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Momentum Spectrum from Scattering in Lead of Sea Level Penetrating Shower Secondaries

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A momentum spectrum of sea level penetrating shower particles has been determined from multiple Coulomb scattering angle measurements on tracks traversing two lead plates in a cloud chamber. The distribution of scattering angles is consistent with a differential momentum spectrum $N(p)$ proportional to p^{-1} for the range 0.6 to 2 Bev/c; and to p^{-2} for the range 2 to 6 Bev/c.

IN the production of cosmic-ray penetrating shower particles, it is of interest to study the basic processes of secondary particle generation and absorption. Multiple production of penetrating particles in single nuclear events is known to occur[1] and to have theoretical basis.[2] "Plural production,"[3] in which several penetrating particles are generated singly in several nuclear collisions, is also known to occur and could give rise to a penetrating shower. The different production theories predict different momentum distributions, $N(p)dp$, of the secondary particles. $N(p)dp$ may generally be represented by $N_0 p^{-s}dp$, where s may vary for various ranges of p. Experimental values of s will be helpful in comparing production theories.

In this experiment,[4] a large cloud chamber (12×24×3 in.), filled with argon-isopropyl alcohol and containing two 1-in. lead plates, was operated at sea level for 750 hours. Three trays of Geiger counters were arranged to select locally generated penetrating showers. These were photographed stereoscopically. The pictures were reprojected through a duplicate optical system onto a viewing and measuring screen where the deflection of a track in passing through a lead plate could be measured to 0.0005 radian. From these data, a spectrum $g(\theta)d\theta$ of the observed absolute scattering angles was made. Among 21 shower events, 59 secondary penetrating particles underwent measurable multiple Coulomb scattering in one or both of the plates. Among all scattering angles measured, no preferred direction (e.g., right or left) of scattering was evident. This fact, together with preliminary measurements of track straightness, indicated no significant systematic track distortions.

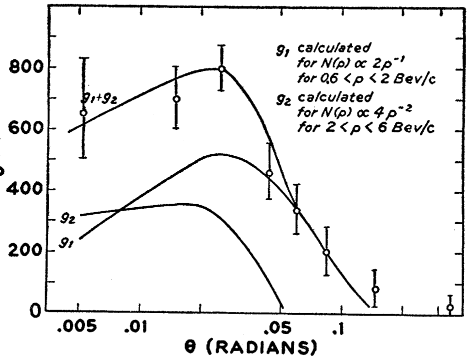

FIG. 1. Comparison of observed multiple scattering angle distribution and the $g(\theta)$ calculated from assumed $N(p)$. Experimental points are indicated by circles.

If $F_t(\theta,p)d\theta=[2\pi\theta p^2 d\theta/E_s^2 t]\exp(-p^2\theta^2/E_s^2 t)$ is the differential probability that a particle of momentum p will undergo a deflection θ due to multiple Coulomb scattering in a plate of thickness, t, then $g(\theta)=\int N(p)\times F_t(\theta,p)dp$. As an approximate solution for $N(p)dp$, a "most probable momentum," defined by $p_m=0.021t^{\frac{1}{2}}/\theta$ Bev/c,[5] where t is in radiation lengths, was found for each measured θ, and the distribution of these most probable momenta $N_m(p_m)dp_m$ was determined. Then, by using $g_m(\theta)=\int N_m(p_m)F_t(\theta,p_m)dp_m$, a close fit of $g_m(\theta)$ to the observed $g(\theta)$ should validate the approximated distribution function. In order to check this scattering method of determining momentum distribution, a $g_s(\theta)d\theta$ was also determined for 24 single particles (presumably μ mesons) which penetrated both plates. The $N_s(p)dp$ found was proportional to $p^{-2.0\pm0.1}$, in general agreement with accepted values.[6]

The penetrating shower secondary particle distribution suggests that for momenta in the range 0.6 to 2 Bev/c, $s=1$, and for higher momenta, $s=2$. Above 6 Bev/c, the statistics are insufficient for determining s. This result compares with that of Butler, Rosser, and Barker,[7] who found $s=1.5$ for p in the range 0.8 to 3 Bev/c.

In Fig. 1 are plotted the observed θ distribution and two calculated θ distributions: g_1 for the momentum distribution $N_1 \propto 2p^{-1}$ for $0.6<p<2$ Bev/c; g_2 for the momentum distribution $N_2 \propto 4p^{-2}$ for $2<p<6$ Bev/c. One can see how these momentum ranges contribute to the observed $g(\theta)$. The large-angle "tail" of observed

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$g(\theta)$ probably consists partly of very-low-energy secondary particles and partly of nuclear scattering events.

Since most of these showers were generated in lead, the secondary particles were probably formed in both multiple and plural production processes. It is therefore difficult to make a unique comparison with either theory. The plural production[3] theory predicts values of $s<1.5$; the multiple production theories[2] predicts $s\sim1.5$ to 2 (Fermi's statistical model) or higher values (Lewis, Oppenheimer, and Wouthuysen). From this fact it may be inferred[4] that a theory such as Fermi's will account for the momentum distribution of at least the higher-energy secondary particles.

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High-Energy Fission of Heavy Elements. Nuclear Charge Dependence*

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Radiochemical studies of the fission of heavy elements (${}_{67}\mathrm{Ho}^{165}$ to ${}_{90}\mathrm{Th}^{232}$) with 450-Mev protons have been performed. Radioactive nuclides varying in mass number from 59 to 115 were isolated from the various targets and, from their measured cross sections, the cross section *vs* mass number dependence was determined on the assumption of a yield *vs* charge distribution curve constant with mass number of the fission product and atomic number of the target nucleus. The integrated fission cross sections, in barns, were calculated to be 0.67, 0.21, 0.061, 0.019, 0.0050, and ~0.002 for thorium, bismuth, gold, rhenium, tantalum, and holmium, respectively. Anomalies in the cross sections and most probable charge values for the heavier nuclides isolated from holmium suggest the existence of another competing process, labelled "fragmentation," along with spallation and fission. The importance of this process in heavy element bombardment is discussed.

I. INTRODUCTION

MANY investigations of the fission of heavy elements, induced by particles and x-rays, have been reported.[1] Using radiochemical methods, Perlman and co-workers[2] showed that fission occurs in the elements tantalum to bismuth with high-energy neutrons, deuterons, and alpha particles. From the studies of Kelly and Wiegand[3] and Jungerman[4] on the cross section of various elements for fission as a function of the energy of the bombarding particle, it is seen that the fissionability increases markedly as the nuclear charge increases. Also, for a given element, except the very fissionable ones like uranium and thorium, the cross section increases substantially as the energy of the bombarding particle increases from 50 Mev to 350 Mev.

A detailed radiochemical investigation of the fission of bismuth with 190-Mev deuterons was made by Goeckermann and Perlman.[5] They showed that the fission-yield curve is a symmetrical single-humped curve, and that the primary fission products could be considered as arising from a fissioning nucleus formed by evaporation of twelve neutrons after the excitation of the target nucleus by the bombarding projectile. The isolated fission products were shown to be neutron-excessive for low mass and neutron-deficient for high mass, as expected from a fission process occurring with a constant neutron to proton ratio. Recently, Biller[6] studied the fission of bismuth with 340-Mev protons and interpreted the results as arising from a distribution of fissioning nuclei.

The work reported in this paper compares the fission process in some of the elements from holmium to thorium. The bombarding particles were 450-Mev protons from the University of Chicago synchrocyclotron. The radiochemical method of isolating the radioactive species, ascertaining their identity, and measuring their radioactivity was used to determine the various parameters of the fission process such as cross section, neutron to proton ratio of the fissioning nucleus, the variation in yield with charge, etc. As the charge of the target nucleus decreases, there is observed a decrease in fission cross section, a decrease in the mass number of the most probable fission products, and a decrease in the neutron to proton ratio of the primary fragments formed in high yield. In contrast, the excitation energy for the fission process remains fairly constant as the nuclear charge is varied.

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