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Calorimetric test of special relativity

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Momentum-analyzed beams of 20 and 17.326 GeV/c electrons with average currents of 4.23 and 4.55, and 9.48, 9.57, 14.4, and 15.66 μA, respectively, are predicted by special relativity to have average powers of 84.5 and 91, and 164.3, 165.8, 249.5, and 271.3 kW, respectively. This prediction is checked to 30% in a calorimetric experiment using the temperature rise in the cooling water of a high-energy beam dump at the Stanford Linear Accelerator Center. To our knowledge, this is the first macroscopic test specifically carried out to test this aspect of special relativity at these particle energies and power levels, although an earlier sequence of tests using copper as the heat absorber have been performed at this laboratory at lower power levels, and confirms the theory to higher accuracy.

I. INTRODUCTION

As has been emphasized by Pierre Duhem,[1] a theoretical structure in physics is never tested in all its aspects, and as has been emphasized by Kuhn,[2] a theory is rarely tested unless an alternative theory is proposed. The alternative theory which led to the test presented here was developed by one of us (R.L.C.) in an effort to understand why the energy expected from beta decay did not show up in a calorimeter. Of course, this is now conventionally explained by neutrino theory, but the early direct tests of that theory by recoil experiments do not look very convincing.

The theory of autodynamics starts with a new discussion of systems in relative motion. A critique of the procedure used to obtain the equations of special relativity theory leads to a simplification of Lorentz's equations and to a unique system of "observer" and "observed." This system is used for phenomena with or without acceleration. Starting from Maxwell's equations in the form

$$(\epsilon/c)\left[\frac{\partial E_x}{\partial t}\right]+\left[\frac{4\pi}{c}\right]\rho v=\mathrm{curl}H,\quad \mathrm{div}D=\frac{4\pi\rho}{\epsilon}\ ,$$

the standard development [as given, for example, in E. G. Cullwick, *Electromagnetism and Relativity* (Wiley, New York, 1957)] leads, with $\beta=(1-v^2/c^2)^{1/2}$, to the connection between frames S and S':

$$(\epsilon/c)\left[\frac{\partial E_x}{\partial t'}\right]+\left[\frac{8\pi}{c}\right]v'\rho'=\left[\frac{\partial}{\partial y'}\right]\frac{H_z-(\epsilon v'/c)E_y}{\beta}+\left[\frac{\partial}{\partial z'}\right]\frac{\epsilon v'_y}{\beta}$$

whereas for autodynamics β is multiplying rather than dividing. Other standard results are unaltered. The principle of momentum and energy conservation is maintained, but the equation relating energy to momentum becomes

$$[(4m_0c^2E-2E^2-m_0^2c^4)^2+4p^2m_0^2c^6]^{1/2}=m_0^2c^4\ .$$

The most appropriate application is to spontaneous autodynamics phenomena without contribution of energy from the external medium. The equations are summarized for comparison as follows:

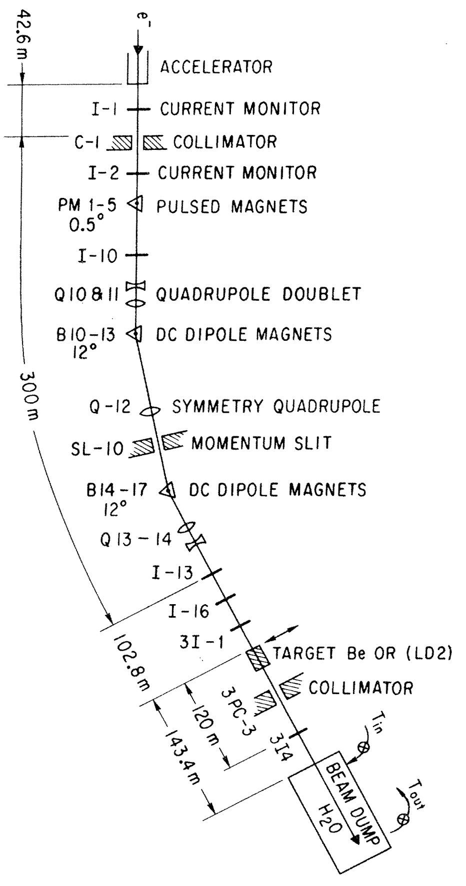

FIG. 1. Beam transport and experimental setup.

Einstein's equations	autodynamics equations
$E=m_0c^2$	$E=m_0c^2$
$m=m_0(1-v^2/c^2)^{-1/2}$	$m=m_0(1-v^2/c^2)^{+1/2}$
$E_c=m_0c^2[(1-v^2/c^2)^{-1/2}-1]$	$E_c=m_0c^2[1-(1-v^2/c^2)^{+1/2}]$
$p=m_0c(1-v^2/c^2)^{-1/2}$	$p=m_0v(1-v^2/c^2)^{+1/2}$
$e_0=\text{const}$	$e=e_0(1-v^2/c^2)$
$U_{e_0}=m_0c^2[(1-v^2/c^2)^{-1/2}-1]$	$U_e=m_0c^2[1-(1-v^2/c^2)^{+1/2}]$

When the experiment of Crane and Halpern[3] was analyzed using theory of autodynamics, the comparison was at least as good for autodynamics as for standard neutrino theory, but the accuracy of the data and scatter of the points did not allow a definite conclusion to be drawn. The theory of autodynamics attempts to explain this by allowing both the charge and the mass of an electron to decrease with velocity in such a way that the e/m ratio, and hence magnetic measurements, are unaffected. However, the theory then predicts that the energy deposited by stopping electrons in a calorimeter will be a small fraction of that predicted by special relativity, the reduction being a factor of

$$\frac{[1-(1-v^2/c^2)^{+1/2}]}{[(1-v^2/c^2)^{-1/2}-1]}\ .$$

For 20-GeV electrons $(1-v^2/c^2)^{-1/2}=2\times10^4/0.511=3.91\times10^4$, this factor is about 2.55×10^{-5} showing that any measurable temperature rise in the cooling water flowing through the Stanford Linear Accelerator Center (SLAC) beam dump immediately rules out autodynamics, if the current in the beam has been correctly measured.

Of course, there are a number of direct and indirect experiments which show that charge cannot vary to the extent contemplated by autodynamics,[4] one of the most sensitive being the differential motion of protons and electrons in atoms. If the charge is given by $q=e(1+kv^2/c^2)$, it has been shown by this type of analysis that[5] $|k|<8\times10^{-19}$ using the overall neutrality of atoms. But since the question had been raised, and the beam dumps at SLAC are instrumented for temperature measurement, therefore providing a calorimeter that could

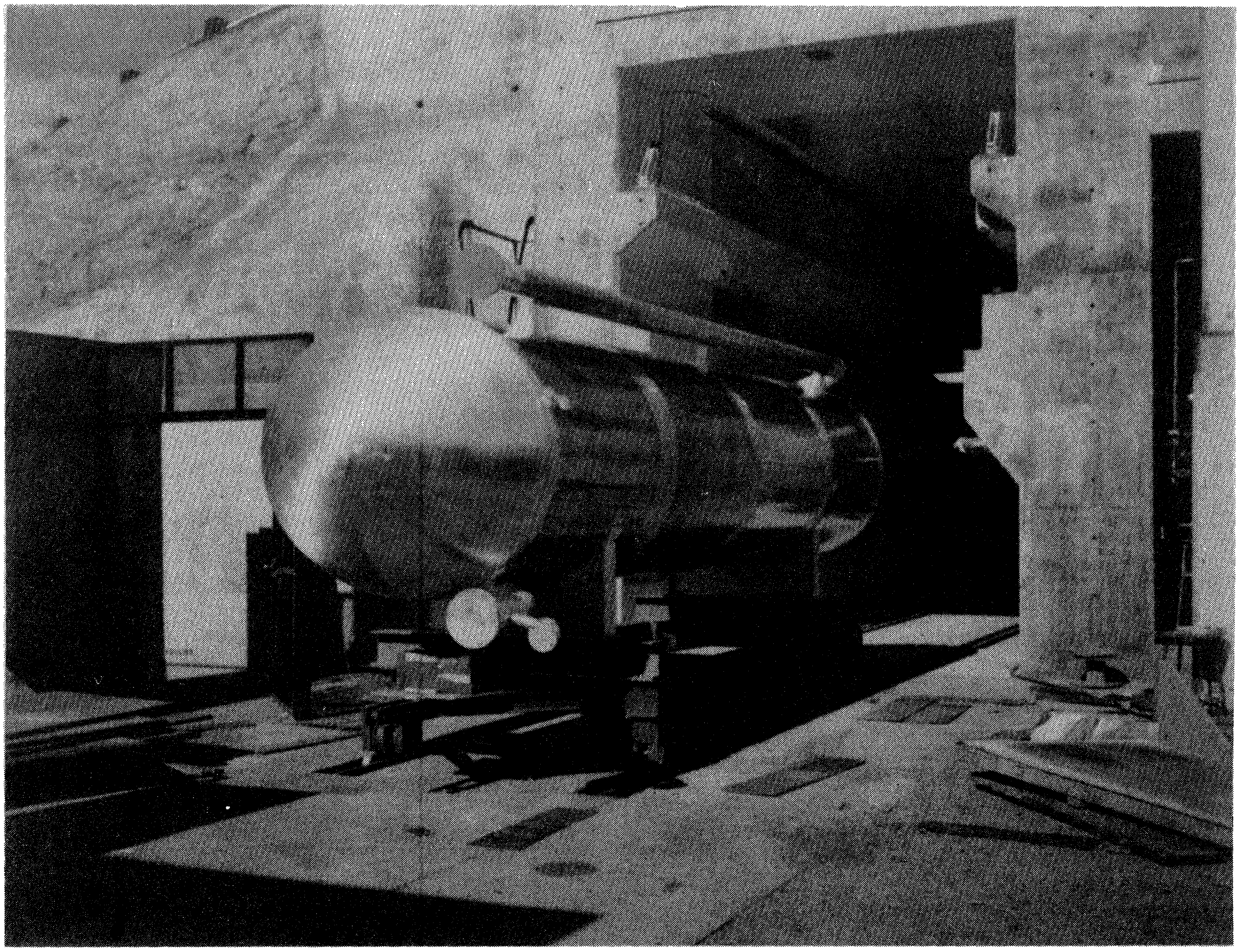

FIG. 2. SLAC 600-kW aluminum beam dump vessel.

TABLE I. Experimental data; $\langle \Delta T_m / \Delta T_{\text{calc}} \rangle_{\text{av,10 values}} = 0.96$, $\Delta T_m = \Delta T - \Delta T_i$.

Date	E_0 (GeV)	I_p (mA)	τ (μsec)	R_{PR} (pps)	P_{av} (kW)	Target status	w (sec^{-1})	T_{in} (°C)	T_{out} (°C)	ΔT (°C)	ΔT_m (°C)	ΔT_{calc} (°C)	$\frac{\Delta T_m}{\Delta T_{\text{calc}}}$
1-25-75	20.0	26.0	1.25	130	84.5	In[a]	28.71	26.0	28.8	2.8	0.8	0.7	1.14
1-25-75	20.0	26.0	1.25	130	84.5	In[a]	25.55	26.0	28.75	2.75	0.75	0.78	0.96
1-25-75	20.0	26.0	1.25	130	84.5	In[a]	15.77	25.75	28.95	3.20	1.2	1.27	0.94
1-25-75	20.0	28.0	1.25	130	91.0	Out	15.77	25.5	28.7	3.20	1.2	1.37	0.88
1-25-75	20.0	28.0	1.25	130	91.0	Out	9.46	25.1	28.6	3.50	1.5	2.28	0.66
1-25-75	20.0	28.0	1.25	130	91.0	Out	28.39	26.0	29.0	3.0	1.0	0.76	1.32
4-04-79	17.326	60[b]	1.5	160	249.5	In[c]	29.66	27.0	29.8	2.8	1.5	2.0	0.75
4-04-79	17.326	58[b]	1.5	110	165.8	In[c]	29.66	24.0	26.8	2.8	1.5	1.32	1.14
4-04-79	17.326	58[b]	1.5	109	164.3	In[c]	29.66	23.5	26.3	2.8	1.5	1.31	1.15
4-09-79	17.326	58[b]	1.5	180	271.3	Out	12.62	21.6	26.6[e]	5.0	3.4	5.09	0.67
		I_p 16.51 μa[d]			286.0	Out	12.62	21.6	26.6[e]	5.0	3.4	5.37	0.63

[a] 5.08-cm (0.14-RL) beryllium.

[b] Current was measured with toroid I-13.

[c] 30.5-cm (0.14-RL) liquid deuterium (LD2).

[d] This was average current from the I-13 integrator.

[e] Beam was lost before steady state was reached.

be used parasitically, it seemed worthwhile to make the test.

It has been pointed out to us that calorimetric tests had already been performed at SLAC using copper as the heat-absorbing substance.[6] Since these tests were carried out in order to provide an absolute calibration for cross-section measurements, the accuracy was pushed down to 1%, which turns out to be a much higher precision than the 30% accuracy reported here. But since the power level we use is 2 orders of magnitude higher, and the method so conceptually simple, we feel justified in publishing our results.

II. EXPERIMENTAL DESIGN

A schematic of the experimental setup is given in Fig. 1. Irrelevant beam transport components and instruments are omitted. After leaving the accelerator the electron beam is collimated and momentum-analyzed using the beam transport system components illustrated in Fig. 1 and then delivered to the targeting pivot. The residual electron beam following its passage through the target is transported to a high-power beam dump for absorption and dissipation into heat.

Beam current is measured at many locations along the beam path by means of current monitors (toroidal current transformers and microwave cavities) whose details are described elsewhere.[7,8] Only data from current monitors I-13 and 3I4 were used in the calculations of average beam power. The instruments were employed for comparison to monitor current losses along the beam path and to verify the values obtained from I-13 and 3I4. This was particularly important for those data points which were obtained parasitically behind other experiments which had either a 5-cm-long [0.14-RL (radiation length)] beryllium target or a 30.5-cm-long (0.04-RL) liquid deuterium target (LD2) in the beam, 120 m ahead of 3I4 and 143.4 m ahead of the beam dump.

The beam dump is shown in Fig. 2. It is a 152-cm-diam aluminum vessel filled with water.[9] It is 20 RL long and the electromagnetic cascade shower is thus fully developed and attenuated for the experimental energies. Temperature sensors (immersion-type thermistors) are mounted in the water inlet and outlet manifolds. These sensors are located approximately 20 m from the dump to allow for complete mixing of the heated return water. The small temperature differentials to ambient and the large volume—to—surface-area ratio of these water pipes minimize heat losses from natural convection and radiation to ambient. The temperature sensors were calibrated for zero off set both before and after the experiments upon reaching steady state.

It should be emphasized that the beam dump is designed to prevent any appreciable temperature rise in the cooling water at maximum beam, and hence not designed as a calorimeter. The water flow rate had to be reduced from the normal operating condition in order to obtain significant measurements.

III. EXPERIMENTAL RESULTS

The data were taken parasitically in conjunction with two different experiments. The results are summarized in

Table I. The first experiment was done at an incident beam momentum of 20 GeV/c with the slit to allow $\pm 0.5\%$ $\Delta p/p$. Current was measured with toroid 3I4. For three of the six sets of data an 0.14-RL-long beryllium target was in the beam. The initial (beam off) steady-state temperature differential or zero off set ΔT_i between the two temperature detectors was measured before and after the tests. For the first six sets of data $\Delta T_i = T_{\text{out}} - T_{\text{in}} = 2.0\,^{\circ}\text{C}$. The temperature difference as measured during the experiment is denoted as $\Delta T = T_{\text{out}} - T_{\text{in}}$ and is given in column 11. The true temperature difference generated by the beam is given in column 12, ΔT_m $(= \Delta T - \Delta T_i)$. Column 13 gives a calculated temperature difference using the measured beam parameters and flow rate, according to $\Delta T_{\text{cal}} = P_{\text{av}}/(wc) = E_0 I_p \tau R_{\text{PR}}/(wc)$, where E_0, I_p, τ, and R_{PR} are the beam energy, peak current, pulse length, and pulse repetition rate, respectively; w and c are the flow rate and the specific heat of water. The last column gives the ratio of the true measured to the calculated temperature difference.

The second experiment was done at 17.326 GeV/c with three cases where the 0.04-RL-long liquid deuterium target was in the beam and two cases without the target. The momentum slit SL-10 was again set to pass $\pm 0.5\%$ $\Delta p/p$. The last two cases are really only one set of data, but current was measured as peak current and also as average current with two different instruments. Current for the last four sets of data came from monitors I-13 A and B and not from 3I4.

As can be seen from the last column, the scatter of data points for the various tests run is approximately $\pm 30\%$. This is principally attributable to the large flow rate required to safely operate the beam dump, i.e., cool the dump window. The large flow rate results in very small temperature rises in the water. However, if all 10 values from the last column are added and averaged, $\langle \Delta T_m / \Delta T_{\text{calc}} \rangle_{\text{av}} = 0.96$.

Clearly, if the experiment had been run as a direct test rather than parasitically, a different calorimeter, or at least different beam conditions, would have been used, and the experimental fluctuations better understood. Since these experiments were performed a new set of parasitic runs were made, but the fluctuations were similar. Since the average was again closer to the theoretical prediction than the fluctuations, we are on the conservative side when we claim a test to 30% accuracy, and do not attempt to assign the smaller error that a statistical argument would allow.

IV. CONCLUSIONS

The 20- and 17-GeV/c beams from the Stanford Linear Accelerator carried both the current, measured by conventional techniques, and the power, measured by the rise in temperature of the cooling water flowing through the beam dump, as predicted by special relativity, to within 30%. Both quantities are many orders of magnitude larger than predicted by the theory of autodynamics as originally proposed. Although the neutrino hypothesis now satisfies most physicists as explaining the situation which leads to the original proposal, discrepancies remain in the literature. Experiments performed since the discovery of parity nonconservation have superceded these and other earlier, and from a conventional point of view anomalous, results—an example of a phenomenon which, according to Kuhn,[10] occurs fairly often in the development of any science. Autodynamics might conceivably be altered to refer only to acceleration of electric charge in regions of particle dimensions, but as a minimum this would require the introduction of some length parameter, or of quantum considerations that have not been tested in this macroscopic experiment. We conclude that at present there is no compelling reason to reject the relation between current, power, velocity, and curvature in a magnetic field of a beam of charged particles as predicted by the special theory of relativity.

ACKNOWLEDGMENT

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[1] P. Duhem, *La Theorie Physique, Son Objet, Sa Structure,* 2nd ed., 1914 [English translation: *The Aim and Structure of Physical Theory,* translated by Philip P. Wiener (Princeton University, Princeton, N.J., 1954)]; we are indebted to A. Grünbaum for calling this early reference to our attention.

[2] T. S. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago, Chicago, 1962).

[3] H. R. Crane and J. Halpern, Phys. Rev. 53, 789 (1938).

[4] D. F. Bartlett and B. F. L. Ward, Phys. Rev. D 16, 3453 (1977).

[5] D. F. Bartlett, J. Shepard, C. Zafiratos, and B. F. L. Ward, Phys. Rev. D 20, 578 (1979).

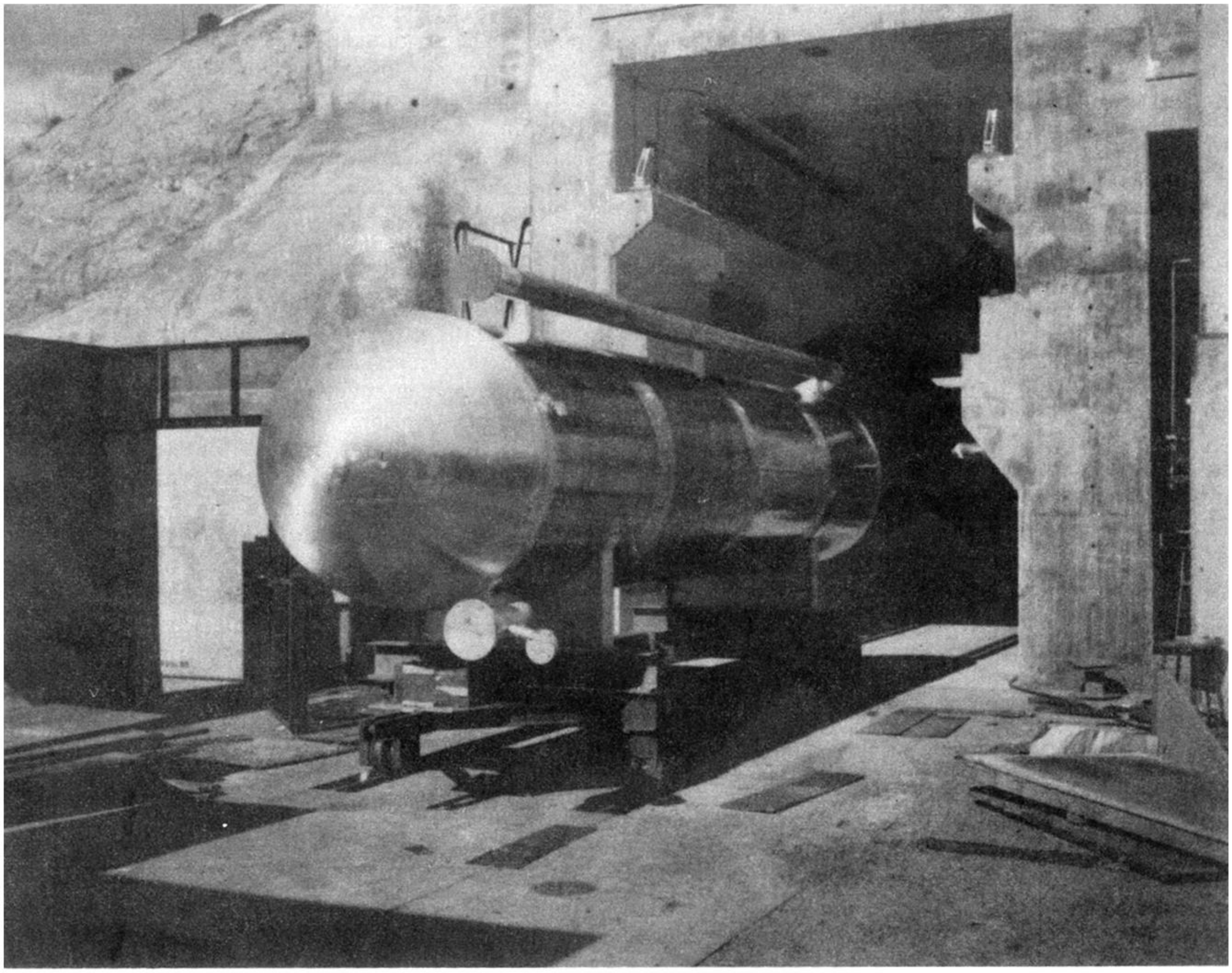
[6] G. E. Fischer and Y. Murata, Nucl. Instrum. Methods 78, 25 (1970).

[7] Stanford Linear Accelerator Center, Report No. SLAC-68, edited by D. A. Neet, Stanford University, Stanford, California, 1966.

[8] *The Stanford Two Mile Accelerator,* edited by R. B. Neal (Benjamin, New York, 1968), p. 502.

[9] D. R. Walz, Stanford Linear Accelerator Center, Report No. SLAC-TN-67-31, Stanford University, Stanford, California, 1967.

[10] Kuhn mentions, for example, Galileo's statement that the period of a pendulum is independent of the amplitude of the arc (Ref. 2, p. 118). A still more puzzling example is presented by him in Isis 49, 132 (1958). As he discusses in *The Essential Tension* (University of Chicago, Chicago, 1977), pp. 196 and 197, Laplace suggested that the rapid heating of air on compression might explain the long-standing discrepancy between theory and experiment for the speed of sound in air, and used subsequent experiments by Delaroche and Bernard to make his case. "But today no one can explain how this triumph can have occurred."



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