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NEW CALCULATIONS AND MEASUREMENTS OF THE COULOMB CROSS-SECTION FOR THE PRODUCTION OF DIRECT ELECTRON PAIRS BY HIGH ENERGY NUCLEI

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Abstract

Recently, new calculations have been made of the direct Coulomb pair cross-section that rely less on arbitrary parameters. More accurate calculations of the cross-section down to low pair energies have been made. New measurements of the total direct electron pair yield, and the energy and angular distribution of the electron pairs in emulsion have been made for ^{16}O at 60 and 200 GeV/amu and ^{32}S at 200 GeV/amu which give satisfactory agreement with the new calculations. These calculations and measurements are presented along with previous accelerator measurements made of this effect during the last 40 years. The microscope scanning criteria used to identify the direct electron pairs is described. Prospects for application of the pair method to cosmic ray energy measurements in the region 10^{13} - 10^{15} eV/amu are discussed.

Introduction The original motivation for this work was to develop a method to measure the energy of cosmic rays above 10 TeV/amu which employs only the electromagnetic interaction [1]. The method would use the energy-dependent cross section for the production of electron-positron pairs from the virtual photon field of a relativistic heavy ion in the field of a stationary nucleus. This requires the measurement of the number of electron pairs occurring along a segment of the primary ion track in nuclear emulsion or other high spatial resolution detectors. The method for measuring primary particle energy above 10 TeV/amu is "ionization calorimetry" which depends on the strong interaction. However, there has been some concern about possible changes in the behavior of nuclear interactions at these high energies. Part of this concern is due to conflicting results of air shower experiments which, by various analysis techniques, have indicated that cosmic rays are either mostly protons or mostly iron near 10^{15} eV. In fact, some central nucleus-nucleus interactions have exhibited unusual features, such as high transverse momentum and high energy density that may indicate a departure from the simple superposition models. A technique for energy measurement that does not depend upon nuclear interactions would be most desirable in this energy regime.

Some of the previous measurements of the electromagnetic pair yield reported in the literature were not consistent with calculations. The calculations converge at the highest energies, but predict different cross-sections below 10^{15} eV/amu. Furthermore the reported experimental results varied widely. We report here the results of our recent calculations and experimental measurements which appear to resolve most of the previous discrepancies.

Accelerator Exposures The CERN EMU04 experiment exposed nuclear track emulsion to oxygen ions at 60 and 200 GeV/amu and sulfur at 200 GeV/amu. The basic configuration was a stack of thick emulsion plates (800 μ acrylic substrate with 500 μ of Fuji 7B emulsion coated on both sides) oriented parallel to the beam and housed in a light-tight box with a thin window facing the beam. The beam intensity was ~3 thousand ions/cm^2. After the exposure, a reference grid was photographed on one side of each emulsion plate. This grid contained a pattern of numbers that allowed unique identification of the primary tracks.

Microscope Scanning A total of 50 meters of heavy ion tracks have been examined under the microscope with a magnification of 1000 [2]. The primary ion track was scanned at a rate of less than 1 cm/hr, focusing over a depth of field of 40 microns centered on the primary ion. Every electron emanating from the primary track with an energy $>$ 2 MeV was recorded. First the emission angle was measured. Then the energy of the observed electron was measured by taking at least three deflection readings for the multiple-scattering angle over a track typically several hundred microns in length. The average multiple-scattering angle is known to be inversely proportional to the electron's momentum. Having found an energetic electron, the surrounding region was examined for an associated track with energy $>$ 1 MeV. This energy is a practical lower limit because the energy uncertainty approaches 50%. For a bonafide electron pair the first distinguishable grain of the electron (positron) track must be within 1 μ of the boundary of the primary track and both candidate electron (positron) tracks, when extrapolated to the primary track, should be coincident within 2 μ. Most of the false pairs arising from a chance coincidence of a delta ray of energy $<$ 1 MeV and a fast knock-on electron of energy $>$ 2 MeV will be eliminated. With this scanning procedure, it is estimated that 1-2% of the accepted pairs ($e_1 > 1$ MeV, $e_2 > 2$ MeV) will be false. We use the kinematic relationship for fast knock-on electrons to establish a basis for checking the energy and angle measurements made by various scanners. Observing and recording the direct electron pairs and the knock-on electrons above a prescribed energy threshold provides a data log that can be reviewed for consistency among scanners.

Calculations New calculations have been performed that predict the total yield, the energy transfer during collision, and the angular distribution of the pairs [3]. This work has incorporated the Weizsacker-Williams (WW) method of virtual quanta as described in [4], including corrections for pair production by low-energy photons (Racah formula [5]) and higher order corrections [6, 7]. The latter include higher-order terms in target atomic number. This approach is accurate if the Lorentz factor γ for the heavy ion satisfies the condition $\gamma >> 1$ and the energy transfer $e = e_1 + e_2$ is such that $(e/m_ec^2) << \gamma$. The WW method has an undetermined parameter corresponding to the minimum impact parameter. The Kelner and Kotov (KK) calculation of the direct pair production cross section [8] has no undetermined parameters but is valid only in the relativistic energy transfer region. If the KK results are matched with the WW calculations in an energy transfer region where both are valid, i.e., $m_ec^2 << e << \gamma m_ec^2$, then the minimum impact parameter is determined.

Results and Discussions The total calculated yield is shown in figure 1 and has been compared to a standard lowest-order quantum electrodynamic evaluation of the yield by Murota-Ueda-Tanaka (MUT) [9]. Previous measurements of the direct electron pair yield produced by monoenergetic beams of electrons, muons, pions, and protons [10-15] are displayed along with the results of this work. With the exception of the muon and proton data, the measured pair frequency matches the most recent calculations [23] rather well. The calculated energy transfer for the $\gamma = 200$ case is compared to the CERN oxygen and sulfur electron pair data (Figure 2). Although there is general agreement between theory and experiment, it is true that there is a measured over abundance of the low-energy pairs for sulfur coupled with a slight depletion of the high-energy pairs. When comparing a previous pair energy transfer distribution [13] from protons with the corresponding ones for oxygen and sulfur, a softening of the energy spectrum for the produced pairs with higher projectile charge is noticed. Figure 3 depicts the energy sharing distribution with the data being split into low and high energy pair groups for protons, oxygen, and sulfur ($\gamma = 200$). All the distributions appear to be normal except for the high energy pair data for sulfur. There is a greater disparity in the energy division for these sulfur pairs. The opening angle distributions in Figure 4 indicate that a fraction of the sulfur pairs have larger opening angles compared to the oxygen data. A possible explanation is that those electron (positron) tracks that are emitted nearly parallel to the heavy primary ion are obscured for a sufficient distance to bias the observations. This may lead to a lower energy electron being selected over an energetic (positron) due to the uncertainty in the location of the first distinguishable grain of the forward track. Therefore, it is possible that a chance association of a lower energy electron occurs reducing R and e and increasing $\Delta\theta_{1,2}$.

More accelerator data from CERN will be scanned to study these systematic errors with higher statistical accuracy. When the systematic errors are clearly understood, this energy measuring technique will be applied to cosmic rays provided a long path length in emulsion is available (> 1 cm) and the dip angle of the track is not too steep.

References

[1] Takahashi Y. et al 1984 Proc. of the Workshop on Cosmic Ray and High Energy Gamma Ray Experiments for the Space Station Era, 17-20.
[2] Derrickson J. H. et al 1988 NASA TM 100347.
[3] Eby P.B. 1989 Phys. Rev. A 39, 2734-2380.
[4] Jackson J.D. 1962 "Classical Electrodynamics". Wiley: New York.
[5] Motz J.W. et al 1969 Rev. Mod. Phys. 41, 581.
[6] Overbo I. et al 1973 Phys. Rev. A, 8 668.
[7] Davies H. et al 1954 Phys. Rev. 93 788.
[8] Kelner S.R. et al 1968 Sov. J. Nucl. Phys. 7, 237.
[9] Murota T. et al 1956 Prog. Theor. Phys. 16, 482.
[10] Cary A.S. et al 1971 Phys. Rev. D 4, 27.
[11] Jain P.L. et al 1974 Phys. Rev. Lett. 32, 1460.
[12] Kinzer R.L. et al 1968 Phys. Rev. Lett. 20, 1050.
[13] Jain P.L. et al 1974 Phys. Rev. Lett. 32, 797.
[14] Butt J.E. et al 1973 Phys. Rev. Lett. 31, 904.
[15] Fortney L.R. et al 1975 Phys. Rev. Lett. 34, 907.

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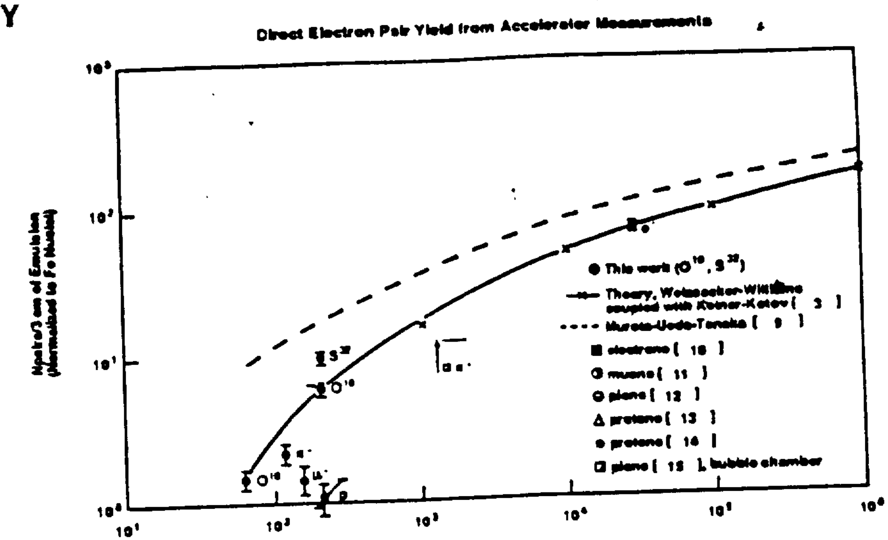

Figure 1 The direct electron pair yield normalized to the equivalent yield of an Fe nucleus in 3 cm of emulsion as a function of the projectile energy. The key lists the projectiles. The targets are nuclear emulsion except for the last entry. The bubble chamber data has a high momentum threshold (10 MeV/c) for pairs; the arrow and bar indicate a correction to the total cross section.

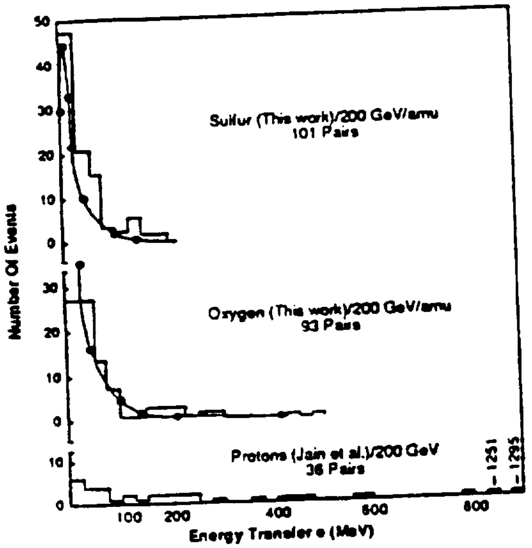

Figure 2 The energy transfer distribution of the electron pairs in emulsion for a beam of protons [13], oxygen, and sulfur at γ = 200.

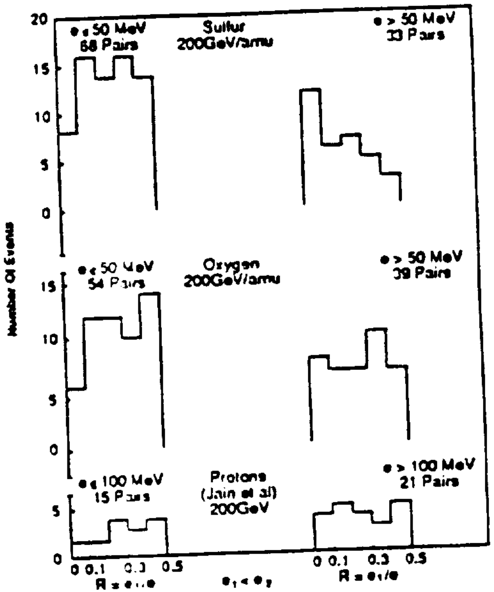

Figure 3 The energy imbalance ratio $R = e_1/(e_1 + e_2)$ in emulsion where $e_1 < e_2$. For each projectile, the R distribution has been divided into a low and high energy group.

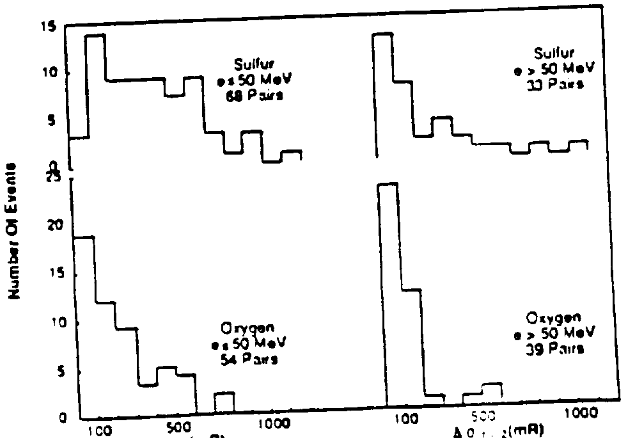

Figure 4 The opening angle distribution in emulsion for oxygen and sulfur with γ = 200 for e ≤ 50 MeV and e > 50 MeV, respectively.