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Ray Hagstrom, and H. H. Heckman

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Evidence Against Copious Threshold Pion Production
In Heavy Ion Collisions

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and H. H. Heckman

July 1977

Abstract

In a recent publication, McNulty et al. reported a very high pion multiplicity in relatively low energy heavy ion interactions in nuclear emulsion. Using an emulsion stack virtually identical to theirs we find a pion multiplicity at least a factor of 30 smaller. We show here that the previously reported multiplicity was based on an erroneous identification of high energy protons as pions.

In a recent publication, McNulty et al.¹ reported a charged-pion multiplicity of 2.1 pions/interaction in the reactions of 280-100-MeV/nucleon ^{20}Ne in Ilford G.5 nuclear emulsion. Bertsch² has made a theoretical calculation of the charged-pion multiplicity expected in nucleus-nucleus collisions based on an independent particle model, which includes the effects of Fermi motion; his model predicts a pion multiplicity less than 2% of that claimed by McNulty et al. Thus, if the multiplicity of 2.1 pions/interaction were true, it would represent strong evidence for the existence of a new cooperative effect in nuclear interactions. We have attempted to verify this result, but find that in the region we scanned the stopping pion multiplicity, at the 95% confidence level, is less than 0.06 of that claimed by McNulty et al. We shall show in this Letter that the discrepancy can be resolved since the results of Ref. 1 were based on a misidentification of fast protons as pions.

We are able to check their experimental results directly since we have on hand a stack of Ilford G.5 nuclear emulsion which had been exposed to 230 MeV/nucleon ^{20}Ne at the Bevalac. Our stack consists of 50 pellicles, each pellicle being 12.0 cm x 7.0 cm x 670 μm . As we show below, our processing was virtually identical to theirs. That our exposure was at 230 MeV/nucleon, instead of at 280 MeV/nucleon, does not affect our comparison because, according to McNulty et al., approximately 70% of their pions were produced below 230 MeV/nucleon.

We checked the results of McNulty et al. by area scanning for stopping charged pions. Based on the pion production frequency as a function of ^{20}Ne energy, the pion energy spectrum, and the pion angular distribution claimed by McNulty et al.,^{1,3} as well as on our measured ^{20}Ne beam profile, we

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calculated the stopping pion density as a function of distance into our emulsion stack.⁴ We chose a scanning volume 6-8 cm into the emulsion stack (the ^{20}Ne beam stopped at 2.4 cm.) for two reasons: (1) the observed stopping track density was low, permitting rapid scanning, and (2) this volume corresponds to the stopping region for those pions which were, according to McNulty et al., clearly distinguished from protons. Our area scan provides a direct, unambiguous test of their pion results.

We scanned for stopping pions and muons over a volume of 1 cm^3 . We should have seen ≈ 50 stopping pions according to our calculations using the data of McNulty et al., but instead we found no pions that traced back to a ^{20}Ne interaction. During scanning we did encounter a number of stopping pions and muons (~ 250). These stopping tracks were easily identified as cosmic ray background because the emulsions were reordered and stacked in Berkeley immediately prior to exposure so that cosmic ray background tracks accumulated earlier would not follow from plate to plate. All of the observed tracks of stopping pions were traced back from their endings but only two followed from one pellicle to another. Our pellicle alignment was carefully checked and the alignment errors were less than $30\text{ }\mu\text{m}$; thus, the tracing of light tracks from plate to plate was a simple procedure. The observed stopping pions which did follow from pellicle to pellicle entered the emulsion perpendicular to the ^{20}Ne beam direction and were not associated with a ^{20}Ne interaction. Since our scanning efficiency for stopping pions is above 90%, we can confidently state that the pion production multiplicity, in the region of pion kinetic energies near 65 MeV, is consistent with zero and is, at the 95% confidence level, less than 0.06 of that claimed by McNulty et al.

To obtain a positive identification of the light tracks which McNulty et al. claim are pions, we quantitatively match the types of tracks seen in the two experiments. This requires the calibration parameters of our emulsion, namely $g_{\min}$, the grain density for a minimum-ionizing singly-charged particle, and α , the mean diameter of developed grains. We calibrated our emulsion in the standard manner⁵ by measuring the blob density B , and lacunarity L , along the track of a proton which stopped after traveling 9 cm in the emulsion.⁶ These values of B and L were used to determine α as $0.6 \mu\text{m}$ and g , the local grain density along this track, thus yielding our value for $g_{\min}$ of 17 grains/100 μm . These values are similar to the values found by McNulty et al. for their emulsion. Thus, a particle with charge Z and velocity β would give the same value for blob density to $\pm 5\%$ in both their and our emulsions, which implies that the event topology of McNulty et al. should be duplicated in our exposure.

We verified their event topology by scanning along a strip in our emulsion at a depth corresponding to a ^{20}Ne energy of 220 MeV/nucleon and analyzing the first 14 events we found. Classifying light tracks according to the same criterion used by McNulty et al., < 40 blobs/100 μ , we found that our estimates of both the percentage of interactions having light tracks ($\sim 80\%$) and the average number of light tracks (~ 3) per interaction having any light tracks agree with their estimates of "roughly 70%" and 2.8. Thus, the light tracks in our emulsion are virtually identical to the light tracks McNulty et al. identified as pions.

From the calibration of our emulsion we can calculate the blob density for any particle of charge Z and velocity β . We find that any proton with energy greater than 100 MeV will give a blob density corresponding to a light

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track, that is, less than 40 blobs/100 μm . We also know that any proton emitted from a ^{20}Ne interaction with an energy less than 200 MeV (~ 31 blobs/100 μm) will stop in our emulsion. We returned to the ^{20}Ne events and found 10 light tracks whose blob densities were between 31 and 40 blobs/100 μm . Our identification of such tracks is unambiguous because it is based solely upon the relationship between blob density and residual range of a particle. Given the same initial ionization rates (as measured by blob density) particles with differing masses will have residual ranges directly proportional to their individual masses. The secondary tracks we followed from the ^{20}Ne interactions had blob densities such that if they were the tracks of pions their ranges would be ~ 1.5 cm while if they were the tracks of protons or heavier particles, their ranges would be ~ 10 cm or greater. None of these tracks were those of pions; all were consistent with protons or heavier. Therefore, most tracks classified as light tracks (and hence as pions in Ref. 1) were actually caused by protons.

In the work of McNulty et al. both the pion energy spectrum and the verification that light tracks were pions were extracted from their Fig. 1 which is reproduced here as Fig. 1. Both axes in Fig. 1 (the blob density, B , a function of velocity and charge, and the multiple-scattering parameter, $p\beta c/Z = \text{momentum} \times \text{velocity}/\text{charge}$) represent experimental measurements by McNulty et al. Their pion identification was extracted from Fig. 1 by noting that the gray and light tracks form distinct bands and the light track band is far from the computed curve of B versus $p\beta$ for protons, and is near the pion curve.

We must explain the bimodal nature of their data to completely resolve the conflicting results. The low correlation between $p\beta$ and ionization

measurements shown in Fig. 1 and the failure of these data to predict our stopping pion density along with our observation that the bulk of the light tracks are protons leads us to examine the information contained in the blob density distribution alone. This distribution is obtained directly from Fig. 1 and plotted as a histogram in Fig. 2. Notice that the bimodal feature of Fig. 1 is contained in Fig. 2. If we assume that all the tracks in Fig. 2 are protons, we can convert the blob density distribution of Fig. 2 into a proton energy spectrum, as shown in Fig. 3. This conversion is done by using standard nuclear emulsion relations⁷ and the emulsion calibration values given in Ref. 1--minimum grain density $g_{\min} = 18.5$ grains/100 m and mean grain diameter, $\alpha = 0.6\text{-}0.7$ μm . The upper peak of Fig. 2 converts to a shoulder in the proton energy spectrum between 100 and 300 MeV, as shown in Fig. 3. Thus, the light tracks are compatible with beam velocity protons (fragments of the projectile). The bimodal feature of Fig. 2 is a consequence of the non-linear relation between blob density and proton kinetic energy in nuclear emulsion.

In summary, using an emulsion virtually identical to that of McNulty et al., we have followed to their endpoints tracks which would have been clearly identified as pions by their technique; we conclusively identify those tracks as being caused by protons or heavier particles. We scanned a region of our emulsion and found a stopping pion density consistent with zero pion production and, at the 95% confidence level, less than 0.06 of the multiplicity claimed by McNulty et al. Since the blob density distribution of McNulty et al. appears reasonable, we conclude that their critical multiple scattering measurements of $p\beta$ are in error. Such systematic underestimation of $p\beta$ from multiple scattering measurements in nuclear emulsion

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can result from the use of too small a cell size or the use of underestimated values for systematic errors.

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FIGURE CAPTIONS

- Fig. 1 Blob density vs. the product of momentum and velocity presented as Fig. 1 in McNulty et al.¹ Tracks identified by inspection as light tracks (pions) are represented as open circles and gray tracks (protons) by closed circles. As discussed in the text, values of $p\beta$ quoted here must be considered unreliable.
- Fig. 2 Blob density distribution from Fig. 1. The bimodal feature of Fig. 1 is contained in the blob density distribution.
- Fig. 3 The proton energy spectrum obtained from the blob density distribution presented in Fig. 2 assuming all tracks are protons. Note that the light tracks appear as protons whose velocities correspond to the beam velocities studied by McNulty et al.

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2. G. F. Bertsch, Phys. Rev. C 15, 713 (1977).
3. P. J. McNulty, private communication: pion angular distribution.
4. Our calculations described the hypothetical production of pions from our beam of ~ 30000 ^{20}Ne nuclei over an area of ~ 10 cm^2 as producing ~ 14000 pions from about 7000 interactions; this is extrapolated directly upward from the report of Ref. 1 which was based upon the study of 189 interactions. Our calculational scheme employed the energy spectrum exhibited in Fig. 3 of Ref. 1 together with the privately communicated angular distribution, Ref. 3; the standard range/energy relations of Ref. 5 were used to predict the stopping points of the so produced pions in the approximation that they travelled via straight paths.
5. W. H. Barkas, Nuclear Research Emulsions (Academic, New York, 1963). Detailed discussions and derivations of all of the formulas we used can be found in this text, especially chapters 8 and 9 (pp. 295, 320).
6. The specific formulas used in calibrating our emulsion and in relating the calibrations of McNulty et al.¹ are all from Ref. 5 and are as follows: (p. 390)
 - a) grain density $g = B/L$
 - b) mean grain diameter $\alpha = -(L/B) \ln L$
 - c) restricted energy loss $i'_{5000} = f(M/(M-g))$; $M = 2.2$ grains/ μm
 - d) proton kinetic energy $\tau = f(i'_{5000})$ tabulated in Ref. 5, p. 383
7. We need to identify blob densities with equivalent proton energies

to make this transformation. In principal the theoretical curves from Ref. 1 as indicated on our Fig. 1 could be used to perform this transformation. We are, however, unable to duplicate the calculations implied by these curves from Ref. 1; we thus have used the standard relations between blob density and kinetic energy from Ref. 5. This standard relation between blob density and kinetic energy is accurate enough so that we correctly predict the residual ranges of protons from our measurements of blob densities. We observe that, whatever calculation underlies the blob density vs. $p\beta$ curves from Ref. 1, the curves as portrayed in Ref. 1 disagree with the stated value for $g_{\min}$ of 18.5 blobs/100 μm in Ref. 1, favoring instead a value nearer to $g_{\min} = 22$ blobs/100 μm .

XBL 778-2538

FIGURE 1

XBL 778-2540

FIGURE 2

XBL 778-2539

FIGURE 3

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