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CHARGED-PRONG MULTIPLICITY AND ANGULAR DISTRIBUTIONS FROM NUCLEON-NUCLEUS INTERACTIONS*

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CHARGED-PRONG MULTIPLICITY AND ANGULAR DISTRIBUTIONS FROM NUCLEON-NUCLEUS INTERACTIONS

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The Echo Lake data on produced-particle distributions from heavy nuclei, presented at Denver in preliminary form, have been completely analyzed. They are compared with more recent accelerator data from a variety of nuclei. The data consistently show that the multiplicity increase, which obeys $\langle n \rangle \propto A^{0.129 \pm 0.004}$, is essentially energy independent and is primarily due to the backward c.m. hemisphere. More recent FNAL data taken with neutrons on results of a search for γ-bursts like those originally reported by Schein et al. is presented.

1. Introduction. In a report to the Denver Cosmic Ray Conference, preliminary results were presented on the topological cross sections from hadronic reactions on heavy elements from the Echo Lake Cosmic Ray Experiment.[1] These data have now been completely analyzed,[2,3] and results may now be compared with more recent data from the FNAL accelerator[4-6] and with theory.[7-11] In a subsequent experiment in a neutron beam at FNAL, aspects of the same problem were explored together with a search for anomalous γ-ray production as reported from cosmic ray emulsion stacks by Schein and others.[12-16]

2. Experiment. The Echo Lake experiment has been described previously. In the data reported here, targets of Al and Fe and later of Sn and Pb replaced the hydrogen target. A final run was made using a C target with the lower wide-gap spark chamber replaced by one with a 6.3 mm lead plate between gaps.[17] This last experiment was undertaken in part to seek evidence for the production and possible reannihilation of magnetic monopole pairs which would result in anomalous production of γ-rays.[18] Such events might account for the narrow jets of γ-rays seen in some earlier emulsion stacks exposed at balloon altitudes.

Recently a more sensitive version of this same experiment was undertaken in a neutron beam at the Fermi National Accelerator Laboratory. Here two wide-gap spark chambers, each with plates 1 m^2 area and with 15 cm gaps, were separated by 0.63 cm of Pb and triggered on events from a CH_2 target produced by neutrons of $\bar{E} \sim 240$ GeV. The chambers were triggered when from one to four charged particles were produced in the target and many charged particles passed through a scintillator following the Pb. This restrictive trigger eliminated ~95% of the inelastic target interactions. Profiting from the Echo Lake experience, care was

taken to ensure high multitrack efficiency, and efficiencies were determined to exceed 95% for over 30 tracks and over angles >±25° to the electric field. Events with up to 175 resolved prongs were seen.

Two target positions were used, one with the target 3 m from the first chamber wherein the sensitive volume subtends the entire forward N-N c.m. hemisphere, and one with the target 31 m from the chamber where a 1 mr cone subtends 3 cm in the chamber for study of narrow γ jets, as reported by Schein et al.

3. Results and Discussion. A. Inclusive production on heavy nuclei. The Echo Lake data were analyzed to determine the A dependence of average multiplicity of relativistic charged prongs parameterized according to $R = \langle n_c \rangle_{NA} / \langle n_c \rangle_{NN}$ and to study any energy dependence of R(A). Crucial to the analysis was a detailed study of necessary corrections to the observed prong multiplicities in order to accommodate effects due to finite target thickness and spark chamber inefficiencies for large prong numbers and angles. For these corrections it was necessary to develop a plausible Monte Carlo model for the prong production. The corrected results are reproduced in Table I.

Table I. Observed and Corrected Average Charged Prong Multiplicities

Target Element	Thickness of Target (g/cm^2)	Ave. E (GeV) [a]	No. of Interactions	Average Charged Multiplicity (Raw Data)	Monte Carlo Corrections	Corrected Average Charged Multiplicity	R [b]
C	17.54	85	121	6.04±0.28	1.30	7.89±0.34	1.26±0.08
		120	105	7.80±0.35	1.30	10.13±0.42	1.48±0.09
		173	68	8.24±0.54	1.39	11.44±0.64	1.55±0.10
		379	61	7.63±0.43	1.61	12.28±0.83	1.40±0.11
Al	20.67	160	70	7.67±0.42	1.47	11.25±0.76	1.54±0.10
		260	67	8.55±0.51	1.51	12.87±1.18	1.58±0.10
		520	24	8.08±1.05	1.74	14.02±2.49	1.50±0.26
Fe	29.98	160	60	8.66±0.53	1.42	12.25±0.89	1.68±0.12
		260	68	10.28±0.61	1.29	13.21±1.16	1.62±0.12
		520	26	9.96±1.05	1.62	16.05±2.90	1.72±0.31
Sn	27.85	160	49	9.77±0.73	1.36	13.31±1.13	1.82±0.15
		260	51	10.72±0.75	1.41	15.14±1.40	1.86±0.15
		520	11	9.09±1.56	1.88	17.05±3.60	1.82±0.35
Pb	32.43	160	40	10.42±0.75	1.42	14.75±1.41	2.02±0.20
		260	39	10.54±0.77	1.48	15.61±1.51	1.92±0.18

a) The energy bins are contiguous and are 16% wide for the C data and 33% wide for the metal data.

b) $R = \langle n_c \rangle (p\text{-}A) / \langle n_c \rangle (p\text{-}p)$, where $\langle n_c \rangle (p\text{-}p)$ is taken from a fit to the ISR and FNAL bubble chamber data (Ref. 15).

Angular distributions have been parameterized in terms of η_p, the log tan of the prong lab angle θ projected onto a plane containing the incident track. The data, with three η_p cuts, are presented in Fig. 1 for one energy.

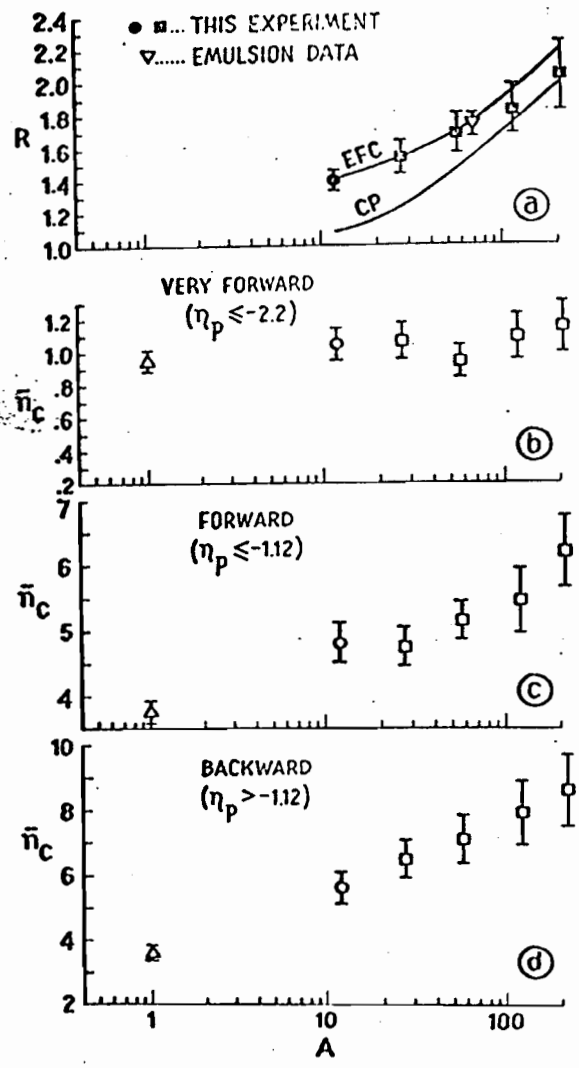

Fig. 1(a) The ratio R of average charged multiplicities in heavy elements to those in hydrogen vs. mass number A. The emulsion point is the mean value of results from Ref. 4. The two lines are theoretical predictions from the Energy Flux Cascade Model of Gottfried (Ref. 7) and the Coherent Production Model of Fishbane and Trefil (Ref. 8). The carbon point is represented by a separate symbol as that data was analyzed somewhat differently. The average energy is 160 GeV, and only statistical errors are shown.

(b) Observed $\langle n_c \rangle$ for $\eta_p \leq -2.2$ vs. A.

(c) Observed $\langle n_c \rangle$ vs. A for "forward hemisphere", $\eta_p \leq -1.12$.

(d) Total (corrected) $\langle n_c \rangle$ vs. A for "backward hemisphere", $\eta_p > -1.12$.

B. Search for anomalous γ events. The Echo Lake data analyzed by Wilkes[17] established that, of a few hundred events, γ production was compatible with $\langle n_{\pi^0} \rangle \simeq 1/2 \langle n_{\pi^\pm} \rangle$ and with a comparable distribution. The FNAL data were analyzed by extending the known π^0 production data with appropriate Monte Carlo modeling. The analysis problem was then to compare the observed prong and vertex distributions from the spark chamber photographs with the Monte Carlo predictions for the different target positions and trigger conditions. The result was that no events were observed outside the normal expectations of π^0 production. The observed events fit either π^0 production or stars in the lead converter produced by inelastically-scattered neutrons, Upper limit cross sections (90% confidence level) are reported in Table II.

Table II. Limiting Cross Sections for Anomalous Multi Photon Production

Target Distance	Number of Vertices (a)	Most Probable Number of γs (b)	Observed Number of Events	σ(μb) 90% C.L.
3M	≥ 10	32	22	≤ 13.2 (c)
			6	≤ 9.2 (d)
	≥ 15	50	0	≤ 0.7 (c)
			0	≤ 2.2 (d)
	≥ 27	91	0	≤ 0.5 (c)
			0	≤ 2.6 (d)
31.5M	≥ 7	12	10	≤ 3.7 (c)
			0	≤ 8.5 (d)
	≥ 9	15	1	≤ 0.2 (c)
			0	≤ 3.3 (d)
	≥ 12	20	0	≤ 0.2 (c)
			0	≤ 3.0 (d)
	≥ 30	50	0	≤ 0.5 (c)
			0	≤ 3.4 (d)

(a) Vertex number inferred from extrapolating prongs from second chamber back into Pb converter

(b) $\langle N_\gamma \rangle$ for the minimum number of vertices

(c) (d) correspond to different γ trigger configurations employed in different parts of the experiments.

4. Conclusion. The Echo Lake data give $R = A^x$ with $x = 0.129 \pm 0.004$, at 160 GeV and at 260 GeV, and $x = 0.128 \pm 0.011$ at 520 GeV. For the "leading particle", $x \simeq 0 (R \simeq 1)$, while for the backward (c.m.) projected hemisphere, $x = 0.167 \pm 0.008$. From analysis of events initiated by neutral hadrons, it was concluded that the Echo Lake "beam" consisted of 70% protons and 30% pions. Busza has recently reported results from pions of 100 and 175 GeV/c at FNAL. While his multiplicities appear at first lower than the Echo Lake values, he notes that agreement is restored by parameterizing according to $\bar{\nu} = A\sigma(hN)/\sigma(hA)$ where σhN and σhA are interaction cross sections of hadrons (pions or nucleons) on nucleons and nuclei respectively. Thus normalized, the two data sets agree with each other and with data from emulsions exposed at FNAL and from π^- Ne bubble chamber data at 200 GeV. All experiments report angular distributions wherein the increase in multiplicity with A is due to an increase in the backward (NN c.m.) hemisphere. The data lend general support to the Energy Flux Cascade model of Gottfried.

The search for anomalous γ production was negative, and a limit of order of microbarns was placed on the production cross section of anomalous events. As the emulsion γ events correspond to a production cross section of from 3 mb (if produced by photons of >100 GeV) to 0.3 mb (if produced by neutrons of >100

GeV) per nucleon, it is concluded that they must in some way be a much higher energy phenomenon or must await another interpretation.

Magnetic monopoles, if they are produced in bound pairs and seen only as annihilation γ's, are not observed to the same limits. The experimental sensitivity here was not set by statistics as much as by tail of the normal production of π° mesons.

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