EARLY RESULTS FROM THE JACEE BALLOON PROJECT*

The JACEE Collaboration†

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ABSTRACT

Balloon-borne emulsion chambers are being used to study the nuclear interactions, energy spectra and chemical composition of cosmic rays over the approximate interval 2 - 200 TeV. The three balloon flights to date have provided the first direct measurements of the proton and helium spectra at these energies. Preliminary data on the chemical composition of heavier nuclei has also been obtained, albeit with poor statistics because of the limited exposure. The investigations show that hadron-nucleus interactions at a mean energy of about 45 TeV are consistent with extrapolations from lower energies. Nucleus-nucleus interactions, on the other hand, seem to exhibit some unexpected characteristics. One Si-AgBr interaction at about 5 TeV/nucleon produced about 1000 charged particles, and several events indicate large transverse momentum particle production for a few secondaries.

Introduction

The Japanese-American Cooperative Emulsion Experiment (JACEE) originated from discussions carried out at the US-Japan Seminar at the Bartol Research Foundation, University of Delaware in October, 1978. The Collaboration was finalized during the summer of 1979. In the interim period the Japanese participants constructed a one-fourth size detector and launched it (JACEE-0) from the Sanriku Balloon Center in Japan in May, 1979. The first full-size detector (JACEE-1) was launched from Palestine, Texas in September, 1979. This was followed by a second flight (JACEE-2), which was launched from Palestine in October 1980. Table 1 gives the relevant characteristics of these three flights. The attempt to launch a third flight (JACEE-3) in October, 1981 was aborted because of a balloon failure. This flight was relaunched in June, 1982 from Greenville, South Carolina.

Table 1. Balloon flight characteristics

Flight	Date	From	Altitude (g/cm^2)	Duration (hr-float)	Area (cm^2)
JACEE-0	5/79	Sanriku	8.0	29.0	1(40x50)
JACEE-1	9/79	Texas	3.7	26.5	4(40x50)
JACEE-2	10/80	Texas	4.0	29.6	4(40x50)
JACEE-3	6/82	S.Carolina	5.0	39.5	1(50x50)

Apparatus

Figure 1 shows a schematic diagram of the vertical configuration of the JACEE-1 chamber. It is comprised of four sections, identifiable according to their function in the experiment. These are, from the top, the charge detector, the target, the spacer, and the calorimeter. All sections are multilayered stacks of track-sensitive materials (emulsions, x-ray films, CR-39, Lexan) alternated with absorbers (acrylic, lead). There are approximately 300 layers of emulsion in the chamber.

The charge detector employs thick (200 - 400 micron) emulsions, which permit accurate determination of the charge of each primary particle via measurements of the grain density, gap distribution, and/or delta ray distribution. Charge measurements in emulsion can be combined with the etch-cone measurements in the plastic detectors for medium ($Z = 6 - 9$) and heavy ($Z > 9$) nuclei. Measurements in electron-sensitive emulsions are adequate for identification of protons and helium. For light ($Z = 3 - 5$) nuclei, gap measurements are used. The dip angle of a track affects the resolution of individual grains in emulsion, and hence the charge resolution. The error in the estimated charge for protons and helium nuclei is within 0.15 e for all angles, by virtue of measurements in both electron-sensitive and reduced-sensitive emulsions. For steep helium and light nuclei, both grain counts and gap length distributions in reduced sensitivity emulsion provide the charge within 0.2 e. The accuracy of charge measurements decreases with charge to a few charge units for iron nuclei, although in principle the resolution could be better than 0.5 e for iron nuclei using CR-39.

The target section is comprised basically of thin (50 - 75) micron) emulsion plates alternated with acrylic sheets. The substantial mass of low-Z material maximizes the interaction probability, while the emulsion optimizes the observation of charged tracks from an interaction vertex. In order to identify nuclear fragments, charge identification layers composed of thick emulsions and etchable plastics are inserted at regular intervals throughout the target. It should be noted that most of the interaction vertices occur in the inert acrylic layers and not in the emulsions.

The spacer section consists of honeycomb paper with a few thin emulsions positioned at regular intervals. This section permits collimated secondary particles from a vertex in the target to diverge

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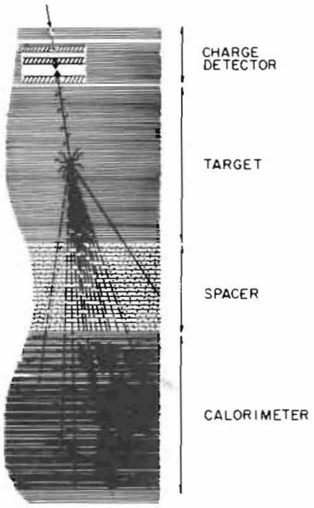

Fig. 1 Schematic of Apparatus.

before they reach the calorimeter. The emulsions facilitate the tracing of tracks through the spacer section. The JACEE-0 and JACEE-2 chambers did not employ the spacer section. This is essentially the only difference in the stack-up of the three flights.

The calorimeter is the energy measuring portion of the apparatus. It consists of 7 radiation lengths of 1.0 and 2.5 mm thick lead sheets alternating with thin emulsion plates and x-ray films. Gamma rays emanating from a vertex in the target initiate electro-magnetic cascades in the calorimeter. The cascades produce dark spots in the x-ray films, the observation of which provides the trigger for an event. Cascade images in the x-ray films also act as templates to locate the cascades in the emulsions. The events are traced back from the calorimeter, through the spacer, to the vertex in the target by observing associated tracks in the emulsions.

An essential feature of the experimental design is the double-coated emulsion plates, which have Fuji emulsion on both sides of an acrylic base. The dimensional stability of the acrylic base provides the accuracy needed for following tracks through the stack of plates. This avoids the usual problems of shrinkage and distortion associated with emulsion pellicles. Furthermore, emulsions of different sensitivities can be used on the two sides of the base. This is especially useful for determining the charge of helium and light nuclei, because there is no ambiguity in locating a single track in the different sensitivity films on the two sides of a plate. Both sides of the plate can be observed by simply changing the focus of the microscope.

The JACEE-3 apparatus launched from Greenville, South Carolina in June, 1982 employed electronic counters in conjunction with the emulsion chamber. A gas Cerenkov counter provided primary energy information over the range 20 - 60 GeV/nucleon. Two solid Cerenkov radiators, teflon and lead glass, provided charge measurements for medium and heavy nuclei. Proportional counter hodoscopes provided primary trajectory information. These counters were located upstream from the emulsion chamber. A scintillator located downstream acted as a burst counter. The objectives of the JACEE-3 flight include studying nucleus-nucleus interactions for known primary energies and charges, as well as calibration measurements for the passive exposures.

Energy Measurements

Energy measurements in the calorimeter section are crucial to the experiment. Basically, the measurements involve a determination of the total gamma ray energy, either by summing the contributions from single gamma rays from target interactions or by determining the summed gamma ray energy directly for interactions occurring in the calorimeter. In both cases the experimental method requires counting the number of electron tracks at various depths in the calorimeter.

For events with the first interaction in the target section, the individual cascades are separated sufficiently well that their energies can be determined by comparing the track counts as a function of depth in radiation lengths with standard cascade development curves based on cascade theory or Monte Carlo Simulations. The JACEE measurements are compared with calculations carried out by Dake, one of the collaborators. His calculations have been calibrated with measurements on electron initiated cascades at Fermilab.[1]

Figure 2 shows examples of Dake's curves for gamma ray initiated cascades, where T is the absorber thickness beyond the first pair creation. These curves show the number of electron tracks within a circle of radius 50 microns about the cascade axis, which corresponds to the JACEE measurements. The data points show the fits of some actual events with the curves. The numbers beside the curves show the primary gamma ray energy in TeV for that curve. The three arrows labeled 0, 45, and 60 degrees show the maximum thickness in radiation lengths for inclined showers.

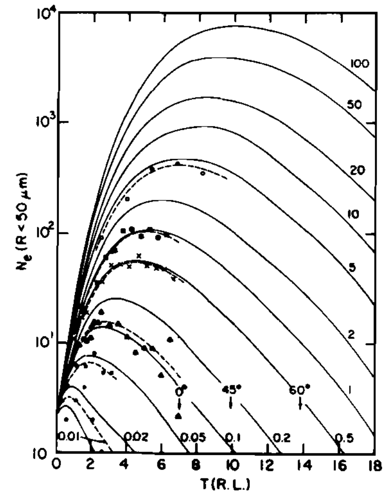

Fig. 2. Longitudinal development of gamma ray initiated cascades.

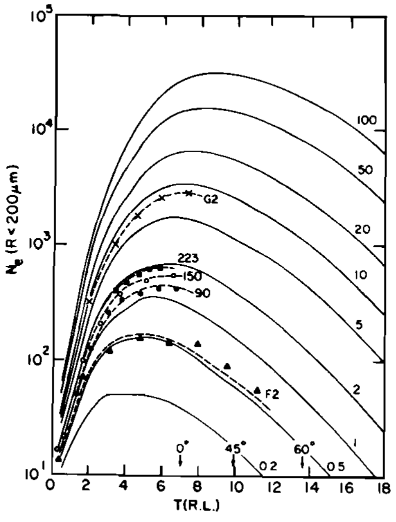

Fig. 3. Longitudinal development of proton initiated cascades.

A substantial portion of the JACEE events have their first interaction in the calorimeter section. In such cases the gamma rays do not have the benefit of the spacer for separation. Consequently, the cascades from some neutral pion parent are often not resolved. In these "lead jets" the track counting is carried out within a circle of radius 200 microns about the cascade axis. The track counts are then compared with simulations by Dake for similar experimental conditions. Figure 3 shows examples of actual events in comparison with Dake's curves for lead jets. The numbers beside the curves specify the primary hadron energy in TeV, while the vertical arrows again show the calorimeter thickness for inclined cascades.

It should be noted that an emulsion calorimeter can be quite thin, because the method of track counting in a small, fixed radius observes only the highest energy electron tracks in a cascade and only the highest energy cascades in a family. The shower maximum of even the highest energy cascade within a small radius is far smaller than the nuclear mean free path, so total ionization calorimetery can be replaced by calorimetry of cascades from the first interaction. In effect, Approximation A of cascade theory is valid for an emulsion calorimeter, whereas Approximation B must be used for a calorimeter that employs a counter, such as scintillator, which is sensitive to both the lowest energy cascade electrons and to the lowest energy cascades in a family.

The invariant mass distributions of gamma ray pairs from a target interaction is used to verify the JACEE energy resolution. A sample distribution is shown in Fig. 4, along with some calculated results. There is a clear peak around 135 MeV/c^2, corresponding to the rest mass of the neutral pion parent of the two gamma rays. The invariant mass distributions observed by JACEE are insensitive to selected changes in the minimum cascade energy. The spread of the neutral pion peak is consistently around 32%, which corresponds to energy resolution of about 22% for individual gamma rays. Summing the individual gamma ray energies should result in improved resolution, but the effect of secondary interactions in the calorimeter degrades the overall resolution so that the sum of the gamma ray energy is about constant at 20% over the range 2 - 20 TeV.

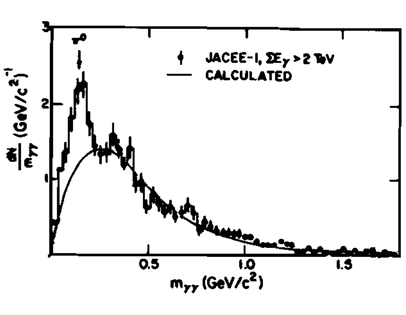

Fig. 4. Invariant mass distribution for gamma ray pairs from target interactions.

The accuracy of measuring the total gamma ray energy within a 200 micron circle has been studied by Monte Carlo simulations. Figure 5 shows an example for proton-lead interactions. The abscissa represents the difference in the measured and produced gamma ray energies divided by the produced gamma ray energy. The solid curve represents a Gaussian distribution with a standard deviation of 21%. The symbols represent simulated results based on fits to the cascade curves calculated by Dake with the restrictions that the gamma ray inelasticity is greater than 0.1 and that the total gamma ray energy is above 1 TeV. Secondary interactions are included. The standard deviation of the simulated distribution is 24%. Similar calculations for helium nuclei have standard deviation of about 27%.

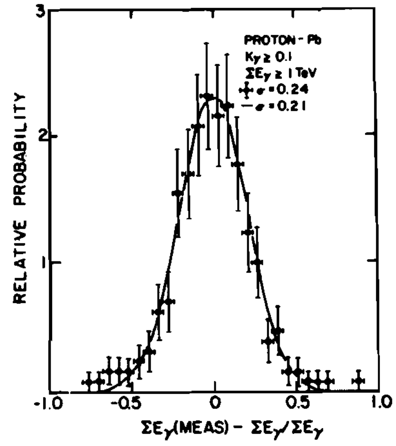

Fig. 5. Resolution for measuring total gamma ray energy from lead jets.

Overall, the resolution of the measured total gamma ray energy in the JACEE apparatus is about 20% for target interactions and about 30% for calorimeter interactions.

Geometrical Efficiency

In order to be detected in the JACEE apparatus, a primary nucleus must interact and produce a cascade large enough to be observed in the x-ray films. The collection efficiency depends on both the geometrical aperature and the number of interaction mean free paths along the primary trajectory in the apparatus. Since the interaction cross section depends on the mass of the primary species, the geometrical efficiency depends on both the primary mass and on the angle of incidence. Figure 6 shows the calculated dependences for the accumulated JACEE exposure. The calculations employed 30 angular bins, and they were done separately for the three JACEE flights. Edge effects, secondary interactions, and interactions in the walls of the apparatus enclosure were taken into account. The calculations permitted consistency checks among the data from different target volumes that were measured by different laboratories.

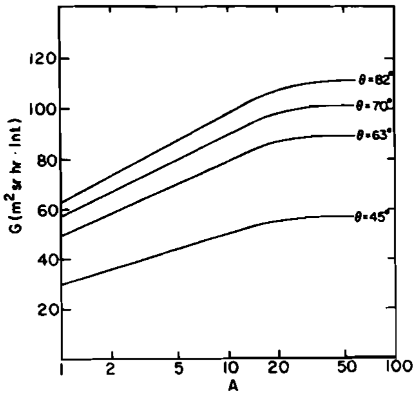

Fig. 6. Mass dependence of geometrical efficiency

Proton and Helium Spectra

One of the main contributions of JACEE is the direct observation of elemental cosmic ray fluxes up to energies approaching, and perhaps overlapping, the extensive air showers. Such measurements are useful for providing calibrations of the methods and computational models used in the air shower interpretations as well as for the main objective of understanding cosmic ray acceleration and propagation. Before JACEE, the highest energy direct observations of cosmic rays were made by the "Proton" satellite experiments, which reported data from about 40 GeV to 20 TeV for protons, to 2 TeV for helium, and to 10^{16} eV for the all-particle spectrum.[3] The "Proton" results indicated that the integral spectral index for protons changed abruptly from -1.7 to -2.3 at 2 TeV, whereas the helium and all-particle spectra maintained the same power law throughout the observation region.

The "Proton" results were in agreement with balloon measurements at the lower energies,[4,5] but the highest energy balloon observations extended only up to 2 TeV for protons and up to 300 GeV for helium. Consequently, the question of the break in the proton spectral index has remained unresolved for more than a decade, although some explanations attributed the apparent spectral break to instrumental effects rather than physical phenomena.[6] The air shower observations generally agree with the all-particle spectrum observed by the "Proton" satellite experiments in the energy range 10^{14} to 10^{15} eV. Nevertheless, the elemental composition of the air shower primaries is far from clear. Some air shower experiments[7] indicate an over abundance of iron group nuclei at 10^{14} to 10^{15} eV, while others[8] report a normal, mixed composition. An enhancement of iron group nuclei could be caused either a steepening of the proton spectrum or by a flatter spectrum for heavier nuclei. At energies around 100 GeV/nucleon direct balloon measurements indicate that heavy cosmic ray source elements have a flatter spectrum than light source elements.[9,10]

Figure 7 shows the present JACEE data for the proton and helium spectra. Also shown are the highest energy data points from the "Proton" experiments (Grigorov et al[3]) and the balloon experiments (Ryan et al[5]). Least squares fits for the JACEE data, and taking into account the steepening by about 0.04 from the rising cross section, indicate spectral indices of 1.72 ± 0.03 for protons and 1.70 ± 0.07 for helium nuclei. No bend in either spectra are observed over the energy range covered. The intensity of both particle species agree with an extrapolation of the Ryan et al[5] data, which in turn is consistent with the Grigorov et al[3] helium data.

The proton and helium spectra given in Fig. 7 were derived from measurements of the measured gamma ray energy. It can be shown that there is a unique relation between the measured gamma ray energy spectrum and the primary spectrum, as long as both the spectral index and the characteristics of the interactions do not change substantially over the energy interval observed.[11] With these restrictions, the difference between the observed and the primary spectrum is simply an energy scale shift, which depends on the actual spectral index and on the gamma ray inelasticity for the species in question. Therefore, it is not necessary to convert the observed gamma ray energies for individual events to the primary energy for that event, in order to obtain the primary energy spectrum. We can have confidence in our proton and helium spectra, because the gamma ray inelasticity for proton interactions has been measured at Fermilab energies for an emulsion calorimeter similar to the JACEE design. The gamma ray inelasticity for helium has not been directly measured, but it has been determined from calculations based on proton interactions and the fragmentation properties of helium, which are rather well known. The situation is less clear for heavier nuclei observations with JACEE at this stage, because we must rely on model calculations only.

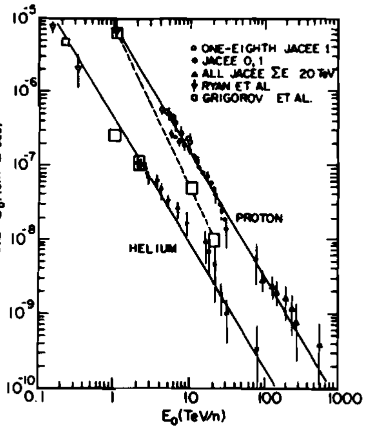

Fig. 7. · Proton and helium spectra.

Heavy Nuclei Composition

The JACEE exposures have not been sufficient to collect statistically reliable data on the spectra of nuclei heavier than helium. Furthermore, the energy thresholds for detecting events in the x-ray films of the calorimeter are known to be somewhat dependent on the mass of the primary nucleus. Therefore, at present, we can only obtain information on the various heavy cosmic ray species by restricting our analysis to the highest energy events observed. In what follows we restrict our discussion to those events having total observed gamma ray energy above 10 TeV, where we are confident that the detection efficiency is essentially 100%. This subset of data presently includes 52 events distributed in charge and energy according to the histogram shown in Fig. 8.

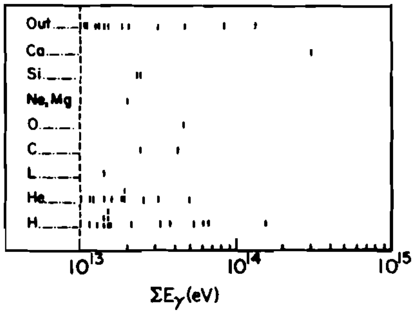

Fig. 8. Events with more than 10 TeV in gamma rays.

Since we do not have sufficient data to determine the gamma ray energy spectrum from heavy nuclei primaries, we must convert the individual gamma ray energies to the primary energies in order to compare our data with the all-particle spectrum reported by Grigorov et al.[3] This conversion requires knowledge of the gamma ray inelasticity distribution, whose measurement is one of the prime objectives of the hybrid counter-emulsion detector to be exposed in the JACEE-3 flight. At present, we must rely on simulations of nucleus-nucleus interactions for estimates of the gamma ray inelasticity. Such calculations show that the average inelasticity decreases with the mass of the primary nucleus, as well as with the mass of the target. Figure 9 shows our best estimate of the total primary energies of the subset of events given in Fig. 8.

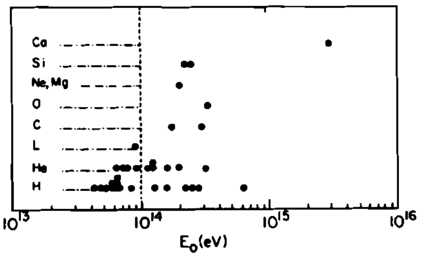

Fig. 9. Primary energy of highest energy events.

Figure 10 compares the JACEE events having energy above 10^{14} eV with the Grigorov et al[3] all-particle spectrum. The two sets of data are consistent within the statistical errors, although the JACEE data tend to indicate slightly greater abundances. The abundance ratios of p:He:CNO:Ne,Mg,Si agree within a factor of two at 100 TeV, and the latter two groups are, within a factor of two, consistent with extrapolations of the GSFC/MPI data[9] using a spectral index of -1.7.

The average mass of the primary nuclei with energy above 100 TeV is observed to be about 10 AMU. There are no iron nuclei in our data sample above 100 TeV. About 10 iron nuclei have been observed, but the highest energy is about 70 TeV. This is below the threshold of 10 TeV for the total gamma ray energy being considered here. It should be noted however, that some of our highest energy events may well be fragments from iron primaries that interacted in the 3 - 4 gm/cm^2 atmosphere overburden during the balloon exposure. Furthermore, extrapolation of the GSFC/MPI results[9] at 100 GeV/nucleon with a differential spectral index -2.7 would predict only 1.8 iron nuclei above 100 TeV for our exposure. The same extrapolation with spectral indices -2.44 and -2.59 would predict, respectively, 7 and 3 iron nuclei above 100 TeV for our exposure.

Hadron-Nucleus Interactions

The JACEE data related to the study of nuclear interactions has been presented at the 17th International Cosmic Ray Conference (Paris, July 1981) and at the Madison Conference on Forward Collider Physics.[12] We will only summarize some of more significant results here.

Figure 11 shows the differential transverse momentum distribution of gamma rays from hadron-nucleus interaction in the region of center of mass pseudo-rapidity 2.5 and Feynman scaling variable 0.03. The slope of the distribution is 190 ± 20 MeV/c which implies that the mean transverse momentum of neutral pions is 380 ± 40 MeV/c if neutral pion decay is the main source of the gamma rays.

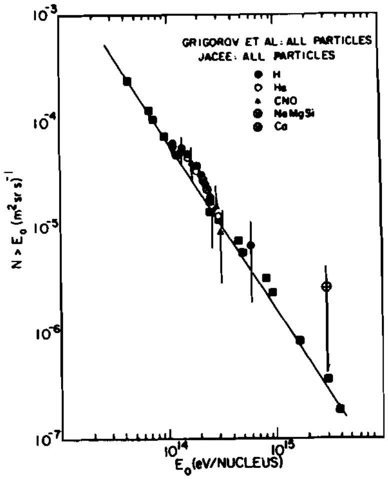

Fig. 10. All-particle spectrum.

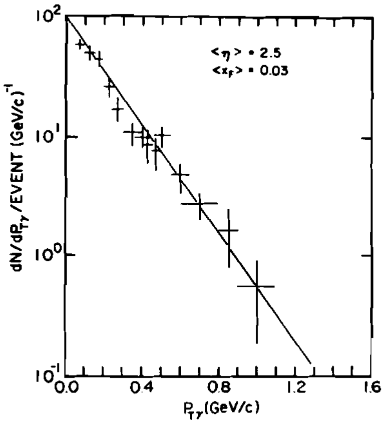

Fig. 11. Transverse momentum distribution.

The normalized pseudo-rapidity distributions of charged particles and gamma rays are compared in Fig. 12. This inclusive data is based on 40 p-C interactions having total gamma ray energy in the range 5 - 65 TeV, which corresponds to a mean primary energy of about 45 TeV. It should be noted that JACEE does not observe low energy, large angle gamma ray initiated cascades. In the present analysis, the threshold energy for individual gamma rays is about 30 GeV, and the angle limit within which the cascades are observed is about 5 x 10^{-3} radians. It is seen, however, that in the unbiased forward region the angular distributions of charged particles and gamma rays are quite similar.

Most of the nuclear interactions occur in the acrylic base of the double-sided emulsion plates. Therefore, there is also a bias against observing charged secondaries emitted at large laboratory angles, and we do not observe the true multiplicity of the events. After correcting for this detection bias our estimated value for the charged particle multiplicity is 24 ± 4 at the mean energy of 45 TeV. This value is in agreement with the UA5 result[13] of 27.4 ± 2.0, so it can be concluded that the charged particle multiplicities increase faster than a + b (ln s), perhaps as $a + b (\ln s) + c (\ln s)^2$.

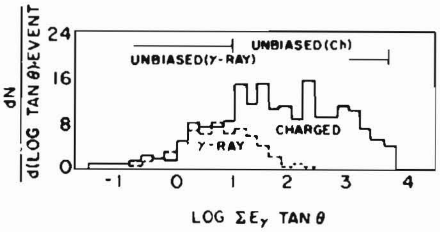

Fig. 12. Pseudo-rapidity distribution.

Nucleus-Nucleus Interactions

From the above discussion it is clear that JACEE has not encountered any major surprises in the area of hadron-nucleus interactions. The results are consistent with extrapolations from lower energy FNAL and CERN-ISR data (but not Feynman scaling. For nucleus-nucleus interactions, on the other hand, there have been some unexpected observations. These include two exceptionally high multiplicity events and several events with apparently large transverse momentum production for a few gamma rays.

One of the high multiplicity events is a Si-AgBr interaction in which the vertex is clearly visible in the top emulsion of a plate near the top of the calorimeter. Figure 13a shows a photomicrograph of the vertex, while Fig. 13b shows a photomicrograph of the event in the bottom emulsion, which is separated from the top emulsion by the 800 micron acrylic base. It should be noted that the core of this event is so dense that it is impossible to determine accurately the charged particle multiplicity in the extreme forward region. The event is still undergoing analysis, but its charged particle multiplicity is obtained to be about 1000.

Figure 14 shows the angluar distribution for the Si-AgBr event.[14] The solid histogram shows our best estimate for the distribution after subtracting the contribution from secondary interactions and pair production from gamma rays. The dashed histogram in the small angle region indicates the actual observations before any corrections. In the extreme forward region the track counts were deduced from the blackness of the core, because individual tracks could not be resolved in the emulsions. The total gamma ray energy for this event was determined to be 9.8 TeV. This implies that the primary energy is 3.6 - 5 TeV/nucleon. (The total energy is 100 - 150 TeV.) At this energy the multiplicity seems to be abnormally large for our current understanding of hadron/nuclear interactions.

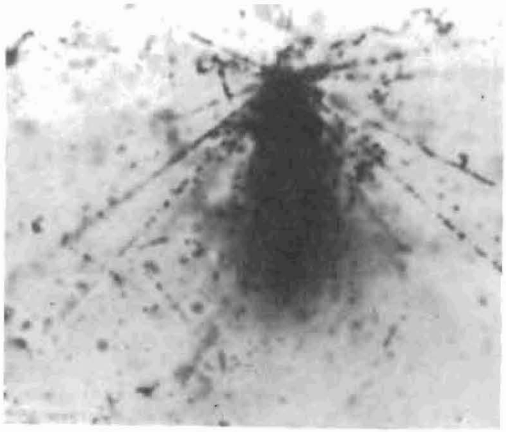

Fig. 13a. Vertex of Si-AgBr event in upper emulsion.

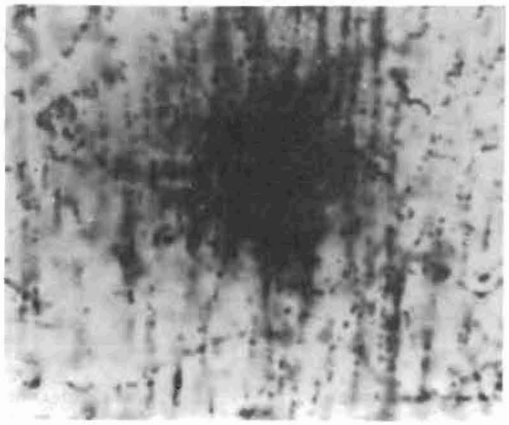

Fig. 13b. Si-AgBr event in lower emulsion 800 microns below vertex.

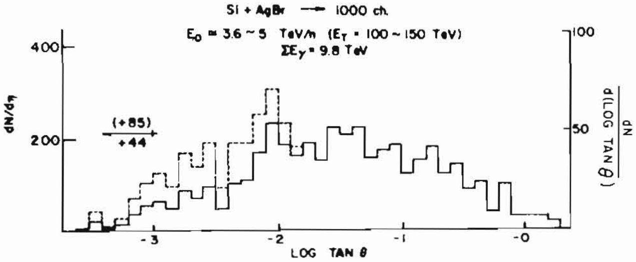

Fig. 14. Angular distribution for Si-AgBr event.

Figure 15 shows the angular distribution of a Ca-C interaction that has charge particle multiplicity of about 600. The vertex of this event occurred in the acrylic base of the top plate of the charge detector. The total gamma ray energy is about 300 TeV, which implies that the primary energy of the Ca nucleus was about 100 ± 30 TeV/nucleon. The total energy was about 4×10^{15} TeV, which seems to be the highest energy event ever observed directly in an

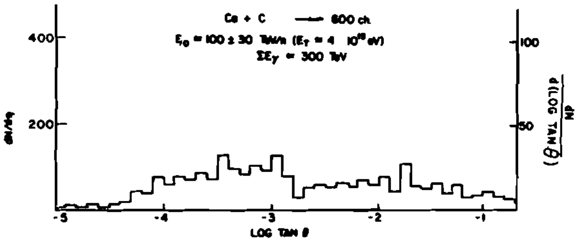

Fig. 15. Angular distribution for Ca-C event.

emulsion chamber. The high multiplicity of this event is not inconsistent with our understanding of nucleus-nucleus interactions at the primary energy involved.

The present exposure of JACEE has resulted in the collection of about 60 nucleus-nucleus interactions with energies above 1 TeV/nucleon. The transverse momentum distributions have been measured for about half of these at the present time. A typical gamma ray transverse momentum distribution is shown by the He-C interaction represented in Fig. 16. The integral distribution is characterized by a single slope of about 180 MeV/c, in line with the distribution of hadron-nucleus interactions. However, five of the events exhibit a flat tail on an otherwise normal distribution. An example is shown by the C-C interaction represented in Fig. 17, while the inclusive distribution for four such events is given in Fig. 18. The slope of the high transverse momentum tail is 540 ± 30 MeV/c, which is three times the mean value expected for the transverse momentum.

It is possible that normal statistical fluctuations, disparity in the energy going into the two gamma rays from neutral pion decay, and/or unresolved gamma rays from pion decay contributed to the apparently large transverse momentum. However, our present estimates indicate that these effects are too small for a full explanation. It is necessary to confirm these preliminary results by statistically reliable data samples. We are in the process of completing the transverse momentum measurements for all the remaining heavy nuclei events in our data sample.

Summary of Results

The JACEE collaboration has performed the first direct measurements of the proton and helium spectra at energies 2 - 200 TeV since the "Proton" satellite results reported by Grigorov et al.[3]
Both spectra are consistent with an integral spectral index of -1.7. The intensities are in agreement with an extrapolation of the lower energy data of Ryan *et al.*[5] The bend in the proton spectrum reported by Grigorov *et al.*[3] around 2 TeV is not consistent with the JACEE data.

The elemental composition above 100 TeV has been estimated, albeit with poor statistics, by using only the highest energy events, i.e., those with total gamma ray energy above 10 TeV, where the detection efficiency of JACEE is believed to be essentially 100%. Our all-particle spectrum is consistent with the "Proton" satellite all-particle spectrum. We observe a mixed elemental composition in the range 10^{14} to 10^{15} eV, which is consistent with extrapolation of the GSFC/MPI results[9] at 100 GeV.

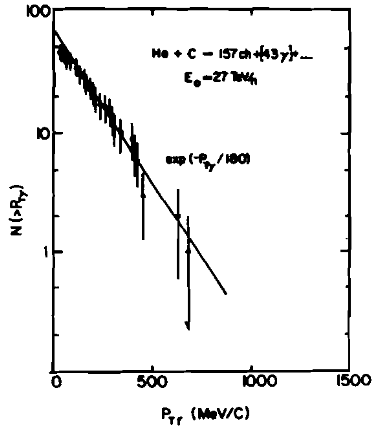

Fig. 16. Typical transverse momentum distribution.

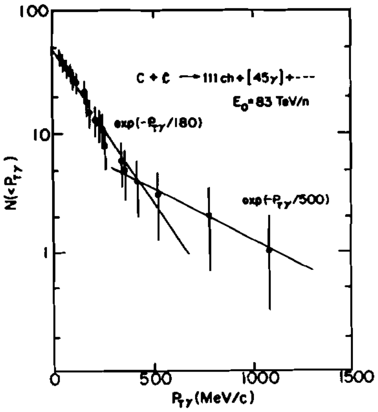

Fig. 17. Transverse momentum distribution with flat tail.

The average mass of the primary nuclei with energy above 100 TeV is observed to be about 10 AMU. There are no iron nuclei in our data sample above 100 TeV, but one iron nucleus has been observed with energy about 70 TeV. Some of our highest energy events may well be fragments from iron primaries that interacted in the 3 - 4 gm/cm^2 atmospheric overburden during the balloon exposure.

The JACEE data on hadron-nucleus interactions at the mean energy of 45 TeV indicate that they are behaving as expected from lower energy observations. The interaction characteristics seem to vary slowly with energy over the range 5 - 100 TeV that has been observed.

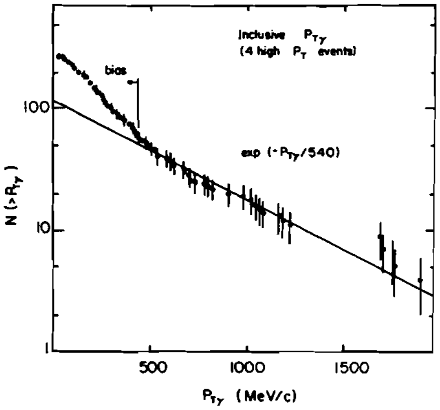

Fig. 18. Transverse momentum distribution from four events having a flat tail.

A Si-AgBr interaction at less than 5 TeV/nucleon that produced about 1000 charged particles, and the apparent production of some large transverse momentum gamma rays in several events, indicate that nucleus-nucleus interactions may not be simply explained as superpositions of hadron-nucleus interactions.

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14. The angular histogram for this event shown in Ref. 12 should be replaced with Fig. 14 presented in this paper.