Further Results on Neutron Production by Cosmic-Ray Particles at Sea Level*

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Further measurements at sea level on neutrons coincident with charged cosmic-ray particles are reported. It is shown that the coincident neutrons are neither incident from the air nor produced in the neutron detector; they are produced in the Pb in our experimental arrangement. The earlier evidence for neutrons associated with the stopping in Pb of charged particles filtered by 12.7 cm Pb is confirmed. Evidence is presented for a second effect-neutron production in Pb in some kind of penetrating ionizing event. These neutron-penetrating particle coincidences may well be related to those discovered by Tongiorgi in penetrating showers; their bearing on the interpretation of neutron-stopped particle coincidences is discussed. With increasing thickness of the Pb filter above the G-M tube telescope, the frequency of the latter is essentially constant, while the frequency of the "neutron showers" increases steadily. Intensity considerations indicate that the bulk of the neutron-stopped particle coincidences are due to μ-mesons stopped in the Pb; the neutron penetrating particle coincidences may well be due to incident nucleons. A very crude estimate of the average number of neutrons per stopped negative meson gives 2 or 3; the systematic errors are so uncertain that we can only conclude that the multiplicity is with high probability less than about 5.

IN a previous communication,[1] we reported the observation of neutrons coincident with the stopping in a Pb absorber of charged particles filtered by 12.7 cm Pb. In a control experiment, in which the anticoincidence counters under the absorber were disconnected, we found a doubling of the neutron coincidence rate, and we suggested that this increase was due to neutrons produced by or contained in penetrating ionizing events. Our investigation of these two kinds of neutron coincidences, coincidences with stoppings and coincidences with penetrations, has been continued[2] with the modified arrangement shown in Fig. 1. The filter is now above the double-coincidence telescope made up of the two G-M tube groups A and B, and the number of boron-ten slow neutron counters[3] in the paraffin thermalizer has been increased to seven. In addition, we now measure concurrently the neutron coincidences $(AB{:}N)$ and $(AB\text{–}C{:}N)$. Coincidences (AB) and anticoincidences $(AB\text{–}C)$ each produce equal "gate" pulses, delayed about 5μsec. and 170μsec. long, through which any neutron counter pulse, N, can pass. If an N pulse occurs while the (AB) gate is on, an $(AB{:}N)$ coincidence is recorded; sometimes, the $(AB\text{–}C)$ gate is also on, and an $(AB\text{–}C{:}N)$ coincidence is then also recorded. Thus we have, in effect, direct observations of $(AB\text{–}C{:}N)$ events—neutrons associated with stoppings—and $(ABC{:}N)$ events—neutrons associated with penetrations. The counts (AB), $(AB\text{–}C)$, N, $(AB{:}N)$ and $(AB\text{–}C{:}N)$ are not only totalized on electromechanical counters but are individually recorded on the moving chart of an Esterline-Angus Company "Operation Recorder." This gives a valuable check on the operation of the equipment.

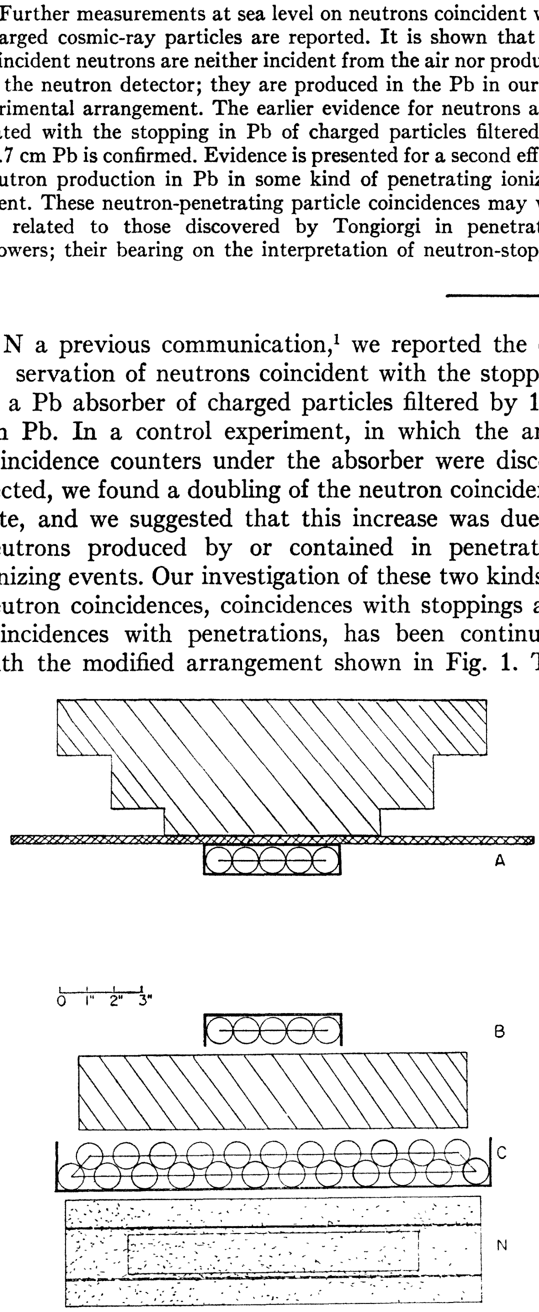

FIG. 1. Arrangement of apparatus.

Measurements have been made (under a thin wooden roof) with and without the 78.9 g/cm^2 Pb absorber for three filter thicknesses—0, 28.8 g/cm^2 Pb, and 158 g/cm^2 Pb (the Pb equivalent of 143 g/cm^2 Pb plus 10 g/cm^2 Fe). For each configuration data were taken with and without 1 mm Cd sheaths on the neutron counters.

The results for neutrons coincident with stoppings, $(AB\text{–}C{:}N)$, are given in Table I. Each box of this table refers to a particular configuration; and in each box we have the data obtained without Cd (top line) and with Cd (third line). The second and fourth lines give the expected numbers of chance coincidences (casuals) in the two cases, taken as the product of the $(AB\text{–}C)$ rate, the N rate, the gate length, and the duration. The sans-Cd rate corrected for casuals is given by the observed

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[1] Sard, Ittner, Conforto, and Crouch, Phys. Rev. **74**, 97 (1948).
[2] The results in the present paper have been reported in part at the Chicago Meeting of the American Physical Society, November 26, 1948, Phys. Rev. **75**, 327 (1949) and in full at the St. Louis meeting of the Mid-West Cosmic-Ray Colloquium, April 9, 1949.
[3] Proportional counters lined with metallic boron enriched in the isotope of mass ten. We are grateful to the Argonne National Laboratory for the continued loan of these counters.

TABLE I. Neutrons associated with stoppings (AB–C:N).

Absorber	Filter: None	Filter: 28.8 g/cm² Pb	Filter: 158 g/cm² Pb equivalent
None (0.69 g/cm² brass in G-M tube walls)	sans Cd: 0 in 107.0h expected casuals: 0.846 with Cd: 0 in 40.22h expected casuals: 0.198 corrected rate: 0	sans Cd: 2 in 111.07h expected casuals: 0.531 with Cd: 0 in 88.67h expected casuals: 0.360 corrected rate: 0.01±0.01/h	sans Cd: 6 in 76.18h expected casuals: 0.257 with Cd: 1 in 58.43h expected casuals: 0.119 corrected rate: 0.08±0.03/h
78.9 g/cm² Pb (plus 0.69 g/cm² brass in G-M tube walls)	sans Cd: 52 in 117.02h expected casuals: 4.30 with Cd: 0 in 25.75h expected casuals: 0.231 corrected rate: 0.41±0.06/h	sans Cd: 129 in 146.32h* expected casuals: 4.19 with Cd: 1 in 38.00h expected casuals: 0.762 corrected rate: 0.85±0.08/h	sans Cd: 157 in 248.85h expected casuals: 2.43 with Cd: 4 in 142.6h expected casuals: 0.790 corrected rate: 0.60±0.05/h

* Actually, only 122 counts in this time, but 38 of them were obtained during a period when the (AB) and (AB–C) rates were low in the same proportion because of a faulty G-M tube and the 38 have, therefore, been scaled up to 45. The estimated statistical standard error of the corrected rate is $(122)^{1/2}$ divided by 146.32h.

counts less the expected casuals, divided by the duration, with a standard error estimated as the square root of the observed counts, divided by the duration. The with-Cd rate corrected for casuals is computed in the same way. If it exceeds its estimated standard error, it is subtracted from the corrected sans-Cd rate to give the "corrected rate" in the fifth line of the box, the two estimated standard errors being compounded quadratically. Otherwise, the "corrected rate" is simply the corrected sans-Cd rate. It is seen that the observed numbers with Cd are always of the order of magnitude of the expected numbers of casuals. This is also the case sans-Cd when the absorber is absent, but when the absorber is in place, the observed coincidences far exceed the expected casuals.

One sees from Table I that the (AB–C:N) rate for all filter thicknesses is essentially zero in the absence of the absorber, and is essentially constant when the absorber is in place. Its vanishing in the absence of absorber is significant, as the (AB–C) rate is then not negligible (2.28/min., 1.68/min., 0.98/min. for the three filter thicknesses) compared with its value when the absorber is in place (11.02/min., 7.85/min., and 2.41/min. for the three filter thicknesses). This shows that the Pb absorber is essential to the production of the neutrons detected. The approximate constancy of (AB–C:N) when the absorber is in place and the filter thickness is changed shows that a large fraction of the coincident neutrons are produced in the absorber by particles present in the air, and that these particles are not electrons. We feel that no quantitative significance need be attached to the changes in (AB–C:N) with filter thickness, because of the poor statistics and because there were sizeable fluctuations in the N rate for each geometry which may possibly have been associated with fluctuations in neutron detecting efficiency.[4]

Table II presents the results for (ABC:N)—neutrons coincident with penetrations; it is made up in exactly the same way as Table I except that (ABC) replaces (AB–C) in the calculation of the casuals. One sees, first of all, that there are essentially no neutron-charged particle coincidences in the absence of filter and absorber. This means that the effect of any neutron showers incident on the apparatus is negligible, as well as neutron production in the paraffin or neutron counters. We conclude that the non-vanishing neutron coincidence rates in Tables I and II represent the effect of neutron production in the absorber or filter. The rates in the first row of Table II are points of the transition curve for "neutron showers" produced in the lead filter by ionizing or non-ionizing radiation from any direction; these "showers" are characterized by having one or more charged particle passing through A, B, and C, and one or more detectable neutron. The steady increase with filter thickness shows that these showers are not associated with the electronic-photonic component. The rates in the second row are harder to interpret, as production and absorption in both filter and absorber are involved.

It is likely that an appreciable fraction of these neutron showers from the filter give (AB–C:N) coincidences when the 80 g/cm² Pb absorber is inserted. Comparison of the rates in the corresponding columns (especially the first!) of the first row of Table II and the second row of Table I shows that this effect does not suffice to explain the major part of the (AB–C:N) coincidences, which must be due either to μ-meson stoppings in the absorber or to proton stoppings there.

[4] Correction for an observed steady increase with time in the (AB) rate for a given geometry (about 5 percent between the middle of October and end of December, 1948) and for an observed increase of neutron detecting efficiency with filter thickness (for Po-Be neutrons originating in the absorber the efficiencies are in the ratio 0.92:0.96:1.00) leaves the (AB–C:N) rates in the ratio 0.45±0.7:0.84±0.08:0.60±0.05.

TABLE II. Neutrons associated with penetrations ($ABC:N$).

Absorber	Filter: None	Filter: 28.8 g/cm² Pb	Filter: 158 g/cm² Pb equivalent
None (0.69 g/cm² brass in G-M tube walls)	sans Cd: 25 in 107.0h expected casuals: 14.7 with Cd: 3 in 40.22h expected casuals: 3.60 corrected rate: 0.10±0.05/h	sans Cd: 50 in 111.1h* expected casuals: 11.9 with Cd: 11 in 88.67h expected casuals: 8.04 corrected rate: 0.34±0.06/h	sans Cd: 49 in 76.18h expected casuals: 7.63 with Cd: 3 in 58.43h expected casuals: 3.46 corrected rate: 0.54±0.09/h
78.9 g/cm² Pb (plus 0.69 g/cm² brass in G-M tube walls)	sans Cd: 92 in 117.0h expected casuals: 11.5 with Cd: 1 in 25.75h expected casuals: 0.608 corrected rate: 0.69±0.08/h	sans Cd: 225 in 146.3h** expected casuals: 16.9 with Cd: 4 in 38.00h expected casuals: 3.08 corrected rate: 1.42±0.11/h	sans Cd: 383 in 248.9h expected casuals: 28.2 with Cd: 14 in 142.6h expected casuals: 9.29 corrected rate: 1.43±0.08/h

* Actually, only 46 counts in this time, but 18 of them were obtained during a period when the (AB) and (AB–C) rates were low in the same proportion because of a faulty G-M tube, and the 18 have, therefore, been scaled up to 22.
** Actually, only 212 counts in this time, but 68 of them were obtained during a period when the (AB) and (AB–C) rates were low in the same proportion because of a faulty G-M tube, and the 68 have, therefore, been scaled up to 81.

Intensity considerations argue against the latter.[5] Consider the no-filter case (first column); here any π-mesons stopped in the absorber would have first to be produced there by stopped protons, and, therefore, an argument against a protonic origin of the (AB–$C:N$) events applies to π-mesons as well. The (AB–$C:N$) rate is 0.4/hr. The meson stopping rate is approximately equal to the difference of the (AB–C) rates with and without the absorber when the 158 g/cm² Pb filter is in place: $2.41-0.98=1.43$/min., which is 210 times greater. As explained below, this ratio corresponds to an average number of neutrons per stopped negative meson of the order of two or three, a plausible result. Little is known, on the other hand, of the frequency with which protons get stopped by nuclear collisions at sea level, other than that it is extremely small. An experiment now under way on the behavior of the neutron coincidence rates with increasing depth should settle the question; in the meanwhile, we proceed on the assumption that the bulk of the (AB–$C:N$) events are due to μ-mesons.

It is not excluded, on the other hand, that the neutron showers are produced by nucleons. Consider again the no-filter case. The ($ABC:N$) rate is 0.7/hr, while the (ABC) rate is 29.1/min., 2500 times greater. Protons compose from 0.5 to 5 percent of these particles.[6,7]

A determination of the average number of neutrons produced per stopped negative meson would indicate the extent of nuclear excitation by μ-meson capture. Our arrangement is not suited for such a measurement; one is tempted, nevertheless, to draw some inferences as to order of magnitude. We have measured the efficiency of the neutron-detecting system for Po–Be neutrons originating in the Pb absorber; this was done by measuring the N rate with a calibrated source placed at various positions inside the Pb. The result is 5×10^{-3}, for incoherent neutron counting. For neutron coincidences, the efficiency is reduced by the factor $1-\exp(t/\tau)$, where t is the gate length, and τ the mean life of a thermal neutron in the detector. τ was measured by observing ($AB:N$) coincidences simultaneously with two different gate lengths, one extending from 5 to 78μsec. after (AB), the other from 5 to 178μsec. The corrected numbers of ($AB:N$) coincidences were 120 and 179, respectively, giving $\tau=80\mu$sec. The coherent neutron efficiency, therefore, is 4.5×10^{-3}. Assuming that the meson-stopping rate is 1.4/min., that 45 percent of these mesons are negative, that the neutrons resulting from this capture are detected with an efficiency of 4.5×10^{-3}, and that the true (AB–$C:N$) rate from the absorber is 0.4/hr., one obtains 2.4 for the multiplicity. The systematic errors in this estimate are so uncertain that we dare only infer that the average multiplicity is less than about 5.

Some indication that the coincident neutrons detected have an energy spectrum like that of Po–Be neutrons is given by measurements we carried out with the boron counters vertical instead of horizontal ("long counter geometry"). The counting rate for Po–Be neutrons was reduced by the factor 0.57±0.13, the corrected (AB–$C:N$) rate by the factor 0.52±10, and the corrected ($ABC:N$) rate by the factor 0.58±0.05. The uncertainties indicated are estimated statistical standard errors.

[5] Statistically significant data obtained at sea-level with a magnetized iron analyzer would settle the question, as protons are not focussed by these devices. The newer data of G. W. McClure and G. Groetzinger, Phys. Rev. **75**, 340 (1949), obtained at 4300 m elevation speak in favor of μ-mesons, though in our ignorance of the geometrical arrangement we must leave room for the slight possibility that the 16 neutron coincidences reported could be ascribed to π^--mesons incident on the analyzer at this altitude.

[6] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948), Table II.

[7] Todd, Henderson, Miller, and Potter, Phys. Rev. **76**, 591, 1949.