Search for Delayed Gamma Decays of Anomalous Nuclear States

T. M. Liss, S. P. Ahlen, P. B. Price, and G. Tarlé
Department of Physics and Space Sciences Laboratory, University of California, Berkeley, California 94720
(Received 1 June 1982)

It has been shown by other workers that some of the fragments of relativistic heavy-ion collisions have an anomalously short interaction length but may revert to normal nuclei within $\sim 10^{-11}$ sec. Lead-glass detectors were used to search for delayed high-energy γ rays emitted from projectile fragments of 940-MeV/u ^{56}Fe interactions with a steel target. The present negative result casts doubt on some recent models in which anomalous states decay electromagnetically to normal nuclei.

PACS numbers: 25.70.Hi, 23.20.Ck

Considerable experimental and theoretical effort is now being directed toward the accumulating evidence for an anomalous form of nuclear matter produced in projectile fragmentation of relativistic heavy ions.[1] The anomalous fragments are characterized by enhanced nuclear interaction cross sections and by relatively long lifetimes. The earliest evidence for this effect,[2,3] which was obtained in cosmic-ray exposures, has recently been supported by results from accelerator experiments[4,5] at beam energies ~2 GeV/u and by reanalysis of old cosmic-ray data.[6] The combined data of nearly 3000 secondary interactions are equally consistent with two interpretations: (1) About 6% of the projectile fragments are anomalous, having an interaction mean free path in nuclear emulsion of ~2.5 cm which is about an order of magnitude smaller than the mean free path for low-mass primary nuclei.[4] To survive for 2.5 cm at 2 GeV/u, the anomalous fragments require a proper mean lifetime $\gtrsim 3 \times 10^{-11}$ s. (2) Nearly all fragments have an interaction length initially reduced by a factor ~0.65 and decay by neutral-particle emission from this anomalous state into normal nuclei with a mean free path of ~0.85 cm (Ref. 6). Jain and Das have claimed[5] that the data of Aggarwal *et al.*[7] show no evidence for anomalously short interaction lengths at energies lower than ~1 GeV/u. However, examination of Table I of Ref. 7 reveals sufficiently large statistical uncertainties that it is difficult either to establish or to rule out the existence of anomalous path lengths below 1 GeV/u. Furthermore, the fact that in some studies data from interactions with projectile energies as low as 400 MeV/u (Ref. 6) and as low as 1 GeV/u (Ref. 3) have been included with apparently no dilution of the effect suggests that the energy dependence is weak.

The statistical nature of the experiments above is a serious shortcoming of the evidence for anomalous nuclear states. It would clearly be desirable to identify a feature associated with a fraction of interaction products which could be used to label unambiguously those products which were in fact anomalous. One such feature which has been suggested by a number of theoretical models is the emission of one or more high-energy photons as the anomalous particle decays electromagnetically into normal matter.[8-12] A distinguishing characteristic of such a photon would be that its point of emission would occur from approximately one to several centimeters beyond the target, as suggested by the experiments described above. The photon energy depends on the excitation levels of the anomalous nuclear fragment which have been estimated to range from ~0.1 to 1 GeV (Refs. 9–12).

By modifying an apparatus used previously to measure the properties of direct γ-ray emission in relativistic nucleus-nucleus collisions,[13,14] we have attempted to identify delayed γ rays characteristic of the decay of anomalous nuclear states produced as projectile fragments in the collisions of 940-MeV/u ^{56}Fe nuclei from the Lawrence Berkeley Laboratory Bevalac with a steel target. As mentioned previously, there is no evidence against the effect at the reduced energy and some indirect support for it. Furthermore, there are definite advantages in searching for delayed γ rays at beam energies of ~1 GeV/u compared with 2 GeV/u. In addition to having to cope with severe red shifts for laboratory angles of 90°, one would also be confronted with greatly enhanced background at the higher beam energy. A particularly troublesome background at the higher energy would be from the decay of $K_s{}^0$ mesons.

Our experimental configuration is shown in Fig. 1. A 41-cm-thick lead collimator with a hole of cross section 1×5 cm^2 permits only γ rays emitted at right angles from points 1.4 to 2.4 cm

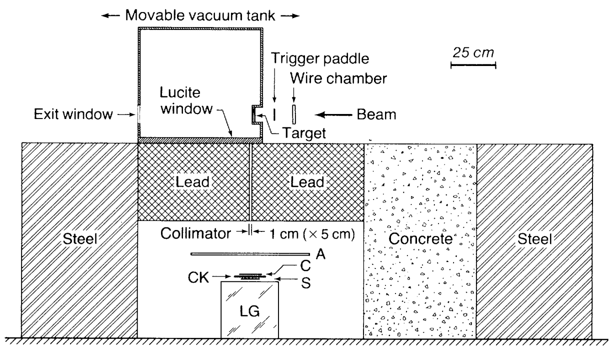

FIG. 1. Schematic of the experimental apparatus.

downstream from the edge of the 0.62-cm-thick steel target to reach the photon detector, which is well shielded within an enclosure made of steel, concrete, and lead. The target is placed at the entrance window of a large vacuum tank which eliminates background from interactions of the beam with air over the hole. To be detected, a photon that emerges from the collimator must pass through the anticoincidence scintillator, A, and produce an electron-positron pair in a 0.18-cm Pb converter, C. The pair produce signals in the Cherenkov counter, CK, and scintillator, S, and deposit the remainder of their energy in a lead-glass calorimeter, LG. A valid photon event is distinguished from an energetic charged particle or neutron by the absence of a signal in A and the presence in CK and S of signals corresponding to two singly charged, minimum-ionizing particles. The detection efficiency for photons ranges from 1.4% at 20 MeV to 6.2% at 80 MeV to ~11% for energies $\gtrsim$ 500 MeV. This experiment was insensitive to photons with energy >1000 MeV or <15 MeV. To reduce background associated with beam spray, we required a coincident signal of the beam trigger scintillator paddle (see Fig. 1) with the $S \cdot CK \cdot \bar{A}$ logic described earlier. No additional selection requirements were imposed.

During our exposure, a total of 1.00×10^9 particles were counted by the beam trigger. Of these, 1.63×10^8 were calculated to have interacted in the target. A total of ten events triggered our event logic and resulted in LG signals with energies (measured above A) greater than the threshold energy of detectability by the LG (~15 MeV). Of these, only one, at an energy of 70 ± 13 MeV, was above 35 MeV, the energy which we regard as our noise cutoff. This choice is justified by our observation of free-running pulse height spectra of the LG during beam spills in which the

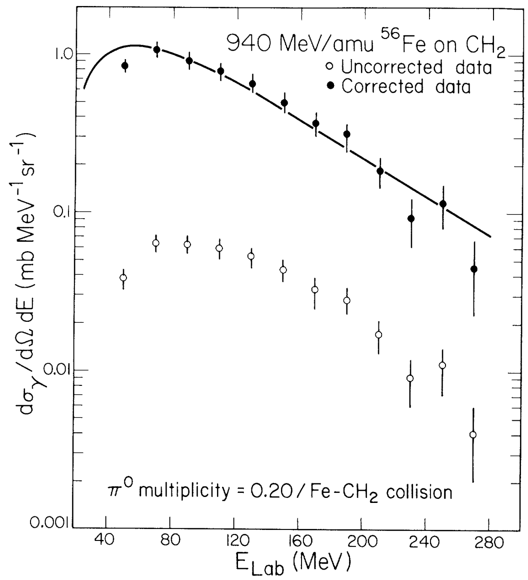

FIG. 2. Cumulative π^0 decay spectra. Open circles have not been corrected for detection efficiency while solid circles have. The curve is the best fit of Eq. (1) to the corrected data with $T_0 = 80$ MeV.

"noise" (neutrons, charged particles) fell off exponentially, becoming negligible at 30 MeV.

To establish that our very low event rate was not due to a defect in our equipment, we accumulated $\pi^0 \to 2\gamma$ decay spectra at four intervals during the run by inserting into the beam a polyethylene target directly above the collimator. Our total CH_2 exposure was characterized by 8.8×10^8 triggers of the beam paddle. The results are shown in Fig. 2 where spectra both corrected and uncorrected for our energy-dependent detection efficiency are presented. The detection efficiency at a given energy may be obtained by taking the ratio of the uncorrected to corrected cross section. The event logic used was identical to that described earlier. The peak of the $\pi^0 \to 2\gamma$ spectrum at ~70 MeV is apparent. The number of observed π^0 γ rays provided a convenient calibration of the detection efficiency of our apparatus. We assumed here, as in Ref. 13, that pion production could be described in the nucleon-nucleon center of momentum (c.m.) frame as isotropic with an energy spectrum

$$dN_{\pi^0}/dT = kpc \exp(-T/T_0), \tag{1}$$

where k and T_0 are constants and T and p are the pion kinetic energy and momentum, respectively. By applying the appropriate relativistic transformations to the π^0 spectrum above, we obtained the best-fit γ-ray spectrum for this model (the solid line in Fig. 2) to our data for a value of $T_0 = 80$ MeV.

To compare the experimental γ-ray spectrum with that expected on the basis of past work, we first use the partial cross sections[15] for Fe on CH_2, together with pion multiplicity scaling[16] as a function of target and projectile mass, to calculate the π^0 multiplicity implied by our data, taking into account small effects due to more than one fragmentation within the CH_2 target. We find $\langle N_{\pi^0}\rangle = 0.20$ per Fe-CH_2 collision. The collective tube model[16] predicts a π^- multiplicity $\langle N_{\pi^-}\rangle = 0.14$ per collision. By using the ratio $\langle N_{\pi^0}\rangle/\langle N_{\pi^-}\rangle \approx 1.7$ measured for 940-MeV protons on ^{64}Cu,[17] we arrive at a predicted value $\langle N_{\pi^0}\rangle \approx 0.23$ per Fe-CH_2 collision. This agrees quite well with our experimental results and provides a useful check of the geometrical and conversion efficiencies used in the analysis of this experiment.

For the purposes of analysis we assume that our single event for the Fe-Fe exposure at $E_{\text{lab}} = 70$ MeV is legitimate, and not due to a background event such as a neutron producing a π^0 at the side of the collimator. Figure 3 shows regions in space of fragment-rest-frame photon decay energy, E_0, versus proper mean lifetime, τ_0, which can be ruled out by our data at a 95% confidence level. The right-hand ordinate is labeled for λ, the laboratory mean free path. The impact that our single event at $E_0 = 140$ MeV has on the analysis is small. For the 6% model, statistical limitations set in at roughly this energy and for the 100% model, the single event takes the two small "bites" on the left-hand side of the region. The low-energy boundary of the 100% model is determined by our detector's noise cutoff at $E_0 \approx 70$ MeV. In determining these regions we have taken into account our energy-dependent detection efficiency, and have assumed that each Fe-Fe interaction produces either 1 or 0.06 anomalous fragments (being guided by Refs. 4 and 6) which decay with the emission of a single photon. It should be noted that since the mean number of fragments which pass over our collimator is greater than one per interaction, we may be underestimating the sensitivity of our γ-ray search by this factor. Also, note that we assume that the anomalous fragment has the beam velocity in determining $E_0 \approx 2E_{\text{lab}}$.

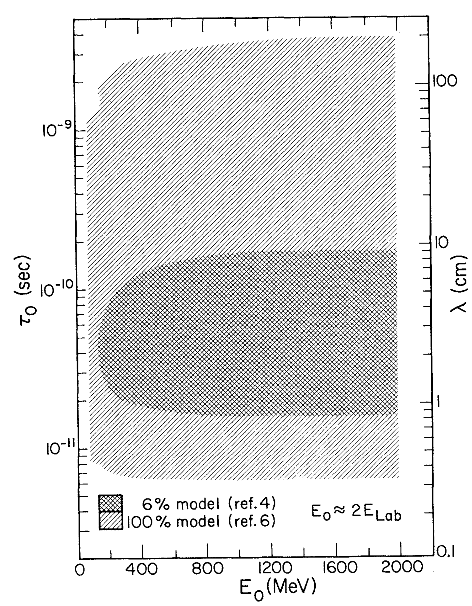

FIG. 3. Regions excluded by this experiment at a 95% confidence level for single-photon decay of anomalons.

Figure 3 shows that in order for the decay model of Ref. 6 ($\lambda \sim 0.85$ cm) to remain viable, anomalous fragments must decay either into photons with $E_0 \gtrsim 2000$ MeV or $\lesssim 70$ MeV or into neutral particles other than photons. Another possibility is for the decay to proceed via the emission of a cascade of low-energy photons. Our data also allow us to rule out γ decay in the 6% model of Ref. 4 unless $E_0 \lesssim 140$ MeV or $\gtrsim 2000$ MeV or $\tau_0 \gtrsim 1.8\times10^{-10}$ s. We note that it is not inconceivable that our single photon at $E_0 = 140 \pm 26$ MeV originated in a decaying nuclear fragment. This would not be surprising if, as suggested in Ref. 10, the excitation energy of the diquark-deuteron responsible for the anomalous behavior occurs just below the pion threshold. This would stabilize the object against pion emission and would also endow a single-photon decay with an energy roughly the same as our observed event. On the other hand, one would expect any nonexotic background of γ rays to be rich in $E_{\text{lab}} = 70$ MeV photons from decay of low-energy neutral pions (see Fig. 2). Resolution of this issue will require experiments with greatly enhanced collecting power.

We thank F. Lothrop, Hank Crawford, and the Bevalac operations staff for their assistance during this experiment. This work was supported in part by the U. S. Department of Energy.

[1]"New Evidence for Anomalously Large Nuclear

Fragments," Phys. Today 35, No. 4, 17 (1982), Search and Discovery section.
[2]B. Judek, Can. J. Phys. 46, 343 (1968).
[3]B. Judek, Can. J. Phys. 50, 2082 (1972).
[4]E. M. Friedlander, R. Gimpel, H. Heckman, Y. Karant, B. Judek, and E. Ganssauge, Phys. Rev. Lett. 45, 1084 (1980).
[5]P. L. Jain and G. Das, Phys. Rev. Lett. 48, 305 (1982).
[6]H. B. Barber, P. S. Freier, and C. J. Waddington, Phys. Rev. Lett. 48, 856 (1982).
[7]M. M. Aggarwal, K. B. Bhalla, G. Das, and P. L. Jain, in Proceedings of the Fifth High Energy Heavy Ion Study, University of California at Berkeley, Berkeley, 18–22 May 1981, Lawrence Berkeley Laboratory Report No. 12652, 1981 (unpublished), p. 410.
[8]Y. Karant, Lawrence Berkeley Laboratory Report No. 9171, 1979 (unpublished).
[9]W. J. Romo and P. J. S. Watson, Phys. Lett. 88B, 354 (1979).
[10]S. Fredriksson and M. Jändel, Phys. Rev. Lett. 48, 14 (1982).
[11]J. Boguta, Lawrence Berkeley Laboratory Report No. 13885, 1982 (unpublished).
[12]W. C. McHarris and J. O. Rasmussen, to be published.
[13]M. P. Budiansky, S. P. Ahlen, G. Tarlé, and P. B. Price, Phys. Rev. Lett. 49, 361 (1982).
[14]M. P. Budiansky, S. P. Ahlen, and G. Tarlé, to be published.
[15]R. Silberberg and C. H. Tsao, in *Proceedings of the Fifteenth International Conference on Cosmic Rays, Plovdiv, Bulgaria, 1977* (Bulgarian Academy of Sciences, Plovdiv, Bulgaria, 1977), Vol. 2, p. 89.
[16]Y. Afek, G. Berlad, A. Das, and G. Eilam, Phys. Rev. Lett. 41, 849 (1978).
[17]S. Hayakawa, *Cosmic Ray Physics* (Wiley-Interscience, New York, 1969), p. 180.