Experimental search for coherent subthreshold pion production

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(Received 19 February 1991)

An experiment has been performed to search for coherent pion production due to the excitation and decay of collective Δ-hole states in the peripheral ^{12}C [^{12}C,^{12}C(1^+,$T=1$; 15.1 MeV)] reaction at 95 MeV per nucleon. We derive an upper limit for the cross section of 60 nb. This value is consistent with present theoretical predictions.

As experimentally demonstrated [1–4] and strongly suggested by various theoretical models [5–14], subthreshold pion production in heavy-ion collisions requires a large overlap of the projectile and target density distributions. Pions are created preferably in central collisions, and the peripheral contribution is small. Despite this fact, peripheral collisions might be more appropriate for revealing coherent phenomena. Brown and Deutchmann [14] suggested that pion production in peripheral heavy-ion collisions can occur because of a coherent excitation of spin-isospin modes through the Δ-hole channel in either projectile or target. Theoretical predictions for production cross sections and pion spectral shapes have been worked out for two systems (^{16}O+^{12}C and ^{12}C+^{12}C) from subthreshold to relativistic energies [15,16].

Consider the reaction

$$^{12}\mathrm{C}+{}^{12}\mathrm{C}\rightarrow{}^{12}\mathrm{C}(1^+,T=1;E^*=15.1\ \mathrm{MeV})+\pi^0+X\ , \tag{1}$$

in which a Gamow-Teller transition ($\Delta S=\Delta T=1$) excites the projectile to the 1^+ $T=1$ state, decaying dominantly by the emission of a $M1$ photon of 15.1 MeV. During the collision, the target is excited to Δ-hole states which decay by emitting a pion. Full identification of the process can be achieved by a coincidence measurement of the outgoing ejectile (^{12}C), the 15.1-MeV photon and the two high-energy photons from the π^0 decay.

An experiment to study this process has been performed at GANIL [4,17]. The experimental setup is presented schematically in Fig. 1. A ^{12}C target of 20.8 mg/cm^2 areal density has been bombarded by a ^{12}C beam of 95 MeV per nucleon energy and of 10^9 particles/sec intensity. The ejectile (^{12}C) has been analyzed by SPEG (an energy loss spectrometer) which permits the full identification of charge, mass, and energy [18,19]. The proper adjustment of the magnetic field and a large (6%) momentum acceptance of the spectrometer allowed us to cover the ejectile energy range from (E_i-260) to (E_i-150) MeV, E_i being the incident energy. This energy loss would correspond to the energy necessary to excite the projectile and to produce a pion.

A set of 30 BaF_2 detectors [20] was used for the simultaneous measurement of the 15.1-MeV photon and of the two gammas from the π^0 decay. The detectors were placed at a distance of 35 cm from the target and covered a solid angle of 1.6 sr. Their angles with respect to the beam axis were 110° (24 detectors) and 138° (6 detectors).

In order to calibrate the detectors, we used two composite sources associating ^{241}Am with ^{9}Be and ^{238}Pu with ^{13}C. They provide gammas of 4.43 and 6.13 MeV, respectively. A third reference point was given by cosmic rays which lose, in a horizontally positioned detector, an energy equivalent to a photon energy of 64.7±0.5 MeV.

In this experiment (20-h data-collection time), we restricted ourselves to measuring in coincidence the ^{12}C ejectile, the 15.1-MeV photon, and only one high-energy gamma assumed to originate from the π^0 decay. A Monte Carlo simulation, taking into account the geometry of the experiment and the kinematics of the reaction, shows that the expected spectrum of photons from the π^0 decay is broad and vanishes below 30 MeV. This 30-MeV threshold defines the high-energy photon

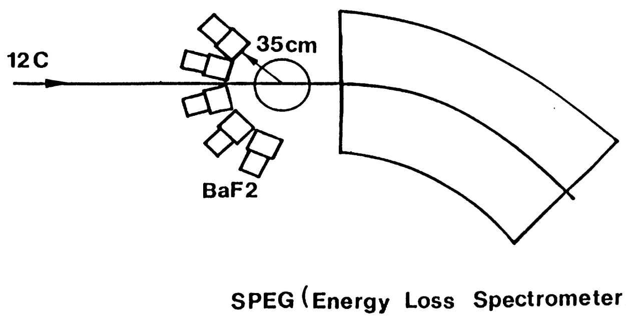

FIG. 1. Scheme of the experimental arrangement. For details see text.

trigger.

We started the analysis by selecting all events in coincidence with the ^{12}C ejectile. In order to discriminate photons from charged particles and neutrons, a correlation spectrum between particle energy and their time of flight was built (Fig. 2). The energy spectrum of photons, triggered by the ^{12}C ejectile kinematic requirement (selected by SPEG), clearly shows a peak around 15.1 MeV (Fig. 3). This peak corresponds to the $M1$ transition in ^{12}C.

We found nine events fulfilling the imposed threefold coincidence condition between the desired ^{12}C ejectile, the 15.1-MeV photon, and one high-energy gamma ($E > 30$ MeV). The number of random threefold coincidences was estimated to be negligible (less than 0.01). It should be emphasized that, since the π^0 is not fully identified by its two decay photons, the triple-coincidence rate represents an upper limit for the process under investigation. To extract an upper bound on the total cross section, further assumptions on the angular distributions are necessary. We shall choose them in order to maximize the upper bound.

First, we have supposed that the angular distributions of the ^{12}C, the 15.1-MeV photon, and the high-energy gamma are independent. Then the measured differential cross section is

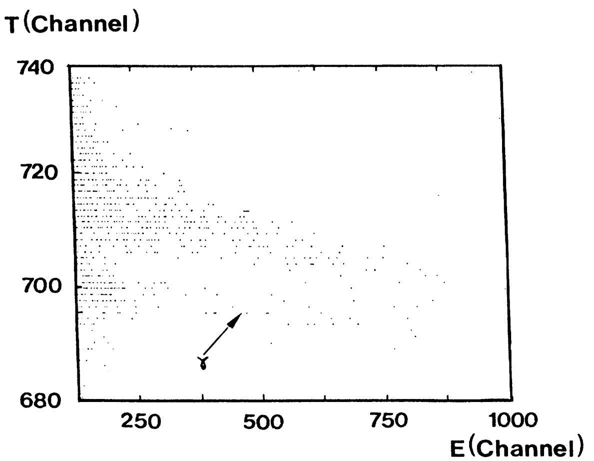

FIG. 2. Correlation between total energy and time of flight of particles detected by BaF_2 detectors.

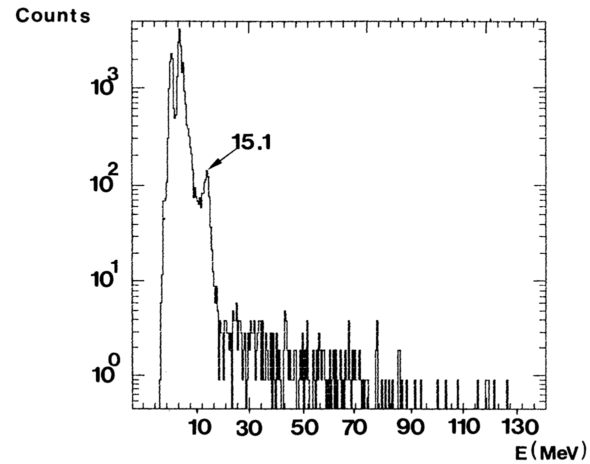

FIG. 3. Energy spectrum of photons detected in coincidence with ^{12}C ejectile with kinetic energy ranging from $(E_i - 260)$ to $(E_i - 150)$ MeV, E_i being the incident energy.

$$\left[\frac{d^3\sigma}{d\omega_1 d\omega_2 d\omega_3}\right]_{\theta_1\theta_2\theta_3} = \sigma f_1(\theta_1) f_2(\theta_2) f_3(\theta_3) , \qquad (2)$$

where σ is the total cross section, θ the angle of particle emission in the solid angle $d\Omega$, and $f(\theta)$ the angular distribution of the emitted particles; the 1,2,3 indices correspond, respectively, to the ^{12}C ejectile, the 15.1-MeV photon, and the high-energy gamma. The angular distribution of the ejectile is parametrized by [21]

$$f_1(\theta) = k \exp(-\theta_1/\gamma) , \qquad (3)$$

with $\gamma = 1.1°$, a value obtained by reproducing angular distributions of ejectiles in ^{12}C-induced reactions at 85 MeV per nucleon.

The 15.1-MeV photon is assumed to be emitted isotropically in the projectile inertial frame. The angular distribution in the laboratory system is obtained by Lorentz transformation. The high-energy gamma is assumed, as in the model described in Ref. [16], to originate from the π^0 emitted isotopically in the laboratory system.

Within the above assumptions, the upper limit for the total cross section of the $^{12}C + ^{12}C \rightarrow ^{12}C(1^+, T = 1; E^* = 15.1 \text{ MeV}) + \pi^0 + X$ process at 95 MeV per nucleon is 60 nb.

The theoretical estimates of the total cross section for subthreshold π^0 production in the $^{12}C[^{12}C, ^{12}C(1^+, T = 1; E^* = 15.1 \text{ MeV})]$ reaction at 95 MeV per nucleon range from 60 to 110 nb, depending on the choice of the NN-$N\Delta$ interaction [16]. It should be emphasized that these estimates do not include pion reabsorption and that, in the energy balance of the reaction, the excitation energy of the projectile is neglected. The semiclassical model used to describe the reaction mechanism assumes indeed that the projectile moves with a constant velocity along a straight-line trajectory. Both effects should reduce the cross section for π^0 production. In this sense the theoretical estimates are also upper bounds. To appreciate the uncertainties of the calculations, it is also important to recall that the description of

TABLE I. Cross section for π^0 production in the $^{12}C[^{12}C,^{12}C(1^+,T=1;15.1$ MeV)] reaction at 95, 200, and 400 MeV per nucleon using the π-exchange and $(\pi+\rho)$-exchange interactions defined in Ref. [16].

E/A (MeV)	V_π (μb)	$V_{\pi+\rho}$ (μb)
95	0.11	0.07
200	1.03	0.64
400	3.27	2.25

subthreshold pion production at 95 MeV per nucleon involves the projectile form factor for momenta as large as 2 fm^{-1}, a region where it is not known accurately.

An interesting experimental possibility is to study the $^{12}C+^{12}C\rightarrow{}^{12}C(1^+,T=1;E^*=15.1$ MeV$)+\pi^0+X$ process still below threshold but at higher energies. At 200 MeV per nucleon, for example, the same calculation as described in Ref. [16] gives cross sections ranging from 0.6 to 1.0 μb, depending on the NN-$N\Delta$ interaction, i.e., 10 times larger than at 95 MeV per nucleon. Coherent subthreshold pion production is therefore much easier to observe at 200 MeV per nucleon. The theoretical description of the reaction mechanism is also much more accurate at these energies. The formalism [16] developed to study Δ excitation in heavy-ion charge-exchange reactions at relativistic energies [22] is expected to be valid and makes it possible to understand within the same approach the production of pions below and above threshold in peripheral heavy-ion reactions. We show in Table I the cross section for π^0 production in the ^{12}C $[^{12}C,^{12}C(1^+,T=1;15.1$ MeV)] reaction below threshold at 95 and 200 MeV and above threshold at 400 MeV using the π-exchange and $(\pi+\rho)$-exchange interactions described in Ref. [16].

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