III. AN EXPERIMENTAL BASIS FOR CLOCK BEHAVIOR

The first experiment to verify the behavior of clocks moving at high speed is described by B. Rossi and D. B. Hall in *Physical Review*, **59**, 223 (1941). A more recent experiment of the same type is described in lucid detail by D. H. Frisch and J. H. Smith in the *American Journal of Physics*, **31**, 342 (1963). Both of these experiments deal with the behavior of the mu-mesons (muons) that are produced near the top of the earth's atmosphere by the interaction of cosmic ray protons with the gas molecules in the atmosphere. Some of these muons then travel toward the earth's surface where they may be detected using appropriate detecting and counting apparatus.

Now the mean lifetime of a muon at rest has been measured to be 2.195 microseconds, or about 2.2 microseconds. Consider the plight of a muon produced at the top of the atmosphere such that it heads straight down toward the Earth's surface. According to pre-relativistic notions, it would travel for a distance equal to the product of its speed times its lifetime before decaying. Thus, even if it traveled at the speed of light, it would travel for an average distance

$$x = (2.2 \times 10^{-6} \text{ sec})(3 \times 10^{8} \text{ m/sec}) = 660 \text{ meters}$$

Since all the muons are produced at the top of the atmosphere, roughly 60,000 meters up, we would expect, if the muons behaved like Newtonian clocks, to see almost no flux of muons at the earth's surface, since they all would have decayed long before they reached the earth. More accurately, we would expect less than 1 in 10^{40} of the mesons produced to reach the earth.

In fact, the observed flux of muons at the earth's surface is quite large, and one must conclude that either they travel much faster than the light velocity on their way down, or else that they live for much longer than 2.2 microseconds. The experiments described in the above papers, in which the muon flux is measured at two different elevations and compared, determine that the moving muons must have a longer mean life, as measured by an observer on earth. For example, Frisch and Smith, in one of their runs on muons moving at $.995c$, measured the muon flux at the top of Mt. Washington in New Hampshire to be 563 counts/hour through their detector, while the flux at Cambridge, Massachusetts, 1907 meters lower, was 408 counts/hour. From these numbers they determined that the muons they observed must live for an average of about 19 microseconds (as measured by Frisch and Smith on earth), or about 9 times longer than the mean life for muons at rest.

Over the past several years, a variety of additional experiments have been performed on decaying particles, all of which confirm the relativistic behavior of fast-moving clocks. In particular, the lifetimes of pi-mesons (26.6 nanoseconds), and K-mesons (12.4 nanoseconds), have both been observed to lengthen appropriately at increased velocities.

A particularly elegant experiment on muons is described in a paper by J. Bailey, *et al.*, in *Nature*, **268** (1977). These experimenters looked at muons, both positively and negatively charged, in the CERN Muon Storage Ring, moving at .9994c. The observed lifetime for these muons was about 64.4 microseconds, or about 29.3 times the rest lifetime. Furthermore, since the muons were traveling in a circular orbit, they experienced large transverse accelerations (of the order of 10^{18} g). This acceleration appeared to have no observable effect on the lifetime. Their results were in complete agreement with SRT, making it clear that such observations have nothing to do with General Relativity.

We can summarize the results of all of these experiments by stating that the hyperbolic form of the locus of "τ-second ticks" on a spacetime diagram has been well-verified, at least for τ lying between 10^{-5} and 10^{-9} seconds. To date, there has been no reason to believe that the locus of "τ-second ticks" deviates from the hyperbolic form for values of τ outside this range.

It is this behavior of real clocks that we use as one of the starting points for our development of SRT.