The production of ρ, ω, A_1, and A_2 resonances has been observed, and partial cross sections are given. The cross section for the $\bar{p}p \to \rho^0 2\pi^+ 2\pi^- \pi^0$ process appears to vary slowly with energy, while the $\bar{p}p \to \omega 2\pi^+ 2\pi^-$ shows a maximum around 2.7-GeV total c.m. energy. A structure of about 2 mb was observed by Amaldi *et al.*[13] in $\bar{p}p$ total-cross-section measurements; this suggests that the $\omega 2\pi^+ 2\pi^-$ channel could have an important contribution to this structure.

Our data show some indication of small bumps in the $(\rho^0\pi^0)$, $(\rho^0\rho^0)$ mass for seven-pion production. No simple explanation has been found for those effects. In order to understand the nature of these structures better, the statistics will have to be increased.

The charged multiplicity was found to be (4.4 ± 0.2). The F/B ratios and the collimation parameters are compared with data at other energies and multiplicities. For a given energy the collimation parameter decreases with increasing number of outgoing pions.

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Experimental Search for a Heavy Electron*

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A search for a heavy electron of the type considered by Low and Blackmon has been made by studying the inelastic scattering of 5-BeV electrons from hydrogen. The search was made over a range of values of the mass of the heavy electron from 100 to 1300 MeV. No evidence for such a particle was observed. Upper limits on the production cross sections were determined and employed to deduce limits on the values of the electron–photon–heavy-electron coupling constant in Low and Blackmon's theory.

I. INTRODUCTION

RECENT experimental investigations of detailed predictions of quantum electrodynamics (QED) have failed to establish conclusively any breakdowns in QED theory. High-energy reactions which have been studied include the photoproduction of electron[1] and muon[2,3] pairs at wide angles, electron-electron scattering,[4] electron-positron scattering,[5] and searches for anomalous structure in the electron.[6–8] In addition, comparisons between theory and experiment have been made for the anomalous magnetic moments of the electron,[9] positron,[10] and muon,[11,12] for the Lamb shift,[13–16]

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[1] J. G. Asbury, W. K. Bertram, U. Becker, P. Joos, M. Rodhe, A. J. S. Smith, S. Friedlander, C. L. Jordan, and C. C. Ting, Phys. Rev. Letters **18**, 65 (1967).

[2] A. Alberigi-Quaranta, M. De Pretis, G. Marini, A. Odian, G. Stoppini, and L. Tau, Phys. Rev. Letters **9**, 226 (1962).

[3] J. K. de Pagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. von Goeler, Roy Weinstein, and A. M. Boyarski, Phys. Rev. Letters **17**, 767 (1966).

[4] W. C. Barber, B. Gittelman, G. K. O'Neill, and B. Richter, Phys. Rev. Letters **16**, 1127 (1966).

[5] A. Browman, B. Grossetête, and D. Yount, Phys. Rev. **151**, 1094 (1966).

[6] G. R. Burleson and H. W. Kendall, Nucl. Phys. **19**, 68 (1960).

[7] J. Goldemberg and Y. Torizuka, Phys. Rev. **129**, 2580 (1963).

[8] R. E. Rand and R. Hofstadter, in *Proceedings of the Twelfth International Conference on High-Energy Physics, Dubna, 1964* (Atomizdat, Moscow, 1965), Vol. I, p. 895.

[9] D. T. Wilkinson and H. R. Crane, Phys. Rev. **130**, 852 (1963).

[10] A. Rich and H. R. Crane, Phys. Rev. Letters, **17**, 271 (1966).

[11] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, and A. Zichichi, Nuovo Cimento **37**, 1241 (1965).

[12] F. J. M. Farley, J. Bailey, R. C. A. Brown, M. Giesch, H. Jostlien, S. van der Meer, E. Picasso, and M. Tannenbaum, Nuovo Cimento **45A**, 281 (1966).

[13] W. E. Lamb, Jr., and Robert C. Retherford, Phys. Rev. **72**, 241 (1947).

[14] R. T. Robiscoe and B. L. Cosens, Phys. Rev. Letters, **17**, 69 (1966).

[15] R. T. Robiscoe and B. L. Cosens, Bull. Am. Phys. Soc. **11**, 62 (1966).

[16] M. F. Soto, Jr., Phys. Rev. Letters **17**, 1153 (1966).

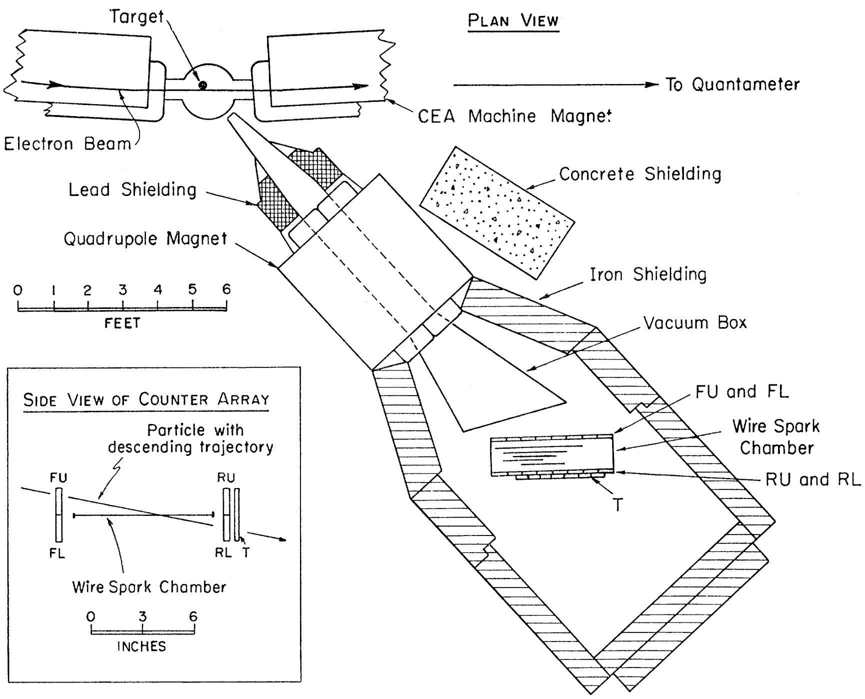

FIG. 1. Experimental site. The inset shows a vertical section of the counters and the wire spark chamber at the focus of the quadrupole magnet. A triple coincidence which satisfied pulse-height requirements and signified an ascending or or descending trajectory caused the spark chamber to be pulsed.

and for the hyperfine splitting in hydrogen,[17] positronium,[18] and muonium.[19,20] Possible breakdowns in QED theory can be described phenomenologically by *ad hoc* modifications of a photon or particle propagator.[21–25] More explicit descriptions have recently been studied by Low[26] and Blackmon,[27] who suggested that possible breakdowns in QED may be the manifestations of new undiscovered particles that take part in the electromagnetic interactions. One such description[28] employs a heavy electron e' coupled to an electron and a photon, $e' \rightarrow e+\gamma$. This coupling would allow the e' to be produced by the electroproduction process

$$e+p \rightarrow e'+p \quad \searrow e+\gamma . \tag{1}$$

The above reaction would produce a sharp peak in the momentum spectrum of the recoiling protons at a given angle. The peak would be similar in shape to the elastic electron-proton peak, provided the lifetime of the e' were typical of particle lifetimes for electromagnetic decay. We have made an experimental search for such a peak and have analyzed our data assuming that the production of the e' is described theoretically by Low's model.

Three other searches have been made for the e' and reported prior to this one. Betourne *et al.*[29] and Budnitz *et al.*[30] looked for the e' by measuring the recoil-proton momentum spectrum in inelastic e-p scattering. Behrend *et al.*[31] performed a coincidence experiment, measuring the recoil protons in coincidence with the presumed decay products from the e'.

II. EXPERIMENTAL ARRANGEMENT

We employed a scattering facility at the Cambridge Electron Accelerator used in our study of electron-deutron elastic scattering.[32] The facility, illustrated in Fig. 1, consisted of a liquid-hydrogen target located in the vacuum chamber of the synchrotron, a quantameter to monitor the bremsstrahlung produced by the beam interacting with the target, and a quadrupole magnet

[17] S. B. Crampton, D. Kleppner, and N. F. Ramsey, Phys. Rev. Letters **11**, 338 (1963).
[18] V. W. Hughes, S. Marder, and C. S. Wu, Phys. Rev. **106**, 934 (1957).
[19] W. E. Cleland, J. M. Bailey, M. Eckhause, V. W. Hughes, R. M. Mobely, R. Prepost, and J. E. Rothberg, Phys. Rev. Letters **13**, 202 (1964).
[20] M. A. Ruderman, Phys. Rev. Letters **17**, 794 (1966).
[21] V. B. Berestetsky, O. N. Krokhin, and A. K. Khlebnikov, Zh. Eksperim. i Teor. Fiz. **30**, 788 (1956) [English transl.: Soviet Phys.—JETP **3**, 761 (1956)].
[22] S. D. Drell, Ann. Phys. (N.Y.) **4**, 75 (1958).
[23] B. De Tollis, Nuovo Cimento **16**, 203 (1960).
[24] J. A. McClure and S. D. Drell, Nuovo Cimento, **37**, 1638 (1965).
[25] N. M. Kroll, Nuovo Cimento **45A**, 65 (1966).
[26] F. E. Low, Phys. Rev. Letters **14**, 238 (1965).
[27] M. Blackmon, Pd.D. thesis, Department of Physics, Massachusetts Institute of Technology, 1967 (unpublished).
[28] Low and Blackmon have made a detailed investigation of the corrections arising from several different models to various QED predictions. The effects of the e' on electron-pair production have also been investigated by F. Gutbrod and D. Schildknecht, Z. Physik **192**, 271 (1966).
[29] C. Betourne, H. Nguyen Ngoc, J. Perez y Jorba, and J. Tran Thanh Van, Phys. Letters **17**, 70 (1965).
[30] R. Budnitz, J. R. Dunning, Jr., M. Goitein, N. F. Ramsey, J. K. Walker, and Richard Wilson, Phys. Rev. **141**, 1313 (1966).
[31] H. J. Behrend, F. W. Brasse, J. Engler, E. Ganssauge, H. Hultschig, S. Galster, G. Hartwig, and H. Schopper, Phys. Rev. Letters **15**, 900 (1965).
[32] J. K. de Pagter, J. E. Elias, J. I. Friedman, G. C. Hartmann, H. W. Kendall, P. N. Kirk, M. R. Sogard, and L. P. Van Speybroeck (to be published).

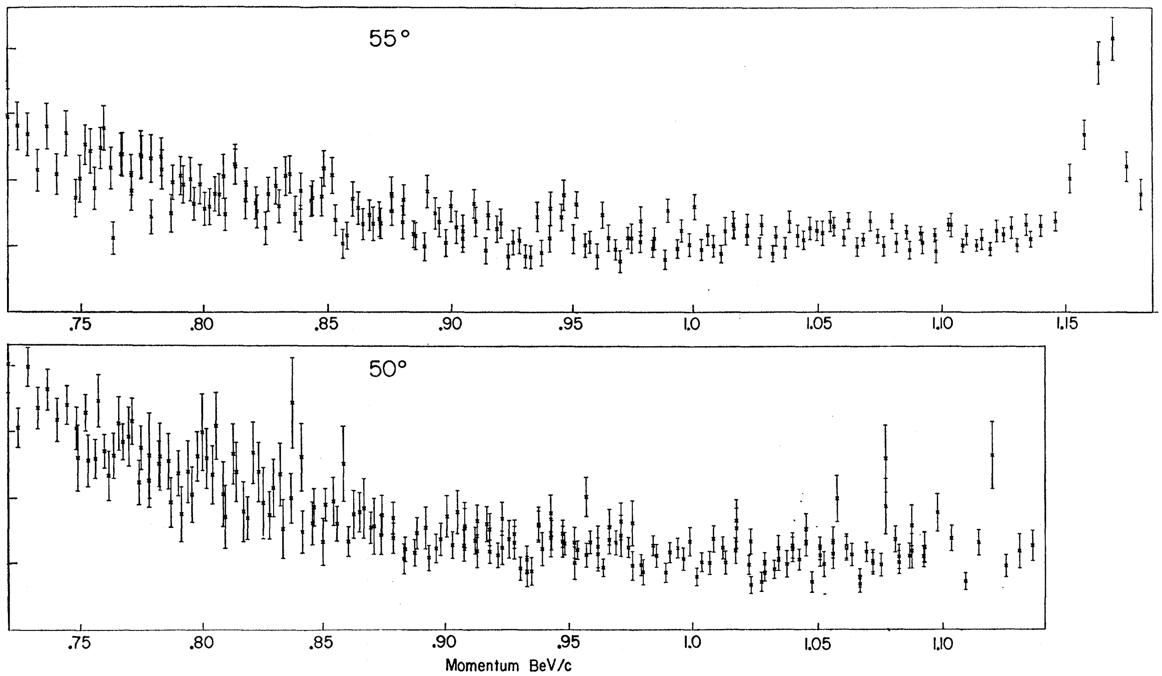

FIG. 2. Proton momentum spectra from electron-proton inelastic scattering. The data illustrated have been corrected for experimental effects and are proportional to $d^2\sigma/d\Omega dp$. They represent about 10% of the data obtained in this experiment. Some of the observed structure in the inelastic spectrum is due to variations in the efficiency of the spark chamber as a function of momentum channel number. The systematic errors included in the limits given in Fig. 3 were based on the observed magnitudes of these variations.

spectrometer. The detection system consisted of a wire spark chamber and five scintillation-counter arrays. Protons were distinguished from other particles of the same momentum by means of specific ionization requirements imposed on three of the counter arrays. This requirement was enforced with the use of differential discriminators which were appropriately adjusted to match the momentum acceptance of the spectrometer. The measured efficiency for detecting protons was greater than 95%. The momentum of a detected proton was determined by measuring the point at which the proton crossed the focal plane of the magnet, with the use of the wire spark chamber which consisted of 64 wires comprising 16 momentum bins. The percentage momentum acceptance of each momentum bin was 0.5%. The recoil angle was determined by using a seven-counter hodoscope. Each counter had an acceptance of approximately 0.3°.

The liquid-hydrogen target consisted of a 0.5-in.-diam cylindrical vessel made of 0.0005-in. Kapton film and was located approximately 1 in. inside the equilibrium orbit of the circulating electrons. After the electrons were accelerated to 5 BeV, the accelerating radio-frequency power was decreased so that the electrons drifted inward and struck the target. The incident-electron flux was determined by measuring with a quantameter the bremsstrahlung yield produced in the target by the circulating beam. The fractional contribution from the target walls was measured to be 0.11 ± 0.013 with a technique to be described elsewhere.[32]

III. EXPERIMENTAL METHOD

Measurements were made of the momentum spectra of recoil protons with the spectrometer positioned at 50°, 55°, and 60°. The yields from elastic electron-proton scattering at 55° and 60° were measured and used as a check of the calibration of our equipment. The inelastic-proton yields were measured in a series of momentum intervals below the momentum corresponding to the elastic peak. The interval spacing was about 4%, so that there was a 50% overlap of adjacent measurements. Since the detector had seven angular bins, the data consisted of the momentum spectra measured at 21 different angles. The range of momenta covered at 50° was 0.76 to 1.12 BeV/c; at 55°, 0.76 to 1.16 BeV/c; and at 60°, 0.82 to 0.96 BeV/c. The corresponding ranges of e' masses at these angles were 900 to 1300 MeV, 100 to 1000 MeV, and 100 to 700 MeV.

IV. DATA ANALYSIS

The measured yields were reduced to differential cross sections $d^2\sigma/d\Omega dp$ by correcting for the efficiencies of the spark-chamber channels, dividing out the solid-angle-momentum acceptances associated with each momentum-angle bin of the detector, and dividing by the product of the target thickness and the number of incident electrons. This product is proportional to the quantameter yield, corrected for target-wall contributions.

The efficiencies of the spark-chamber channels were measured with the use of a Kapton target, by comparing

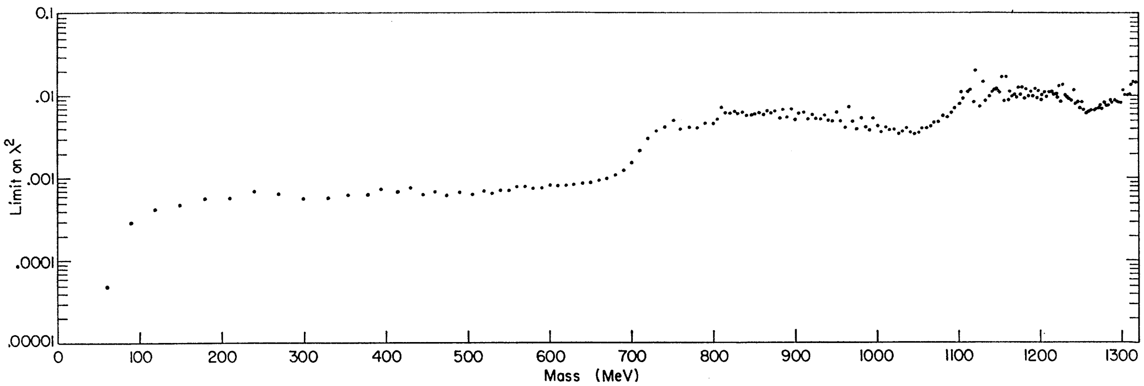

FIG. 3. Limits of λ^2 versus mass of the heavy electron. The points represent upper limits with 97% confidence of values of λ^2 derived from our data as described in Sec. IV.

the number of events detected by the chamber with the number of events that satisfied proper trajectory and specific ionization requirements. This procedure required a knowledge of the momentum spectrum of the recoil-proton spectrum from Kapton. This dependence was measured during the experiment. The spark-chamber yield was corrected for dead-time losses. The solid-angle-momentum acceptances of the bins were calculated using a ray-tracing technique.[33] Two examples of the final momentum spectra of the 21 measured during the experiment are shown in Fig. 2.

The proton elastic-peak yields were evaluated by fitting a resolution function to the elastic peak with the use of the method of least squares. The resolution function was approximately Gaussian and the fractional full width at half-maximum was determined to be 0.0223. This value was in good agreement within the uncertainty of the determination, with a value of 0.0216 calculated from the geometry, the momentum and angle-acceptance intervals of the equipment, and multiple scattering in the target. The elastic electron-proton-scattering cross sections measured in this experiment were in agreement with other recent measurements.[34]

The search technique was designed to detect peaks in the recoil-proton momentum spectra arising from e' production. At each angle the spectra were analyzed for peaks by fitting the resolution function plus a background function at a series of values of the recoil momentum. These values were separated by about $\frac{1}{4}$ of the full width at half-maximum of the resolution function to insure that a possible peak due to the e' would not be overlooked. The method of least squares was used to make the fits. The errors in the cross sections were evaluated from the error matrices resulting from each fit.

The values of the experimental cross section were compared to the values of the theoretical electroproduction cross section computed from the Hamiltonian

$$H_I=(e\lambda/m')\bar{\psi}_{e'}\sigma_{\mu\nu}\psi_e f^{\mu\nu}+\text{H.c.},$$

where λ is the $ee'\gamma$ coupling constant, m' is the mass of the e', and $f^{\mu\nu}$ is the electromagnetic field tensor. The theoretical cross section for proton detection, evaluated in the laboratory system, is given by[27]

$$\frac{d\sigma}{d\Omega}=\frac{4\alpha^2\lambda^2}{t^2m'^2}\left|\frac{p^2}{ME_0[p(M+E_0)-E_pE_0\cos\theta]}\right|\times\left\{\left[F_1^2+\left(\frac{q^2}{4M^2}\right)F_2^2\right]\times\left[-m'^4M^2-M^4t+(\tfrac{1}{4}m'^2+M^2)t^2+(2M^2+m'^2)st-s^2t-st^2-\tfrac{1}{4}t^3\right]+(F_1+F_2)^2\left[\tfrac{1}{4}t^3+\tfrac{1}{4}m'^2t^2-\tfrac{1}{2}m'^4t\right]\right\}, \quad (2)$$

where $t=-q^2=2M(M-E_p)$ and $s=M(M+2E_0)$. Here E_p, p, and θ are the energy, momentum, and angle of the recoil proton (with mass M), E_0 is the energy of the incident electron, and $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors which are normalized so that $F_1(0)=1$, $F_2(0)=\mu-1\cong1.79$. This formula is equivalent to another published expression.[29]

The following procedure was used for obtaining limits on λ^2 from the data. The e' mass associated with each cross-section measurement was computed from the kinematics of the measurement, and a value of λ^2 was obtained from the ratio of the measurement and Eq. (2). The values of λ^2 that resulted were sorted into e' mass bins with a width selected to correspond to momentum intervals of 0.5%. The final value of λ^2 for each mass bin was taken as the weighted average of all the measurements falling within this bin. The final values were consistent with zero. We have taken as our limiting values of λ^2 the sum of twice the statistical error in λ^2 and our estimate for the systematic error in the measurements. The systematic error was largely a result of variations in the efficiency of the spark chamber as a function of

[33] C. H. Moore, S. K. Howry, and H. S. Butler, Stanford Linear Accelerator Report, 1965 (unpublished). We wish to thank Dr. Karl Brown of SLAC for his assistance in utilizing this program.

[34] T. Janssens, R. Hofstadter, E. B. Hughes, and M. R. Yearian, Phys. Rev. **142**, 922 (1966).

momentum channel number. The structure in the measured momentum spectra introduced by these variations did not have the same functional form as the resolution function and thus did not lead to false peaks in the inelastic spectrum. The limits on λ^2 derived in this way are shown in Fig. 3. The values of the e' production cross section corresponding to these limits ranged from 0.2 to 3.0×10^{-33} cm^2/sr at scattering angles of 55° and 60°, and from 0.7 to 3.0×10^{-33} cm^2/sr at 50°. Figure 4 shows the results of this experiment compared with the results of previous experiments.[29,30,31]

V. RESULTS AND CONCLUSIONS

In this experiment we found no evidence for the existence of a heavy electron e' in the mass range investigated, having assumed the e' would be electroproduced through reaction (1) and thus produce a sharp peak in the recoil-proton momentum spectrum. We found limiting values for the size of a possible peak by fitting the elastic peak shape to the measured spectra at a series of values of momentum separated by an amount small compared to the width of the elastic peak. The values obtained for possible peak heights were consistent with zero within the errors of the measurements. Limiting values for the $ee'\gamma$ coupling constant in Eq. (2) were obtained by comparing our limits on the cross section for the electroproduction of the e' with the predictions of the theoretical model.

Compared with earlier measurements,[29–31] this experiment has set new upper limits on the values of λ^2 in an extended mass range from 1000 to 1300 MeV and has lowered existing limits over the range from 100 to 500 MeV. The results are summarized in Fig. 4.

The limits for λ^2 determined in this experiment are about a factor of 2 smaller than the limits imposed by the measurements of the electron anomalous magnetic moment based on the calculations of Blackmon.[27] Figure 4 shows this bound compared to our experimental limits.

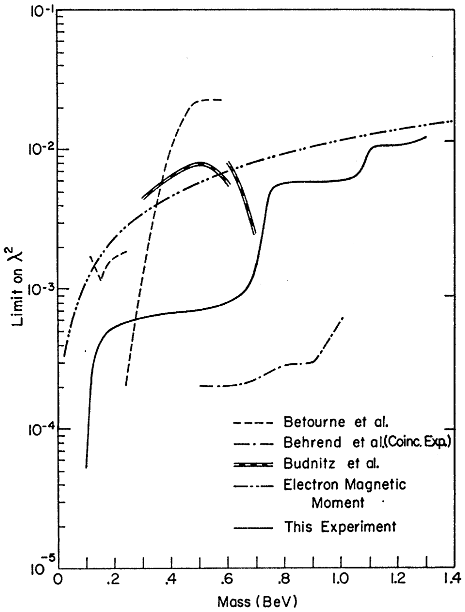

FIG. 4. Comparison of upper limits on the values of λ^2 from various experiments (see Refs. 29–31). The limits on λ^2 imposed by the anomalous magnetic moment of the electron are also shown. It should be noted that considerably different procedures were used for calculating the quoted limits in the experiments shown above. We have calculated the limits on λ^2 ascribed to Budnitz *et al.*, (see Ref. 30) from the limits quoted on their cross-section measurements.

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