# THE INTEGRAL AND DIFFERENTIAL RANGE SPECTRA OF SEA-LEVEL MESONS

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[*Manuscript received November* 30, 1953]

*Summary*

The differential and integral range spectra of the hard component of cosmic rays in water and lead have been determined up to a thickness of 1500 g cm$^{-2}$ of water, and 2800 g cm$^{-2}$ of lead. The differential results indicate that there is no anomaly with an intensity greater than 5 per cent. in the differential momentum spectrum in the region below 4 BeV/c. A comparison of the integral range and momentum spectra supports the energy loss data of Halpern and Hall in preference to those of Bethe and Bloch in the case of water. No such distinction of the theories is possible in the case of lead and, although the integral absorption curve in lead agrees with that obtained by Heyland and Duncanson (1953*b*), there is an unexplained discrepancy between experiment and theory. The intensity of knock-on showers as a function of thickness of water absorber has also been determined.

## I. Introduction

In an earlier report (Dyer 1953) an account was given of a determination of the integral and differential range spectra of sea-level mesons in water. The differential data obtained did not possess sufficient accuracy to lead to a conclusion on the reality of an anomaly in the momentum spectrum near 3 BeV/c referred to by several authors (Blackett 1937 ; Glaser, Hamermesh, and Safonov 1950 ; Caro, Parry, and Rathgeber 1951).

As there was some evidence of an anomaly, the integral and differential spectra (in the neighbourhood of 4 BeV/c) were studied further with improved equipment. A greater reliability was obtained by replacing battery operated circuits with mains operated ones, adequately stabilized against voltage fluctuations.

Since the water-hole was available during the winter months only, corresponding measurements were made with a lead absorber during the summer. The results of both experiments are reported in this paper.

## II. Lead Absorption Experiment

The general design of the counter telescope was largely determined by the fact that a quantity of lead in ingot form of the order of $1\frac{1}{2}$ tons was available on loan. In order to obtain the necessary absorber thickness only one arrangement of the lead was possible, that is, within the telescope with the cross-sectional dimensions of the absorber approximately 9 by 6 in. The differential absorber had a thickness of 20 cm.

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The telescope arrangement is shown in Figure 1. Counters $A$, $B$, and $C$ had an effective length of 18 cm, and counters in tray $D$ had an effective length of 50 cm. The counters placed around trays $B$ and $C$ were in anti-coincidence

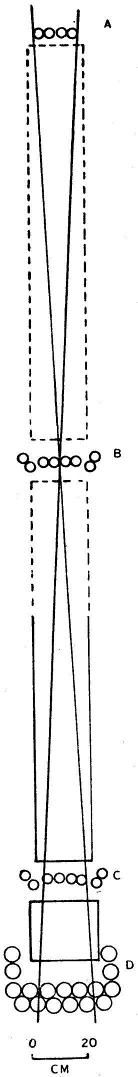



Fig. 1

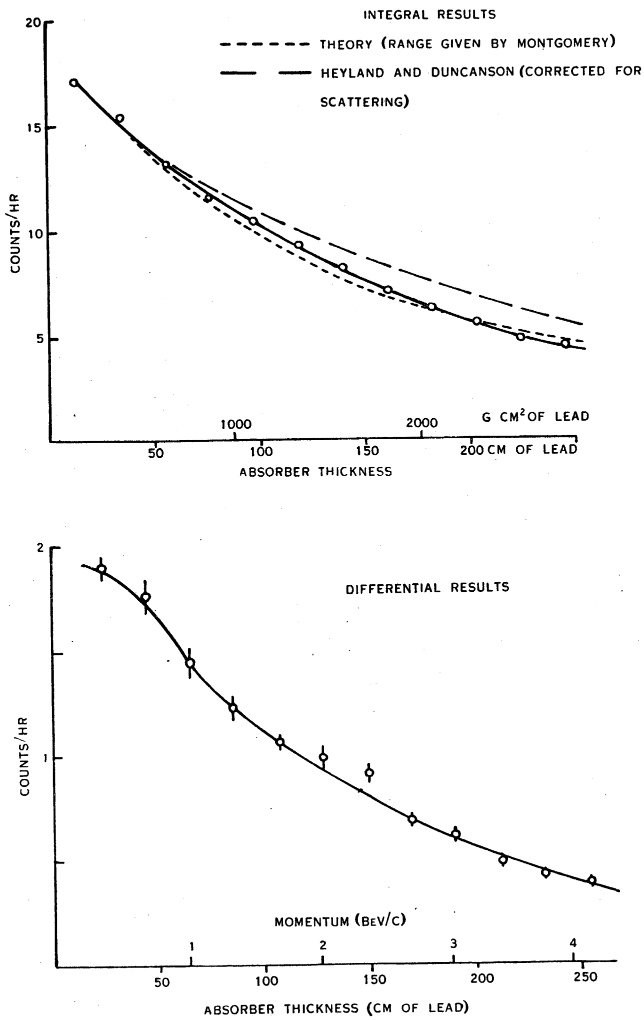



Fig. 2

Fig. 1.—Counter arrangement for lead absorption experiment.
Fig. 2.—Integral and differential range spectra in lead.

with the threefold coincidence arrangement $ABC$ and provided protection against side showers. Coincidences $ABC$ and $ABC$-$D$ were recorded for absorber thicknesses of from 14 cm up to 245 cm in steps of 21 cm. The coincidence circuits had a resolving time of 5 $\mu$sec.

The anti-coincidence background rate was obtained by removing the differential absorber and a smoothed correction applied to the differential counting rates.

The final results are plotted in Figure 2 and presented in Table 1.

TABLE 1

INTEGRAL AND DIFFERENTIAL RANGE SPECTRA IN LEAD

| Integral | | Differential | |
|---|---|---|---|
| (counts/hr) | Range (g cm$^{-2}$) | (counts/hr) | Mean Range (g cm$^{-2}$) |
| $17\cdot2\pm0\cdot2$ | 159 | $1\cdot90\pm0\cdot06$ | 272 |
| $15\cdot4\pm0\cdot3$ | 397 | $1\cdot77\pm0\cdot08$ | 511 |
| $13\cdot2\pm0\cdot2$ | 636 | $1\cdot45\pm0\cdot07$ | 749 |
| $11\cdot6\pm0\cdot2$ | 874 | $1\cdot22\pm0\cdot06$ | 987 |
| $10\cdot5\pm0\cdot1$ | 1112 | $1\cdot06\pm0\cdot03$ | 1226 |
| $9\cdot4\pm0\cdot2$ | 1350 | $0\cdot99\pm0\cdot05$ | 1463 |
| $8\cdot2\pm0\cdot1$ | 1589 | $0\cdot92\pm0\cdot04$ | 1702 |
| $7\cdot1\pm0\cdot1$ | 1828 | $0\cdot68\pm0\cdot03$ | 1941 |
| $6\cdot3\pm0\cdot1$ | 2065 | $0\cdot61\pm0\cdot03$ | 2179 |
| $5\cdot7\pm0\cdot1$ | 2305 | $0\cdot48\pm0\cdot02$ | 2419 |
| $4\cdot9\pm0\cdot1$ | 2545 | $0\cdot42\pm0\cdot02$ | 2657 |
| $4\cdot6\pm0\cdot1$ | 2780 | $0\cdot38\pm0\cdot02$ | 2895 |

## III. Water Absorption Experiment

The new counter telescope used in conjunction with the underwater equipment described previously (Dyer 1953) is shown in Figure 3. The main features of the earlier arrangement were preserved, but larger counting rates were obtained by increasing the size of the counter trays.

Threefold coincidences *ABC* were recorded of particles traversing 10 cm of lead, and the number stopping in a further 10 cm of lead obtained by means of the double-layer anti-coincidence tray *D*. Two counters *E* were placed on either side of tray *B* in anti-coincidence with trays *ABC* to provide protection against side showers and showers produced in absorber *a*.

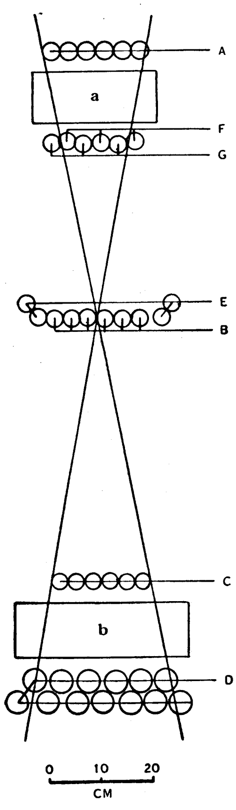
An additional tray of counters *FG* was placed immediately under absorber *a* with alternate counters connected in parallel. Coincidences *AFG* were selected and recorded and used also as an anti-coincidence " suppression " pulse on the coincidence arrangement *ABC*. Events *AFG* would be mainly knock-on showers and with this counter arrangement would be detected with an efficiency of about 50 per cent. The use of counters *EFG* in this manner provided adequate protection against unwanted events.

The counters *ABCEFG* had an effective length of approximately 18 cm and were 3 cm in diameter. The counters in tray *D* had an effective length of 40 cm and were 5 cm in diameter. All counters were of the Maze type and were constructed according to the technique of MacKnight and Chasson (1951).

The coincidence and amplifier circuits (resolving time 5 $\mu$sec) were located in the underwater tank and operated from stabilized B+ and heater voltages.

The main power supply and recording unit was situated in a hut adjoining the water-hole.

The integral and differential range spectra were determined down to a depth of 14 m of water in steps of approximately 1 m, and the anti-coincidence back-



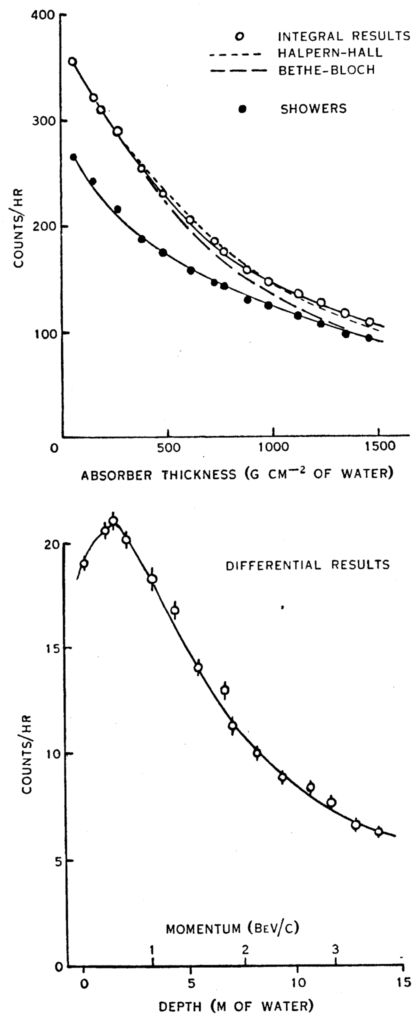




Fig. 3 Fig. 4

**Fig. 3.**—Counter arrangement for water absorption experiment.

**Fig. 4.**—Integral, differential, and shower curves in water.

ground measurement was made by removing the differential absorber. At the same time measurements of the shower intensity (*AFG*) were obtained over the same range of absorber thickness.

The results are presented in Figure 4 and in Table 2.

## IV. Discussion of Results

### (a) *Integral Spectra*

The integral results are compared in Figure 5 with the curve given by Rossi (1948). In order to convert to equivalent range in g cm$^{-2}$ of air use was made of the data given by Montgomery (1947) for the range of mesons in air and lead. The momentum-range relation for water was obtained by integrating the energy loss data given by Halpern and Hall (1948), and all results were normalized to Rossi's curve at 98 g cm$^{-2}$ of air.

Table 2

Results of Underwater Investigation

| Depth (m of water) | Integral (counts/hr) | Differential (counts/hr) | Showers (counts/hr) |
|---|---|---|---|
| 0 | 355 $\pm 1\cdot3$ | $19\cdot0\pm0\cdot3$ | 265 $\pm1\cdot3$ |
| 1·03 | 321 $\pm1\cdot9$ | $20\cdot5\pm0\cdot5$ | 241 $\pm1\cdot6$ |
| 1·30 | 310 $\pm1\cdot7$ | $21\cdot0\pm0\cdot4$ | 232 $\pm1\cdot0$ |
| 2·12 | 290 $\pm1\cdot4$ | $20\cdot1\pm0\cdot4$ | 216 $\pm1\cdot3$ |
| 3·24 | 254 $\pm1\cdot6$ | $18\cdot3\pm0\cdot5$ | 194 $\pm1\cdot3$ |
| 4·29 | 230 $\pm1\cdot3$ | $16\cdot8\pm0\cdot4$ | 177 $\pm1\cdot2$ |
| 5·52 | $205\cdot2\pm1\cdot1$ | $14\cdot0\pm0\cdot3$ | $158\cdot6\pm1\cdot2$ |
| 6·70 | $185\cdot1\pm1\cdot2$ | $13\cdot0\pm0\cdot4$ | $147\cdot0\pm1\cdot0$ |
| 7·12 | $174\cdot8\pm1\cdot2$ | $11\cdot2\pm0\cdot4$ | $142\cdot0\pm1\cdot1$ |
| 8·19 | $159\cdot0\pm0\cdot9$ | $10\cdot0\pm0\cdot2$ | $129\cdot0\pm1\cdot1$ |
| 9·36 | $147\cdot5\pm1\cdot0$ | $8\cdot9\pm0\cdot3$ | $120\cdot7\pm1\cdot0$ |
| 10·72 | $136\cdot2\pm1\cdot0$ | $8\cdot4\pm0\cdot3$ | $112\cdot3\pm0\cdot9$ |
| 11·77 | $127\cdot4\pm0\cdot7$ | $7\cdot6\pm0\cdot2$ | $103\cdot8\pm0\cdot7$ |
| 12·90 | $116\cdot2\pm0\cdot8$ | $6\cdot5\pm0\cdot3$ | $97\cdot3\pm0\cdot7$ |
| 14·00 | $108\cdot3\pm0\cdot6$ | $6\cdot1\pm0\cdot2$ | $91\cdot8\pm0\cdot6$ |

The general agreement with the Rossi curve can be seen from Figure 5, and in particular it will be noted that the results for water agree somewhat better than those for lead. Rossi's curve is based on the work of Ehmert (1937) and Wilson (1938), and the present results lie within the experimental errors of their measurements.

### (b) *Differential Spectra*

For the purpose of deciding the reality of an anomaly in the momentum spectrum, a differential measurement of the type described here possesses a greater degree of sensitivity than an integral one.

When both differential experiments are taken into account, it can be said with confidence that no anomalies greater than 5 per cent. exist in the momentum spectrum below 4 BeV/c.

This result agrees with that of Brini, Rimondo, and Filosofo (1952) who, from a similar experiment using an iron absorber, concluded that there are no irregularities greater than a few per cent. Similarly, Heyland and Duncanson (1953*a*, 1953*b*) decided by a detailed investigation using a lead absorber that there are no significant anomalies in the region 0–365 cm of lead.

By making use of the normalizing factors fitting the integral results to the corresponding Rossi curve, and the equivalent ranges in air and lead given by Montgomery (1947) it is possible to estimate the absolute intensity of the differential spectrum from the present results (Fig. 6). It is seen that the

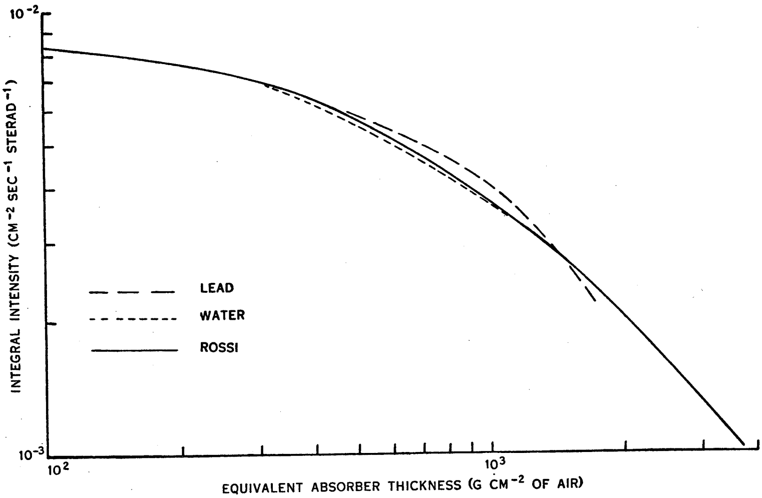



Fig. 5.—Integral range spectra in absolute units.

experimental curves are of similar shape to the Rossi differential curve but lie somewhat higher. This result is consistent with the suggestion offered by York (1952) that the Rossi curve is 20 per cent. too low.

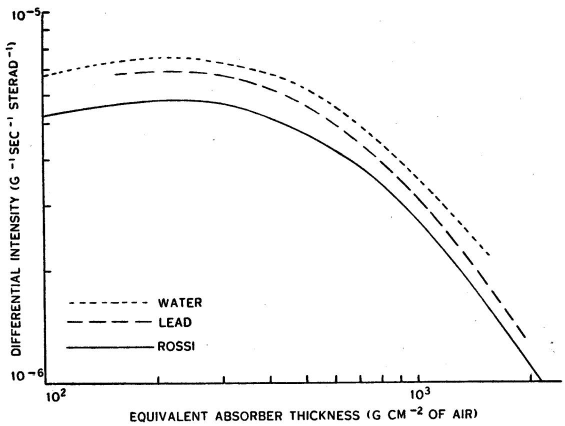



Fig. 6.—Differential range spectra in absolute units.

### (c) *Shower Measurements*

The intensity of knock-on events as a function of thickness of water absorber has been presented in Figure 4. Two aspects of this shower measurement are of interest: (*a*) the ratio of the number of knock-on events to the meson intensity and (*b*) the way in which this ratio varies with depth. Janossy (1948, p. 245) calculates the ratio of knock-on events at sea-level to be 0·10, and this agrees with the present results when it is noted that this type of counter arrangement has a detection efficiency of approximately 50 per cent. for two-particle showers.

The variation of this ratio with depth is shown in Figure 7 in which the value at zero depth has been normalized to the above value of 0·10. Two calculations of the variation of the intensity of knock-on events with depth underground have been made (Janossy 1948, p. 247 ; Hayakawa and Tomonaga 1949), but these authors are mainly concerned with very great depths and no profitable comparison with their results is possible.

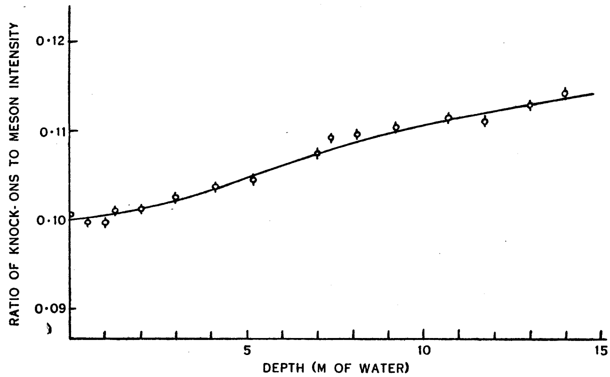



Fig. 7.—Ratio of knock-on showers to meson intensity as a function of depth.

## V. Range–Momentum Relation for High Energy Mesons

It is evident from the work of George (1952) that the only significant process causing energy loss for mesons with energy less than 4 BeV is that of ionization. Thus by comparing the intensity-depth curves with curves based on the integral momentum spectrum and theoretical energy loss data it should be possible to make some test of the different theories.

The chief point of interest lies in the difference between the familiar Bethe-Bloch energy loss curve and that given by Halpern and Hall (1948). The data for water provide a good test in this respect because of the large polarization effect predicted for water by Halpern and Hall. This is not so in the case of lead below 4 BeV/c and the difference between the two theories is insignificant for our purpose.

Thus in Figures 2 and 4 theoretical absorption curves are presented making use of the data given by Halpern and Hall (1948) for water, Montgomery (1947) for lead, and the integral momentum spectrum as determined by the Melbourne cosmic ray spectrometer. To permit normalization at the minimum absorber thickness the following information was used : a range of 14 cm of lead corresponds to 0·29 BeV/c ; 10 cm of lead corresponds to 0·24 BeV/c and to 58 g $cm^{-2}$ of water.

Considering first the results for water, it is seen from Figure 2 that the experimental results are in much better agreement with the theory of Halpern and Hall than with that of Bethe and Bloch. The slight discrepancy below 1000 g $cm^{-2}$ of water can be attributed to loss of particles by scattering out of the coverage of the counter telescope. Because of the directional selectivity of the telescope it is plausible to assume that at these shallow depths more mesons will be scattered away from the telescope than scattered in, resulting in a net loss of particles.

The discrepancy above 1000 g $cm^{-2}$ portends the very large departure found by Rathgeber (1951) in a similar comparison extended down to very great depths.

The results for lead show very different behaviour. The departure from theory at about 1000 g $cm^{-2}$ of lead is in the wrong direction to be explained by scattering. It will be seen from Figure 2 that the results obtained in a similar experiment by Heyland and Duncanson (1953*b*), when corrected for scattering, exhibit an even greater departure from the theoretical curve. The uncorrected data of these authors are found to coincide with the results of the present experiment.

## VI. Acknowledgments

The author is indebted to Professor L. H. Martin for his active interest in the problem and to Dr. H. D. Rathgeber for advice in the design of the experiment. Thanks are due to Mr. H. Waters and his associates who assisted in maintenance of the cosmic ray station. The cooperation of the authorities of the City of Box Hill is also acknowledged.

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