[1] N. A. Tolstoi and A. V. Shatilov, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 109 (1956), Soviet Phys. JETP **3**, 81 (1956).
[2] M. E. Bishop and S. H. Klebson, J. Appl. Phys. **24**, 660 (1953).
[3] K. W. Böer and H. V. Vogel, Ann. Physik **17**, 10 (1955).
[4] N. A. Tolstoi, Радиотехника и электроника (Radio Engg. and Electronics) **1**, 1135 (1956).
[5] A. Rose, Phys. Rev. **97**, 1538 (1955).
[6] V. E. Loshkarev and G. A. Fedorus, Izv. Akad. Nauk SSSR, ser. fiz. **16**, 81 (1952).

Translated by P. F. Schmidt
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SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 3 SEPTEMBER, 1958

MEASUREMENT OF THE MASS OF 660 Mev PROTONS

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Submitted to JETP editor September 12, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 555-558 (March, 1958)

Measurements of the momentum p and velocity v of 660-Mev protons were conducted in the external beam of the synchrocyclotron. The mass $m_1 = p/v$ was compared with the value computed in accord with the relativistic relation $m_2 = m_0[1 - (v^2/c^2)]^{-1/2}$. Both mass values are in agreement within the limits of the experimental error. The observed relative deviation was $\Delta m/m = 0.004(1 \pm 0.6)$.

INTRODUCTION

THE accuracy with which the theory of relativity, now a classic one, describes high-velocity effects, as well as possible deviations from the theoretical predictions, may be rightly questioned. The existence of such deviations can, of course, be rejected from purely theoretical considerations requiring the preservation of the internal completeness of the basic theory. The decisive answer, however, indisputably belongs to the experiment. The large experimental material available confirms, on the whole, the existence of relativistic effects in nature but contains little data with respect to the degree of accuracy of the theoretical predictions. It is often claimed that the successful operation of cyclic high-energy particle accelerators gives an accurate confirmation of the relativistic dependence of the mass on velocity. Farago and Janossy,[1] however, having analyzed the corresponding experimental material, have concluded that the relativistic relation is confirmed to a considerably lesser extent than it is generally assumed. Quantitative results from accelerators now in operation are indefinite to a few percent. It was found in direct experiments with electrons[1] that the experimental error is rather large (2 — 10%). Grove and Fox[2] carried out an experiment with protons, using a 140-inch synchrocyclotron. They determined the equilibrium orbit for 385-Mev protons and measured the angular frequency on the orbit. The results are in agreement with the relativistic law of the variation of mass. An analysis of the data is, however, rendered difficult by the complex motion of protons inside the accelerator on the one hand, and by the scant information provided by the authors on the other.

The purpose of our work was to compare the proton mass calculated according to the relativistic relation $m_2 = m_0[1 - (v^2/c^2)]^{-1/2}$ (from the measured value of v) with the value $m_1 = p/v$ found from the measured proton momentum and velocity. The measurements were conducted in an external beam of protons of about 660 Mev, which made it considerably easier to determine the possible errors.

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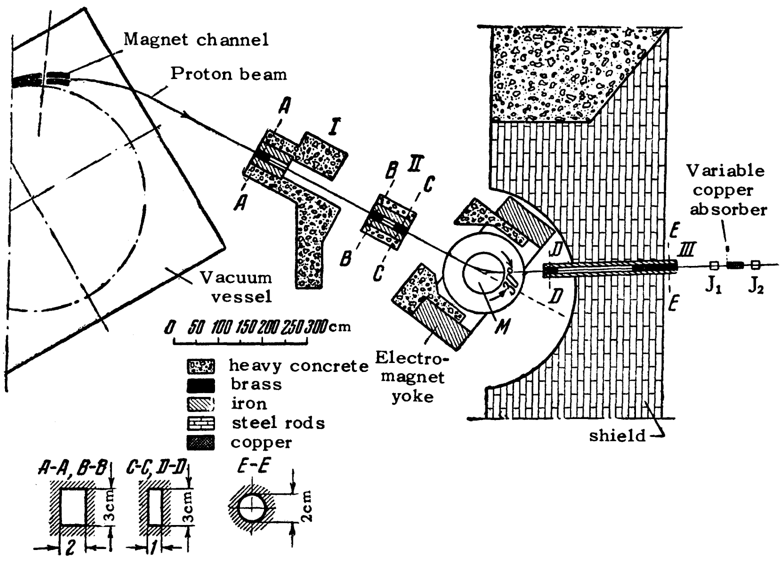

APPARATUS AND METHOD

A general diagram of the experimental arrangement is shown in the figure. The external beam of the six-meter synchrocyclotron passed through collimators I and II, was deflected in the field of electromagnet M with poles 1 m in diameter, then passed through collimator III and struck the ionization chamber J_1. The shape and dimensions of collimator openings are shown in the figure. Adjustment of the collimating system was carefully checked by exposing an x-ray film.

The current in the coils of electromagnet M was adjusted to obtain maximum counting rate in chamber J_1. The film exposed at the exit from collimator III then recorded a sharp image of the proton beam, symmetrical with respect to the collimator axis. The magnetizing current was stabilized within 0.1%. Fluctuations of the magnetic field intensity were smaller still, since the iron core was almost saturated.

An accurate determination of the momentum of protons from measurements of the magnetic field was impossible in practice, because of stray fields of the synchrocyclotron magnet and of the magnet M. The momentum of the protons of the beam traversing the collimating system was measured using the method of current carrying filament.[3-5] A Litz wire 0.2 mm in diameter was threaded through all collimators and was supported three meters from the exit from collimator III by means of a silk thread with attached weight Q on a miniature pulley. As is well known, a stretched wire carrying a current I in magnetic field assumes the form of the trajectory of a charged particle with momentum $p = aQ/I$. If the tension Q of the wire is expressed in grams and the current I in amperes, then the momentum of a singly charged particle in Mev/c will be given by the relation

$$p = 2.943\,Q/I.$$

In the above formula the weight and elastic stresses of the wire are neglected. The accuracy with which the force of the weight Q is converted into wire tension depends on the accuracy with which the pulley is centered and on the quality of its bearings. It was found experimentally, for the pulley used, that it takes a difference of 0.3 g to upset the equilibrium between two 300 g weights hanging on a thread looped over the pulley.

By varying the current continuously at a constant tension Q = 300 g, a position was found such that the thread passed freely through the collimators along their axes. The corresponding current was measured with a calibrated ammeter of 0.001 amp accuracy.

As a check, a measurement of the proton momentum was carried out in which the tension due to a weight of 300 g was transmitted to the wire by means of a pendulum suspension. For the wire tension and the force due to the weight to be equal, it was necessary that the horizontal distance from the pendulum suspension point to the point of junction with the horizontal wire be equal to the vertical distance from the point of suspension to the horizontal wire. The error in the value of tension depends only upon the accuracy of length measurements. The suspension point of the pendulum was attached to the frame of an overhead crane in the hall where the experiments were carried out. The above distances, amounting to about 5 m, were made equal to within ±5 mm. The results of these measurements were in good agreement with those obtained with the pulley.

To determine proton velocities we made use of earlier results obtained by measurement of the angle of the Cerenkov radiation.[6] The mean velocity of the protons in the external beam was found to be $v_0/c = 0.8090 \pm 0.0005$. The mean range $\overline{R}_0$ of protons in copper was determined from the Bragg curve simultaneously with the velocity measurements. In the present work only the Bragg curve and the mean range $\overline{R}$ were measured for the proton beam separated by the collimating system. As shown by Mather and Segrè,[7] the Bragg curve depends on the energy distribution of the beam particles, but the mean range is always equal to the thickness of absorber, for which the current in the ionization chamber amounts to 0.82 of the maximum value. Correction to the value of the mean proton velocity was found from the difference in the mean ranges $\Delta\overline{R} = \overline{R} - \overline{R}_0$, based on the stopping power for copper. A copper absorber with an automatically variable thickness from 254.6 to 270.7 g/cm^2 and a second ionization chamber J_2 were placed behind the first chamber for the measurement of the Bragg curve. The chambers J_1 and J_2 and the copper absorbers were those used in previous measurements, which were carried out simultaneously with the measurement of the proton velocity.

RESULTS AND DISCUSSION

In the measurements of the proton momentum by the method of the current-carrying conductor it was found that $Q = 300.0 \pm 0.3$ g and $I = 0.681 \pm 0.001$ A. Hence

$$p = 1296.5 \pm 2.3 \text{ Mev}/c.$$

A series of measurements was carried out with Q = 200 g. These yielded a result consistent with the first series, within the accuracy limits. This means that for Q = 200 g the errors arising from neglecting the weight and elasticity of the wire are no larger than the errors in the measurement of the current and tension of the wire.

It was found from the measurements of the mean range of the protons that the energy of the protons used in the experiment was slightly higher, and their range larger by 3.8 g/cm^2, than $\overline{R}_0$ measured previously. Repeated measurement of the Bragg curve showed that the accuracy of measurement of the range difference ΔR amounted to 10%. For determination of the corresponding correction to the value of proton energy, the stopping power of copper for protons of velocity $v/c = 0.81$ was found from the formula of Bethe[8] to be equal to $-dE/dx = 1.73$ Mev/g-cm^{-2}. It follows that the difference in the mean energy of protons of mean velocity v_0 and of the beam protons used in the present experiment amounts to $\Delta E_1 = 6.6$ Mev.

Since the momentum measurement pertains to protons near the magnetic analyzer and the velocity v and range were measured after the protons traversed about 5.5 m of air, it was necessary to introduce a correction for the energy loss in air. This amounted to $\Delta E_2 = 1.5$ Mev. The total correction is therefore $\Delta E = \Delta E_1 + \Delta E_2 = 8.1$ Mev.

Since the relative value of the correction amounts only to 1.2%, the error in its determination can be neglected. The corresponding correction to the velocity is calculated according to the relativistic expression for energy. Assuming the rest energy of the proton to be 938.2 Mev (Ref. 9), we obtain for the mean velocity a value $v/c = 0.8112 \pm 0.0005$. The fact that, while aiming at detecting small deviations from the basic relativistic relation $m = m_0[1 - (v^2/c^2)]^{-1/2}$, we used a relativistic relation to determine the corrections ΔE and Δv, is justified by the small magnitude of the corrections.

Using the values for the momentum and velocity of protons given above, we obtain

$$m_1 = p/v = 1598.2 \pm 3 \text{ Mev}/c^2$$

and

$$m_2 = m_0[1 - (v^2/c^2)]^{-1/2} = 1604.3 \pm 1.9 \text{ Mev}/c^2.$$

Hence

$$\Delta m = m_2 - m_1 = 6.1\,(1 \pm 0.6)$$

or

$$\Delta m/m = 0.004\,(1 \pm 0.6).$$

(the errors represent standard deviations).

The results are, within the limits of the experimental errors, in agreement with the relativistic law of the variation of mass.

In conclusion the authors wish to express their gratitude to Prof. L. Janossy for his interest in the work and their appreciation to B. S. Neganov and Iu. D. Baiukov for assistance and valuable discussion.

[1] P. S. Farago and L. Janossy, Nuovo cimento **5**, 1411 (1957).

[2] D. J. Grove and J. C. Fox, Phys. Rev. **90**, 378 (1953).

[3] J. J. Thomson, Phil. Mag. **6**, 13, 561 (1907).

[4] I. Loeb. Compt. rend. **222**, 488 (1946).

[5] M. S. Kozodaev and A. A. Tiapkin, Приборы и техника эксперимента (Instruments and Meas. Engg.) **1**, 21 (1956).

[6]V. P. Zrelov, Report, Inst. Nucl. Studies Acad. Sci. U.S.S.R., 1954.
[7]R. Mather and E. Segrè, Phys. Rev. **84**, 191 (1951).
[8]M. S. Livingston and H. A. Bethe, Revs. Mod. Phys. **9**, 263 (1937).
[9]Cohen, Layton, Du Mond, and Rollet, Revs. Mod. Phys. **27**, 363 (1955).

Translated by H. Kasha
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SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 3 SEPTEMBER, 1958

RANGE AND SPECIFIC IONIZATION OF MULTIPLY-CHARGED ION IN A GAS

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Submitted to JETP editor September 20, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 559-568 (March, 1958)

The range and specific ionization in air, argon, and hydrogen have been measured for the ions from Be to Ne at velocities between 1.5×10^8 and 12×10^8 cm/sec. For $v \leq 5 \times 10^8$ cm/sec, the specific ionization and the range of an ion is approximately proportional to the particle velocity v. At higher velocities, the range is proportional to v^2 and the specific-ionization curves have a flat maximum, as in the Bragg curve for α particles. The stopping power of a substance, B, is not the same for all ions and decreases with increasing Z of the ion.

1. INTRODUCTION

In connection with the study of nuclear reactions induced by multiply-charged ions and by hypernuclei, interest has increased recently in the passage of charged ions of light elements, with atomic numbers $Z > 2$, through matter. Particularly interesting are the ranges and specific ionizations of these ions. A theoretical prediction of these characteristics is a rather complicated matter, owing to the difficulties of accounting for the charge exchange, which comes prominently into play at an ion velocity v close to the velocity of its orbital electrons. Recent publications describe the stopping of ions in photo emulsion[1-3] and in air,[3-5] using certain simplifying assumptions concerning the effective ion charge and the stopping power B of the substance. These reports need an experimental verification.

The only information available up to recently was on the ranges (referred to air) of recoil nuclei in a condensation chamber, at velocities from 2×10^8 to 7×10^8 cm/sec.[6-11] A short time ago reports were published on the ranges of many accelerated ions in gases, at velocities below 1×10^8 cm/sec,[12] and of lithium,[13] beryllium, and nitrogen[14] ions at higher velocities. The ranges of certain multiply-charged ions in photoemulsion[15-18] and of nitrogen ions in nickel[19] were also measured. As to specific ionization, there exist, in addition to a report[19] concerning its constancy at velocities from 10×10^8 to 20×10^8 cm/sec, also data (in gases) for neon and nitrogen ions in the velocity region below 3×10^8 cm/sec (Ref. 20), and also for lithium ions.[13,21]

In this investigation, we studied the ranges and the specific ionizations of ions from Be to Ne, at velocities from 1.5×10^8 to 12×10^8 cm/sec in argon, air, and hydrogen.

2. DESCRIPTION OF THE EXPERIMENT

In this work, as in the work reported in Ref. 13, we employed a focused ion beam extracted from a 72-cm cyclotron. After passing through a system of 1×10 mm slits, the beam entered the registering apparatus (Fig. 1).