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Observation of high energy gamma rays in intermediate energy nucleus-nucleus collisions

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High energy electrons and positrons observed in medium energy nucleus-nucleus collisions are shown to be primarily due to the external conversion of high energy gamma rays. The reaction ^{14}N+Cu was studied at $E/A=40$ MeV, and a magnetic spectrograph was used with a specially constructed multiwire proportional counter plus Cerenkov detectors. A stopping target yield of $1.8\pm0.6\times10^{-6}$ photons with $E_\gamma>25$ MeV was measured per incident beam particle. The direct yield of e^+e^- pairs is less than 2% of the gamma yield.

Recent measurements of pion production with heavy ions of energy per nucleon far below the nucleon-nucleon threshold[1-3] have yielded cross sections too large to be explained by incoherent processes. Other manifestations of coherent processes such as the production of gamma rays, electrons, and nucleons with energies approaching the total energy available in the laboratory systems have received little attention. High fluxes of leptons are often observed in detection systems but are usually attributed to uncharacterized background. During an experiment to measure charged pion production for ^{14}N+Cu collisions at $E/A=40$ MeV using an Enge split-pole magnetic spectrograph,[4] a much larger than expected background of high energy electrons and positrons was observed. By comparison of the target-in to target-out spectra, it was deduced that most of the leptons were produced by gamma rays from the Faraday cup which were converted to electron-positron pairs in the material of the entrance aperture of the spectrograph. The Faraday cup in the spectrograph was located only 15 cm behind a relatively thin target ($\Delta E=21$ MeV for the incident beam). The electron production by gamma rays from the Faraday cup was verified by shadowing the spectrograph with a thick carbon absorber placed between the target and the entrance aperture. This had essentially no effect on the observed yield of electrons and positrons. In this paper we show that a large yield of high energy gamma rays is produced in reactions at intermediate energies, report the yield of these high energy gamma rays, and set an upper limit on the direct production of electrons and positrons.

The method for the detection of the high energy gamma rays was to convert the photons to electron-positron pairs immediately at the target and measure the energy spectrum of the electrons and positrons with an Enge magnetic spectrograph. The beam was ^{14}N(5+) accelerated by the National Superconducting Cyclotron Laboratory K500 cyclotron to an energy $E/A=40$ MeV. The target was 0.77 g/cm^2 of Cu, which is sufficiently thick to stop the ^{14}N ions. The target was backed with a 3 g/cm^2 converter of either Be, Cu, or Pb. The three converter elements (including target) had very different conversion efficiencies (4, 13, and 24%, respectively, for 50 MeV gamma rays) which permitted the separation of the yield of electrons and positrons due to the pair conversion of gamma rays from that originating from other sources.

The positron-sensitive element of the detector telescope was placed at the focal plane of the Enge split-pole spectrograph and consisted of a multiwire proportional counter designed for efficient detection of fast singly charged particles at 45° incidence.[5] It was backed by a plastic scintillator and two plastic Cerenkov detectors, all 2.5 cm thick. The requirement for a valid event was a coincidence of both planes of the proportional counter, the scintillator and both Cerenkov counters. A variety of tests were conducted to check that the electrons and positrons had energies consistent with those calculated from the field setting of the spectrograph. Absorbers were placed between elements, and the detector responded as one would expect for electrons. The detector was calibrated using electrons from the beta decay of ^{8}Li, which has an end point of 13.1 MeV. The ^{8}Li was made by bombarding a Be target with the same ^{14}N beam.

The positron energy spectra taken at a laboratory angle of 17° are shown in Fig. 1 for the three different converters. In order to obtain a gamma-ray yield, both a thermal Planck distribution of the form

$$\frac{dN}{dE}=\frac{KE^2}{e^{E/T}-1}\ ,$$

and an exponential form ($Ke^{-E/T}$) for the gamma-ray distribution were assumed. In these equations, K is the overall normalization. For the Planck form, T is a temperature, and in the exponential form, T is the slope parameter. Fitting of e^+ and e^- spectra was done by simulating the converter plus spectrograph system in a Monte Carlo program which included multiple scattering and the momentum sharing by the electron-positron pair.[6] The electron or positron

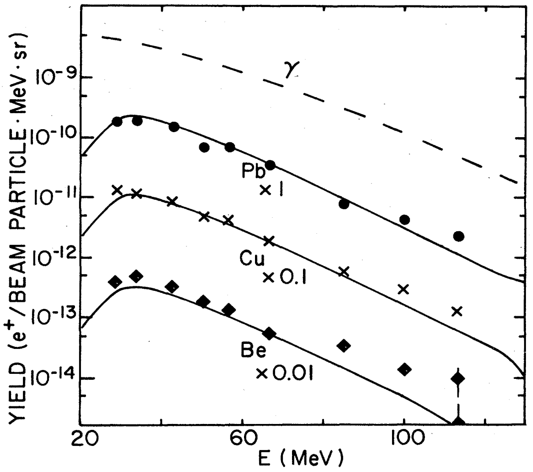

FIG. 1. The data points give the e^+ yield as a function of energy for ^{14}N + Cu at $E/A = 40$ MeV for three different converters at $\theta_{\rm Lab} = 17°$. The dashed curve shows an assumed gamma-ray yield based upon a thermal source and the solid curves show results of the Monte Carlo calculation described in the text for the conversion positrons.

was assumed to be emitted at zero degrees with respect to the gamma ray, which is a good approximation for pair production at these energies. Figure 1 shows the measured positron spectra for the three converters. The Planck photon spectrum which best fits the positron data is also shown in Fig. 1. The temperature parameters for a Planck distribution at 0°, 17°, and 14° are 12.1 ± 2, $12.2 \pm .8$, and 10.7 ± 1.4 MeV, respectively, and the slope parameters are 17.2 ± 2.7, 18.8 ± 1.8, and 15.8 ± 2.1 MeV for the exponential form. Since a stopping target was used, only the thick target cross section could be obtained. It is most probable, however, that the cross section increases rapidly with increasing beam energy, and that the present measurement is equivalent to a thin target measurement at a beam energy per nucleon not far below 40 MeV. Clearly, any quantitative comparison with theoretical predictions would require an assumption concerning the beam energy dependence of the cross section.

One way to compare theoretical models to the results of the present experiment is to assume a Planck form for the gamma-ray distribution and to use a beam energy dependence in which the temperature of the source is proportional to the beam energy. The yield can then be calculated by integrating over the beam energy. Corrections can also be made for the Doppler shift of the gamma rays using a source velocity taken from the fireball model[7] ($\beta = 0.117$). With this energy dependence and assuming isotropy, we obtain a total cross section of 0.65 mb at $E/A = 40$ MeV for production of photons with an energy of more than 25 MeV.

The positron yields measured at 0°, 17°, and 40° show little difference, as can be seen in Fig. 2. Multiple Coulomb scattering in the converter would smooth the angular dependence. This is expected for low energy positrons (with a mean scattering angle $\theta_{\rm rms} = 27°$ for 20 MeV gamma rays in the Pb converter), but the high energy positrons [$E(e^+) > 70$ MeV] should closely follow the angular distribution of the gamma rays ($\theta_{\rm rms} = 8°$ at 70 MeV).

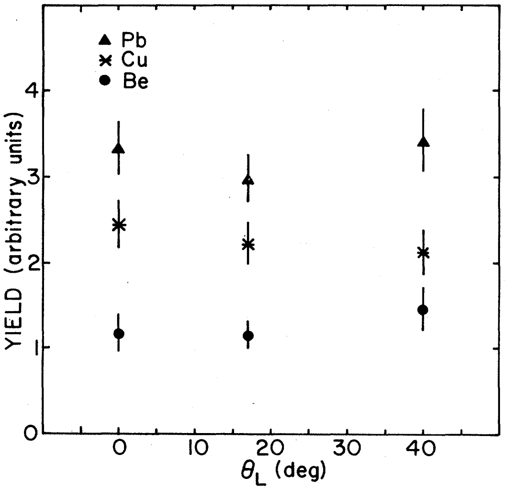

FIG. 2. The angular distribution of high energy (70–105 MeV) e^+ for the Pb, Cu, and Be converters.

It is possible from our data to extract an upper limit on the production of electron-positron pairs created directly within the collision. By extrapolating the positron yield to zero converter efficiency and taking into account the conversion in the Cu target itself, we find that the direct positron yield is less than 2% of the gamma-ray yield discussed above. This limit is consistent with the internal conversion coefficient at these gamma-ray energies. It is interesting to note that the calculations of direct bremsstrahlung production of electron-positron pairs for Pb on Pb collisions by deReus and Greiner predict yields well below our upper limit.[8]

Vasak *et al.*[9] have suggested that nucleus-nucleus bremsstrahlung may be the mechanism of pion production

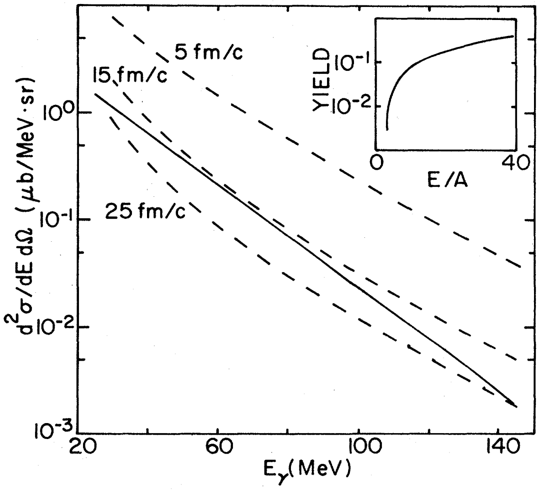

FIG. 3. Calculated bremsstrahlung production with stopping time $\tau_S = 5$, 15, and 25 fm/c (dashed curves). The insert shows the beam energy dependence of 50 MeV photons in this process assuming $\tau_S = 15$ fm/c. The solid line is the gamma yield at $E/A = 40$ MeV estimated from the data assuming the bremsstrahlung model's beam energy dependence.

at these intermediate energies and that high energy gamma rays should also be produced. The bremsstrahlung model we have used to compare with our data is based on the earlier work of Budiansky and co-workers.[10,11] The model treats the projectile and target as uniform density spheres which interpenetrate and come to rest without changing shape. The velocities of the nuclei in the center of mass are assumed to exponentially decrease with a characteristic stopping time τ_s. All motion is assumed to take place parallel to the beam axis. This last condition, while simplifying the problem, results in a quadrupole angular distribution with no yield at $\theta = 0°$, and is not consistent with the data which is more suggestive of thermal production. Nevertheless, in Fig. 3 the calculated angle-averaged bremsstrahlung energy spectrum is compared with the data. Note the strong dependence of the bremsstrahlung yield on the stopping time τ_s. A stopping of time $\tau_s = 15$ fm/c gives the best fit to the gamma-ray yield and roughly reproduces the slope of the energy spectrum. This is a larger stopping time than the value of 6 fm/c obtained by Vasak *et al.*[9] in the analysis of the π^0 data from 35 MeV/A ^{14}N+Ni of Ref. 3.

Ko *et al.*[12] have recently calculated photon bremsstrahlung in a cascade framework. Although their model is not directly applicable to beam energies as low as in the present work, a conclusion of their calculation is that incoherent bremsstrahlung due to neutron-proton scattering dominates the bremsstrahlung yield for all but the heaviest systems. This incoherent bremsstrahlung is nearly isotropic much like our data. Their calculation predicts a $1/E$ gamma-ray energy dependence, which is less steep than our data.

The source of these high energy gamma rays is an interesting question. We have recently learned of work with heavy ions at higher energies, where similar gamma-ray spectra have also been observed.[13] If the source is thermal, comparisons between the π^0 and γ yields may give new insights into the hot region. If the source is nucleus-nucleus bremsstrahlung, high energy gamma rays may prove to be a powerful new probe of the dynamics of nucleus-nucleus collisions and may serve as a signature for central collisions.

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[1] H. Heckwolf, E. Grosse, H. Dabrowski, O. Klepper, C. Michel, W. F. J. Müller, H. Noll, C. Brendel, W. Rösch, J. Julien, G. S. Pappalardo, G. Bizard, J. L. Laville, A. C. Mueller, and J. Peter, Z. Phys. A **315**, 243 (1984).

[2] H. Noll, E. Grosse, P. Braun-Munzinger, H. Dabrowski, H. Heckwolf, O. Klepper, C. Michel, W. R. J. Müller, H. Stelzer, C. Brendel, and W. Rösch, Phys. Rev. Lett. **52**, 1284 (1984).

[3] P. Braun-Munzinger, P. Paul, L. Ricken, J. Stachel, P. H. Zhang, G. R. Young, F. E. Obenshain, and E. Grosse, Phys. Rev. Lett. **52**, 255 (1984).

[4] J. E. Spencer and H. A. Enge, Nucl. Instrum. Methods **49**, 181 (1967).

[5] K. Beard, W. Benenson, E. Kashy, B. Sherrill, J. van der Plicht, and J. Yurkon, Michigan State University Cyclotron Laboratory Annual Report (1982–83), 1984, p. 102.

[6] J. W. Motz, H. A. Olsen, and H. W. Koch, Rev. Mod. Phys. **41**, 581 (1969).

[7] J. Gosset, H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall, Phys. Rev. C **16**, 629 (1977).

[8] T. deReus and W. Greiner (private communication).

[9] D. Vasak, W. Greiner, B. Muller, Th. Stahl, and M. Uhlig, Nucl. Phys. **A428**, 291c (1984).

[10] M. P. Budiansky, Ph.D. thesis, University of California, Berkeley, 1981.

[11] M. P. Budiansky, S. P. Ahlen, G. Tarle, and P. B. Price, Phys. Rev. Lett. **49**, 361 (1982).

[12] C. M. Ko, G. Bertsch, and J. Aichelin (private communication).

[13] H. Noll, Gesellschaft fur Schwerionenforschung, Report No. GSI-85-9, 1985 (ISSN No. 0171-4546) (unpublished); E. Grosse, talk given at the International Workshop on Gross Properties of Nuclei, Hirschegg, 1985; in Proceedings of the 6th High Energy Heavy Ion Study and 2nd Workshop on Anomalons, Lawrence Berkeley Laboratory Report No. LBL-16281, 1983.