.

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[1]T. M. Cormier, *et al.*, Phys. Rev. Lett. 38, 940 (1977).

[2]H. Feshbach, J. Phys. (Paris) 37, 177 (1976).

[3]See Y. Kondo, Y. Abe, and T. Matsuse, Phys. Rev. C 19, 1356 (1980), and references therein.

[4]H. J. Fink, W. Scheid, and W. Greiner, Nucl. Phys. A188, 259 (1972).

[5]R. L. Phillips, K. A. Erb, D. A. Bromley, and J. Weneser, Phys. Rev. Lett. 42, 566 (1979).

[6]H. Chandra and U. Mosel, Nucl. Phys. A298, 151 (1978).

[7]E. R. Cosman, R. Ledoux, and A. J. Lazzarini, Phys. Rev. C 21, 2111 (1980).

[8]T. M. Cormier *et al.*, Phys. Rev. Lett. 40, 924 (1978); and Ref. 7.

[9]R. G. Markham, Sam. M. Austin, and M. A. M. Shahabuddin, Nucl. Phys. A270, 489 (1976).