# ENERGY LOSSES OF FAST $\mu$ MESONS IN THICK LAYERS OF MATTER

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If energy losses of $\mu$ mesons in the ground are taken into account [by formulas (1) and (2)], it is found that the $\mu$-meson spectrum previously measured underground (depth ~40 m water equivalent) agrees with the results of the corresponding measurements[2,3] performed at sea level.

IN the present article, we compare the $\mu$-meson spectrum underground (at a depth of ~40 m water equivalent), measured in 1958 by the mass-spectrometer method,[1] with the $\mu$-meson spectrum at sea level obtained recently by Pine, Davisson, and Greisen,[2] embracing the $\mu$-meson energy region up to the value of ~200 Bev.

Since the change in the spectrum depends primarily on the $\mu$-meson energy loss in the ground, the obtained results can be a check of the theoretical formulas for determining the energy loss.

To transform the spectrum at the ground to our depth of observation, it is necessary first to know the thickness of the ground and to take into account the energy loss by means of the known theoretical formulas.

1. In a previous work[1] we were unable to measure sufficiently accurately the thickness of the ground above the apparatus or to determine its density. We therefore employed comparative measurements of the intensity of the hard component at sea level ($I_0$) and at the given depth ($I$) by means of a separate telescope composed of three rows of counters with a lead filter. The intensity ratio was

$$I_0/I = 11.13 \pm 0.43.$$

Starting from this value and the $\mu$-meson spectrum at sea level, according to the data of Caro et al.,[3] we determined the minimum value of the $\mu$-meson momentum ($p_0$) necessary for the traversal of the given layer of ground. This turned out to be ~9.8 Bev and corresponded to a $\mu$-meson range of ~40 m in water.*

On the other hand, we determined the depth from the direct data of Ehmert[4] on the intensity of cosmic radiation at different depths under water.

According to the formulas used by Ehmert to approximate his experimental data, our depth was also equivalent to ~40 m of water.

On the basis of the above, and also from a comparison of the obtained ratio $I_0/I$ with the data of other authors, we conclude that the amount of ground above our setup was 4700—4800 g/cm$^2$ and that its stopping power was equivalent to ~40 m of water.*

2. The energy loss, $dE/dx$, of a $\mu$ meson passing through the ground (in the energy region > $10^9$ ev), calculated with the formula obtained by Barrett et al.,[5]† is

$$-dE/dx = 1.88 + 0.0766 \ln (E_m'/\mu c^2) + 3.5 \cdot 10^{-6} E, \quad (1)$$

where

$$E_m' = E^2/(E + \mu^2 c^2 / 2\mu_e)$$

and $dE/dx$ is expressed in Mev g$^{-1}$ cm$^2$. This formula takes into account the energy losses due to ionization (with allowance for the polarization of the medium), bremsstrahlung, pair production and nuclear interaction. As for the latter, in the energy region of interest to us ($10^{10} - 10^{11}$ ev), it gives a small contribution (2 — 3%) to the total loss. The values of the total $\mu$-meson energy loss calculated according to formula (1) are in good agreement with the calculations of Murdoch, Ogilvie, and Rathgeber.[6] At energies < $10^9$ ev, we took the value of the energy loss as 2.1 Mev g$^{-1}$ cm$^2$.

3. A $\mu$ meson having a momentum $p$ at sea level will have, after passing through a layer of ground of thickness $h$ g/cm$^2$, a momentum $p_1 < p$, owing to its being slowed down. In the recalculation of the spectrum it should be borne in mind that there is a change in the width of the momentum interval to which the same particles

*It should be mentioned that the particles are slowed down in the ground less than in water. In the range region of interest to us, $R_2 \approx 1.19\, R_1$, where $R_1$ and $R_2$ are the ranges of the particles in g/cm$^2$ in water and in the ground, respectively.[2]

†In reference 2 the last term of this formula was taken equal to $3.0 \times 10^{-6}$ E.

belong at sea level ($dp$) and at the given depth ($dp_1$), namely:[7]

$$dp_1/dp = k = [B(p_1)/B(p)]\,[f(p/\mu)/f(p_1/\mu)], \qquad (2)$$

where in the energy region $p < \mu^2/\mu_e$

$$B = \log\frac{4\mu_e^2(p/\mu)^4}{I^2(z)} - 2\frac{(p/\mu)^2}{1+(p/\mu)^2}.$$

4. The table gives all data necessary to transform the Pine-Davisson-Greisen spectrum to our depth. Additional data for the analogous transformation of the spectrum of Caro et al.[3] are also shown here.

In columns 2 and 3 of the table are shown the values of the absolute $\mu$-meson intensity at sea level (according to references 2 and 3); column 4 shows the momentum loss $\Delta p$, calculated according to formula (1), in passing through a layer of ground of thickness 4750 g/cm$^2$; column 5 gives the corresponding momentum of the $\mu$ mesons at our depth ($p_1 = p - \Delta p$); column 6 gives the values of k calculated according to formula (2); and, finally, columns 7 and 8 give the values of the absolute intensities of the $\mu$ mesons at our depth.

Figure 1 duplicates the $\mu$-meson momentum spectrum at our depth[1] and was obtained from measurements with magnetic fields $H_1$ = 3300 oe and $H_2$ = 6300 oe. On the same figure are shown the values of the intensity recalculated from sea level (see table).

## DISCUSSION OF RESULTS

1. From Fig. 1 it is seen that the experimental data[1] are in good agreement with the Pine-Davisson-Greisen spectrum transformed to our depth of observation. For momenta $p \gtrsim 0.5$ Bev it is observed that the calculated values of the intensity are a little higher than the experimental values, which is probably due to not taking into account the scattering of slow particles in the ground in the recalculation of the spectra[2,3] to our depth.

| Momentum p at sea level (Bev/c) | Absolute intensity at sea level, $10^{-8}$cm$^{-2}$sec$^{-1}$sr$^{-1}$ (Mev/c)$^{-1}$ | | Momentum loss over path of 4750 g/cm$^2$ underground (Bev/c) | Momentum $p_1$ at depth of 4750 g/cm$^2$ underground (Bev/c) | $dp_1/dp$ | Absolute intensity of particles with momentum $10^{-8}$cm$^{-2}$ ×sec$^{-1}$sr$^{-1}$(Mev/c)$^{-1}$ | |
|---|---|---|---|---|---|---|---|
| | from ref. 3 | from ref. 2 | | | | * | † |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 10 | 10 | 10 | ~9.8 | ~0.2 | 0.79 | 12.7 | 12.7 |
| 10.4 | 9 | 9 | ~9.9 | ~0.5 | 0.70 | 12.8 | 12.9 |
| 10.9 | 8 | 8.05 | 10.0 | 0.9 | 0.74 | 10.7 | 10.8 |
| 11.94 | 6.7 | 7.2 | 10.14 | 1.8 | 0.79 | 8.45 | 9.05 |
| 14.9 | 4 | 4.3 | 10.4 | 4.5 | 0.88 | 4.55 | 4.9 |
| 20 | 1.72 | 2.1 | 10.77 | 9.14 | 0.93 | 1.85 | 2.26 |
| 30 | 0.555 | 0.73 | 11.2 | 18.7 | ~0.96 | 0.58 | 0.76 |
| 40 | 0.230 | 0.33 | 11.5 | 28.4 | ~1 | 0.23 | 0.33 |
| 50 | 0.12 | 0.17 | 11.8 | 38.1 | ~1 | 0.12 | 0.17 |
| 60 | | 0.11 | 12.0 | 47.8 | ~1 | — | 0.11 |

*With spectrum of reference 3. †With spectrum of reference 2.

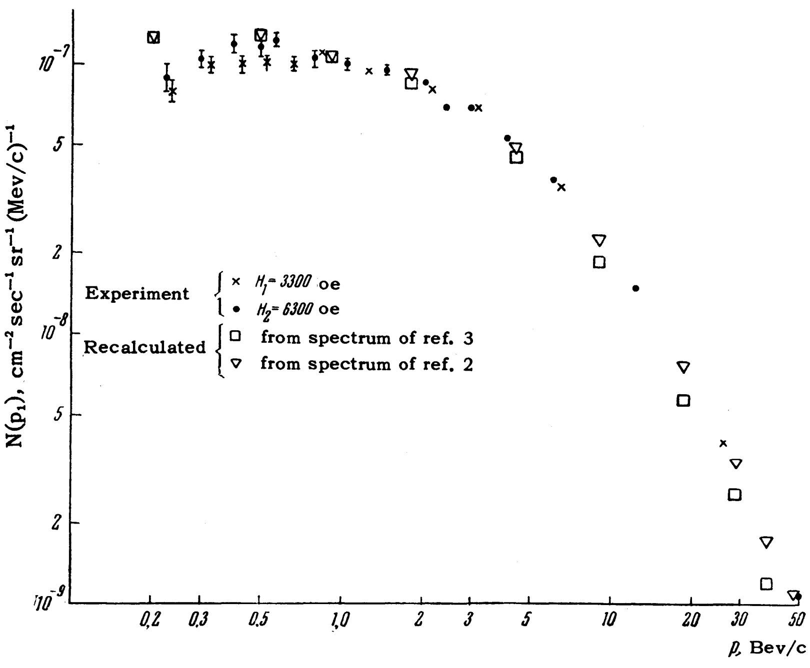


FIG. 1. Experimentally measured $\mu$-meson momentum spectrum underground (for two values of the magnetic field) and spectra recalculated from sea level.

The spectrum of Caro et al.[3] in the energy region $\gtrsim$ 15 Bev is somewhat steeper than the spectrum in reference 2, but the difference in the spectra is within the limits of statistical accuracy of both experiments. It may be dependent on the specific character of each apparatus, for example, a different effectiveness for excluding shower events.

We note that previously,[1] in transforming the spectrum of Caro et al.,[3] we did not take into account the increase in the $\mu$-meson energy loss with increasing energy (the increase between 10 to 60 Bev is ~20%). An account of the increase in the energy loss leads to somewhat poorer agreement between the recalculated data of Caro et al. and the experimental data in the high-energy region (see Fig. 1).

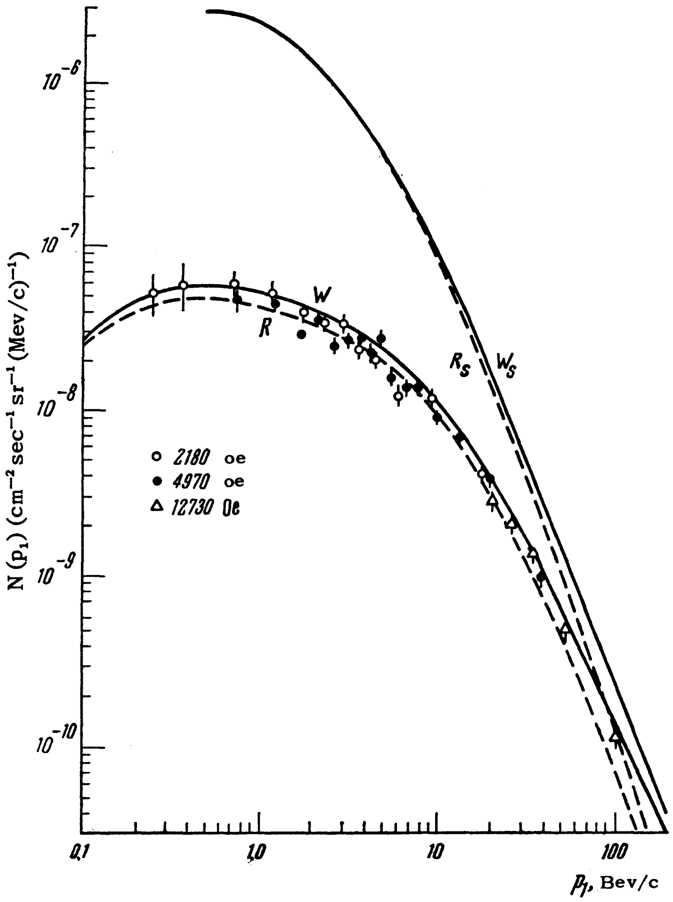


FIG. 2. $\mu$-meson momentum spectrum[6] at depth of 7000 g/cm$^2$ and comparison with spectrum at sea level ($R_S$, $W_S$).

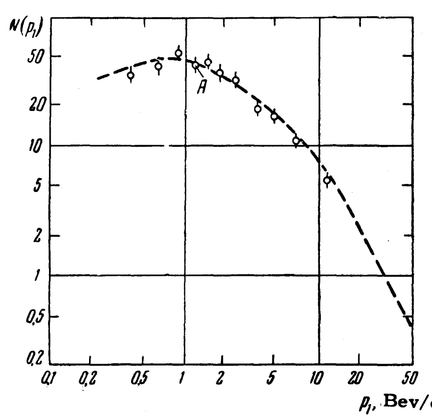


FIG. 3. $\mu$-meson momentum spectrum[9] at depth of 3800 g/cm$^2$. Circles indicate experimental data;[1] A — point of normalization of both spectra.

2. Murdoch, Ogilvie, and Rathgeber[6] obtained the $\mu$-meson momentum spectrum at a depth of 7000 g/cm$^2$ below the ground up to momentum values of ~100 Bev/c (Fig. 2). In comparing their spectrum with the spectrum at sea level,* the authors took into account only the values of the $\mu$-meson energy loss and obtained agreement between the transformed spectrum and the measured one.

3. A measurement of the momentum spectrum under the ground at a depth of 3800 g/cm$^2$ was carried out in reference 9. The authors found that their spectrum was in agreement with the spectrum of Caro et al., recalculated to their depth with allowance for scattering of the particles in the ground.† However, comparing their results with the data of reference 1, they erroneously assumed that both experiments were carried out at the same depth (see Fig. 3). As a matter of fact, there is a considerable difference in the depths (3800 and 4750 g/cm$^2$), which, first, does not allow a direct comparison of both spectra, and, second, removes the apparent discrepancy in the results as noted by the authors[9] with regard to the value of the energy loss in the ground.‡

## CONCLUSIONS

Good agreement is observed between the $\mu$-meson differential spectrum measured at a depth of

*The spectrum for sea level was used in two forms (see Fig. 2): 1) the directly measured[8] spectrum extrapolated above 20 Bev/c, varying as $p^{-2.75}$ and denoted $W_S(p)$; 2) the same spectrum, but corrected[5] for $\pi$–$\mu$ decay in the atmosphere, denoted $R_S$ (the latter being in agreement with the data of reference 3).

†In the energy region considered here, the spectrum of Caro et al. is practically no different from the Pine-Davisson-Greisen spectrum.

‡This misunderstanding arose from a certain vagueness in terminology: on the one hand, the authors, in measuring the intensity of cosmic radiation under thick layers of water, expressed the thickness in meters of water; on the other hand, in a number of articles the thickness of the ground is expressed in meters of water equivalent, where layers of ground and water are considered to be equivalent if they contain equal amounts of matter in g/cm$^2$. As shown above, however, such layers are not at all equivalent as regards the slowing down of charged particles.

~4700 g/cm[2] underground in the energy region $2 \times 10^8$ to $5 \times 10^{10}$ ev[1] and that calculated for the given depth on the basis of the Pine-Davisson-Greisen spectrum[2] by taking into account the $\mu$-meson energy loss in the ground. The spectrum of Caro et al.[3] transformed to the given depth of observation gives somewhat poorer agreement with the experimental results in the high-energy region, but the accuracy of the latter is not sufficient to ascribe any great significance to this difference. The authors of the latter work[6,9] also arrive at the conclusion that the $\mu$-meson differential spectrum obtained by them at depths of 3800 and 7000 g/cm[2] are in agreement with the $\mu$-meson spectrum at sea level recalculated for these depths; the $\mu$-meson spectrum at sea level used there is in close agreement with the Pine-Davisson-Greisen spectrum in the energy region under consideration.

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