Study of High-Energy Gamma Rays from Relativistic Nucleus-Nucleus Collisions

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(Received 19 January 1982)

First measurements of 40–500-MeV γ rays from collisions of 2-GeV/amu Ne and Ar with Ca and Pb targets are presented. Implications with regard to production of bremsstrahlung photons and of π^0, η, and $\Delta(1232)$ particles are discussed.

PACS numbers: 25.70.-z, 25.70.Fg

The study of the collisions of heavy, relativistic nuclei with heavy stationary nuclei offers a unique means to probe the nature of the response of nuclear matter to extremely violent stresses. Unfortunately, it is difficult to unravel the details of the collision process during the short time for which the two nuclei are in contact and are most likely to be in a highly condensed state. Previous experiments[1] have been concerned primarily with the emission of hadrons from the collisions and have provided information on the characteristics of the fragment sources at a relatively advanced stage. To elucidate the early stages of the collision process, we have initiated experiments to measure high-energy γ-ray emission from central collisions of relativistic nuclei; except for work by DeJarnette *et al.*,[2] this area has been largely ignored by experimentalists. Kapusta[3] was the first to suggest that such measurements would be a useful probe of the dynamics of the collision process through the production of nucleus-nucleus bremsstrahlung. In this Letter, we present for the first time γ-ray spectra obtained at the Lawrence Berkeley Laboratory Bevalac for photon energies from 40 to 500 MeV and for several beams, targets, and angles. In addition to the observation of what we believe to be nuclear bremsstrahlung, we have determined the basic features of π^0 production and have set limits on the production of γ rays from the decay of other particles.

The experimental setup is shown in Fig. 1. Two multiwire proportional chambers (WC1, WC2) were used for beam alignment. The detectors B1 and B2 formed a trigger for central collisions, which are characterized by the absence of high-velocity, heavily charged fragments emitted in the forward direction. B1 was a scintillator which was triggered by every beam particle. B2 was a Cherenkov radiator which was used in anticoincidence with B1 if the B2 signal corresponded to particles penetrating B2 for which $\sum Z^2 \gtrsim 27$ (under the assumption of beam velocity). Photons produced by central collisions in the target (T) were detected after passing through a tunnel in a Pb shield and through a CH_2 slab F which filtered out low-energy charged particles. The photon then passed through scintillators A1, A2 which generated a veto signal if a charged particle penetrated them. The Pb sheet C was a converter with an efficiency ~ 17% for converting a photon to an electron-positron pair. These two particles produced signals in scintillator S and Cherenkov radiator Ck and then deposited the rest of their energy in lead-glass LG1–LG6. A valid photon event was determined by the absence of signals in A1, A2, and B2, and the prescence of signals in B1, S, and Ck. The signals from S and Ck were required to correspond to those of two relativistic, singly charged particles. The lead-glass was calibrated at the Lawrence Livermore Laboratory electron linac where its linear response was confirmed, the absolute energy scale established, and the resolution determined to be full width at half maximum of $5.7\%/\sqrt{E}$, where E is the electron energy in gigaelectronvolts.[4] The following tests provided convincing evidence that our data correspond to γ rays with very little contamination. Spectra taken with the target removed and spectra taken with

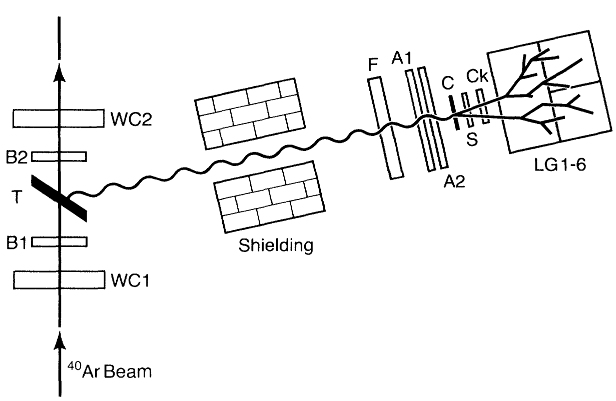

FIG. 1. Experimental setup.

the converter removed verified that we were observing neutral particles originating from the target. By varying the target-detector distance to give detector solid angles of 1.5 to 4.5 msr, we found that distortions of the photon energy spectra due to coincident neutrons were negligible. The possibility that a neutron could mimic a photon by producing charged secondaries in C was tested by replacing the Pb converter with an Al converter with the same number of radiation lengths. If all events were due to photons, then the count rates for the two types of converters would be identical. Had substantial numbers of neutrons been triggering the detector, there would have been an increased count rate with the Al converter. Figure 2 shows the results of one such comparison. By using data on pion production[5] and on cascade proton production[6] we have estimated the relative probability for neutrons to simulate photon conversions in Pb as compared with Al. From this estimate and the data in Fig. 2, we calculate that neutron contamination is less than 4% (84% confidence level) and is independent of energy.

For each spectrum, the dominant feature is the exponential dependence on energy of photon production. The straight lines through the data are least-squares fits which exclude the low-energy bin (40–80 MeV). The data above 100 MeV are described well by these fits [the discrepancy at 300 MeV in Fig. 3(a) is barely statistically significant]. In this energy range, photons are due predominantly to π^0 decay. If we assume that π^0's are emitted isotropically in the nucleon-nucleon center of momentum (CM) frame with an energy spectrum $dN_\pi/dT = kp\exp(-T/T_0)$, which has been used to describe π^- production,[7] the photon spectrum in the CM frame is $dN_\gamma/dE = 2kT_0\exp[-(m^2/4E+E-m)/T_0]$, where m is the π^0 mass, E is the photon energy, T is the pion kinetic energy, p is the pion momentum, and the constants k and T_0 are the normalization and slope factor, respectively. By properly adjusting T_0 and k, this expression fits our data as well as the simple exponential. Values of T_0 obtained for different configurations are given in Table I (typical error ≈ 5 MeV). The dependence of T_0 on CM angle indicates nonisotropic emission in the CM frame. It has been shown[8] that even for highly anisotropic distributions of π^0's, the decay spectrum at a given angle is an accurate reflection of the π^0 spectrum at the same angle, provided the π^0 energy is greater than ~ 100 MeV. Thus, the slope factors in Table I provide meaningful estimates of the π^0 slope factors for pion CM energies in the range ~ 100–350 MeV. Our results may be compared with data on charged pions. Renfordt *et al.*[9] have observed slope factors of 106 and 98 MeV at CM angles of 0° and 90°, respectively, from central collisions of 1.8-GeV/amu ^{40}Ar ions with KCl. These are consistent with the slope factor of 105 MeV reported here for Ar + Ca at 134° in the CM frame. By averaging production rates at the two angles for the Ar + Pb configuration, we estimate a production

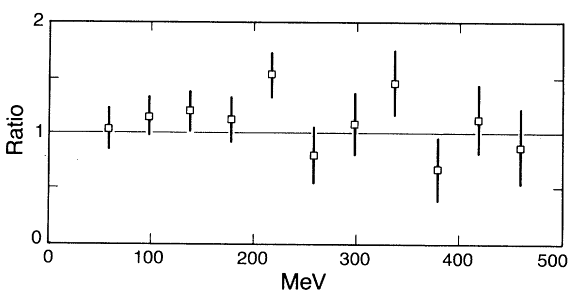

FIG. 2. Neutron-background check. The ordinate is the ratio of counts with Al converter to counts with Pb converter.

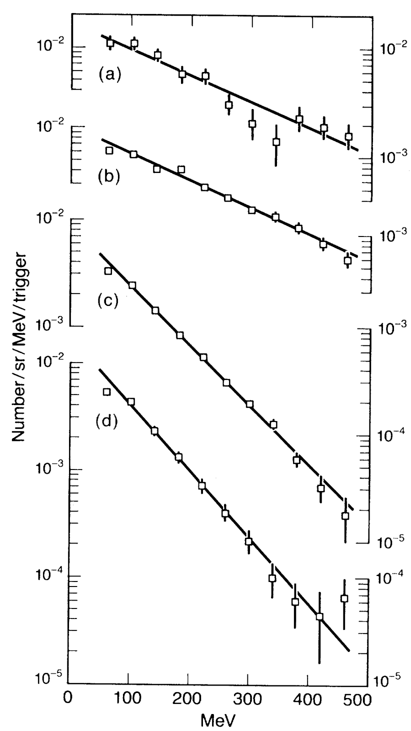

FIG. 3. Gamma-ray spectra in lab for (a) Ar + Pb at 30°, (b) Ne + Pb at 30°, (c) Ar + Ca at 90°, and (d) Ar + Pb at 90°.

of 6 π^0's per central collision. Lu *et al.*[10] measured the mean π^- multiplicity for the same configuration and found it to be 5.6. This result and the above result for T_0 confirm, as has often been expected,[10,11] that the features of neutral-pion emission are quite similar to those of charged-pion emission for systems with $N \approx Z$.

Figure 4 shows our data for Ar + Pb at laboratory angles of 30° and 90° along with possible contributions from nuclear bremsstrahlung. The curves that follow the data at high energy are spectra of decay photons from π^0's with energy distributions characterized by the parameters in Table I and with angular distributions that are either isotropic in the nucleon-nucleon CM frame or highly anisotropic. The low-energy data at 30° exceed the curve calculated for a purely isotropic distribution. Some deviation is expected, due to the actual anisotropy of the π^0's. The observed deviation, however, would appear to require an extreme degree of anisotropy. The parameters of Table I are valid for energies $\gtrsim$ 100 MeV. If more low-energy pions are produced than predicted by extrapolation, this could account for some of the deviation, but the distribution of photons from low-CM-energy π^0's would peak around 120 MeV in Fig. 4(a). Nor can the deviation be explained by the decay of excited nuclear fragments produced in the central collisions. Such fragments have too small an energy[12] to cause significant Doppler shifts in the energy of decay photons [reaction-induced nuclear decay γ rays have maximum energies well below 20 MeV (Ref. 13)]. A more likely explanation, in our opinion, is the production of bremsstrahlung. By taking into account the finite charge distributions of the colliding nuclei we have estimated this contribution.[8] Our model assumes the nuclei to be uniformly charged spheres which interpenetrate one another. Assuming a deceleration proportional to velocity, we characterize the nuclear transparency by the time $\hbar/\epsilon$ required for the projectile to slow to $1/e$ of its initial speed in the nucleus-nucleus CM frame. The curves in Fig. 4 labeled 1, 10, and 100 are the results of the calculation for three values of ϵ(MeV) that bracket a physically plausible range. For 1 MeV, the nuclei would be transparent, passing through each other without coming to rest in the CM frame; 100 MeV corresponds to a very violent collision in which the projectile would come to rest within 2 fm. The bremsstrahlung is very strongly forward peaked and makes a negligible contribution at 90°. A large bremsstrahlung contribution at 30° suggests a significant nuclear opacity with the possibility of a large degree of compression for central collisions of Ar with Pb at 1.8 GeV/amu. This conclusion is consistent with the observation[14] that the Coulomb distortion of charged-pion spectra from high-energy heavy-ion collisions requires charge at rest in the CM frame ~10^{-22} s following the collisions. It is also consistent with the observation[15] that in central collisions of light nuclei on heavy nuclei the projectiles seem to be stopped within the target matter.

TABLE I. π^0 slope factors (T_0).

Projectile + target	Lab angle	CM angle	T_0 (MeV)
Ar + Pb	30°	65°	73
Ne + Pb	30°	68°	69
Ar + Ca	90°	134°	105
Ar + Pb	90°	134°	90

Other particles besides neutral pions can decay radiatively and, in principle, could have been produced in this experiment.[16] However, only the decays of Δ(1232) resonances and η mesons had a reasonable chance of being ob-

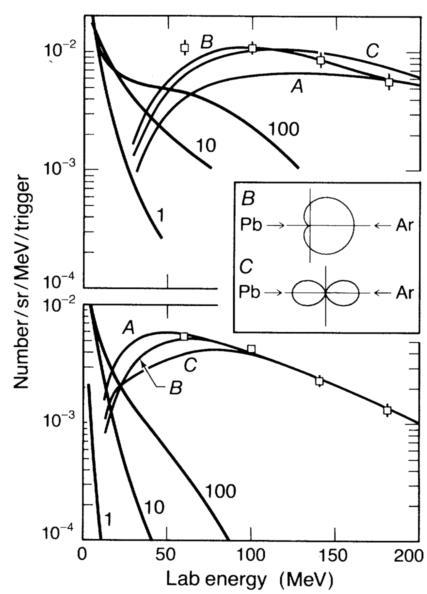

FIG. 4. Data for Ar + Pb at 30° (top) and 90° (bottom) lab angles with pion and bremsstrahlung contributions. For curve A, pions are isotropic in the CM frame. For curves B and C, pions have CM emission patterns shown in the inset.

served. If we assume that each of these is produced isotropically in the nucleon-nucleon CM frame and that the spectrum and slope factor for η production are the same as for π^0 production, then we deduce at the 95% confidence level that $\eta/\pi^0 < 0.06$ and that the number of Δ's (including possible regeneration) is less than 65 per collision for central collisions of 1.8-GeV/amu Ar with Ca.

We thank Fred Lothrop and the Bevalac staff for their cooperation. This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics, of the Office of High Energy and Nuclear Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

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