sible. We also thank T. D. Lee for his helpful discussions. We are grateful for the cooperation of the Minister für Forschung und Technologie, the Joint Research Program of FOM and ZWO of the Netherlands, the U. S. Department of Energy, and the Institute of High Energy Physics of the Chinese Academy of Science in this endeavor. We especially thank Dr. F. J. Eppling, Dr. M. Deutsch, Dr. H. Feshbach, Dr. G. Soehngen, and Dr. G. Weber for their valuable advice and support. We thank Miss I. Schulz, Miss S. Marks, Mr. P. Berges, and Mr. D. Osborne for technical and administrative help. We also thank D. Hubert, G. Kessler, J. Kouptsidis, and F. Schwickert as well as our technicians from Rheinisch-Westfälische Technische Hochschule, Massachusetts Institute of Technology, and DESY for their dedicated services which contributed to the efficient installation of this experiment.

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Measurement of the Relative Total Hadronic Cross Section *R* at PETRA

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We report the first measurement of the ratio $R=(\sigma_{e^+e^-\to\text{hadrons}})/(\sigma_{e^+e^-\to\mu^+\mu^-})$ (with negligible τ-lepton contribution) at a center-of-mass energy $\sqrt{s}=13$ GeV and $\sqrt{s}=17$ GeV, from the just finished electron-positron colliding-beam facility PETRA. The detector, MARK-J, has an approximately 4π solid angle and measures γ, e, μ, and charged and neutral hadrons simultaneously. Our results yield $R(\sqrt{s}=17\text{ GeV})=4.9\pm0.6$ (statistical) ±0.7 (systematic error), and $R(\sqrt{s}=13\text{ GeV})=4.6\pm0.5$ (statistical) ±0.7 (systematic error). The ratio $R(\sqrt{s}=17\text{ GeV})/R(\sqrt{s}=13\text{ GeV})$ is 1.08 ± 0.18.

The high-energy electron-positron colliding-beam accelerator PETRA was finished ahead of its schedule. In the last two months we have been able to use the facility in a stable condition with a luminosity between 10^{29} and 10^{30} cm^{-2}/sec to perform our experiment. The machine operates in two-bunch mode. The lifetime is typically three hours and the filling time has been kept to a maximum of thirty minutes. Thus we are able to perform our physics experiments without much difficulty.

The detector we used, known as MARK-J, is shown in Fig. 1. It is a detector designed to measure and distinguish hadrons, electrons, neutral particles, and muons. It covers a solid angle of $\varphi=2\pi$ and $\theta=9°$ to $171°$ (θ is polar angle and φ is azimuthal). The detector is symmetrical in both φ and θ directions.

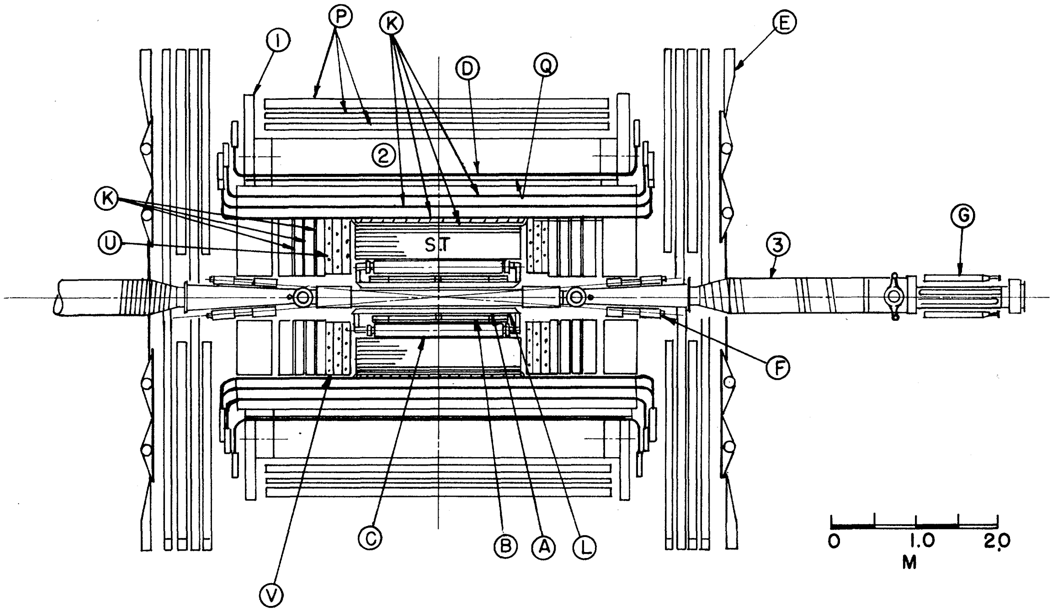

FIG. 1. Side view of the MARK-J detector: A, B, and C, shower counters; D and E, trigger counters; F and G, monitor counters; K, calorimeter counters; and L, Lucite trigger counters. 1, Al ring; 2, magnet iron; 3, beam pipe.

As shown in Fig. 1, the particles leaving the intersection region pass through 32 Lucite Cherenkov counters, L, sixteen on each side of the intersection point. These counters are used to distinguish charged particles from neutrals and are insensitive to synchrotron radiation. They have been tested in an energetic π beam at the CERN proton synchrotron and found to be 100% efficient. These counters cover down to an angle of $\theta = 9°$ to 171°. The twenty A counters have one tube at each end, are made out of three radiation lengths of lead sandwhiched with 5 mm of scintillators, and cover an angle region of $\theta = 12°$ to 168°. The 24 B counters are constructed identically to the A counters and cover an angle region of $\theta = 16°$ to 164°. The counters A and B enable us to locate shower maxima in various θ and φ directions. The sixteen C shower counters consist of twelve layers (twelve radiation lengths) of lead-scintillator sandwich also with one tube at each end. The drift chambers S and T have twelve planes each and U and V have ten planes. They are used to sample hadron showers and measure the original muon angles with a spatial resolution $\approx 400\ \mu$m.[1,2] The hadron calorimeter K consists of 192 counters sandwiched with magnetized iron to measure hadron showers. The chambers Q, R, and P have ten to sixteen planes each. The 32 D and 16 E hodoscopes have dimensions of 30 cm×4.5 m×1 cm and 80 cm×4.5 m×1 cm, respectively. At each end of the D and E hodoscopes there is a phototube. With a mean timing circuit we obtained a timing resolution $\sigma = 0.5$ ns independent of the position in which the particles enter the counter. The D and E counters are used to trigger on single- and multiple-muon events and to reject cosmic rays and beam sprays. One quarter of the complete assembly was tested and calibrated at a muon, electron, and pion beam at CERN. The gain of all the counters was adjusted according to the test results. For this experiment the forward and backward parts of the detector (i.e., the U and V chambers, the E counters, etc.) as well as information on the magnetic field were not used.

A very loose trigger was used which collects candidates for electron pairs, single-muon events, muon pairs, and hadron events. For electron pairs we require that the opposite quadrant of A and B counters be in coincidence and that each quadrant have a minimum energy of 0.5 GeV. For single-muon events we require at least two A counters, two B counters, and one D counter triggered. For muon pairs we require at least two A counters in coincidence with a pair of opposite-quadrant D counters. For hadrons we require at least four A counters and three B counters, and each quadrant A, B, or C to be in coincidence with the opposite quadrant and at least have two pairs of the opposite quadrant triggered.

Cosmic-ray and accidental events were mostly rejected by requiring the event trigger to be in coincidence with the beam bunch signal to ± 15 ns. With a luminosity of 10^{29} to 10^{30} cm^{-2}/sec most of the loose trigger comes from residual cosmic rays and beam spray. The trigger rate is typically 4–5 per second. A microprocessor is used to require that the S and T chambers have at least three counts for hadron triggers. This reduces the tape-writing rate by an order of magnitude.

The counters F and G are luminosity monitors. They are designed to measure the forward-backward $e^+e^- \to e^+e^-$ reaction. These F and G counters are made out of scintillators in front, which define the acceptance, and lead-glass hodoscopes which measure the angle and energy of the electron pairs. For this experiment the luminosity was monitored in two ways: (1) by using the forward G counters, which consist of 56 lead-glass hodoscopes[3] each with a dimension of $8\times 8\times 70$ cm^3 and located 5.8 m from the intersection point, as monitors, and (2) by using the L, A, B, and C hodoscopes which measure the forward-angle Bhabha scattering ($11.5° < \theta < 26°$). The radiative correction for Bhabha scattering is +4.6% at $\theta = 14°$ and +1.3% at $\theta = 90°$ for $\sqrt{s} = 17$ GeV.[4] It is slightly smaller at $\sqrt{s} = 13$ GeV. The results of measurements (1) and (2) after radiative correction agree with each other to within 10%.

The total energy of each interaction and directions of particles or groups of particles was computed from the time and pulse-height information of the shower counters and calorimeter counters. From the difference in time between the two phototubes on each shower counter and from the ratio of their pulse height we obtained two independent measurements of the position along the beam direction at which the particles struck the counter. The azimuthal position was determined by the finely segmented shower counters. The algorithms used were developed from analysis of test-beam data which were accumulated for incident electrons and pions between 0.5 and 10 GeV. This method enables us to determine the θ and φ angles to $< 5°$ for e or γ and $< 15°$ for μ or hadrons.

For each particle, or group of particles emitted within a cone of 20° which were not separable in the counters, the vector momentum was computed from pulse-height and counter-position information using the position of the interaction region.

To eliminate the bulk of the beam-gas background, which is mainly low energy and one sided, we first require that the total energy deposited in the calorimeter be greater than 5 GeV and that the computed total $p_\perp$ and total of $p_\parallel$ each be less than 50% of the observed energy.

One part in a thousand of the raw events pass the above criteria, and pictures of each surviving event were scanned by physicists on a videoscreen to assure that the counter tracks are reasonably fitted. We further demanded at least one track in the drift chambers pointing back to the interaction region to distinguish hadronic events from beam-gas events. The interaction region is defined by $ee \to \mu^-\mu^+$ events to $\sigma = 2$ cm. To discriminate against events of electromagnetic origin such as $ee \to ee$, $ee \to ee\gamma$, and so forth, we have accepted three types of events with different shower properties which are as follows:

(1) Two narrow showers penetrating into the third and fourth layer of the hadron calorimeter counters (K). There is a total of 33 radiation lengths from the intersection region. To discriminate against e^+e^- and $\gamma\gamma$ final states, the total energy in the K calorimeter counters is required to be greater than 7% of the total shower energy in $A + B + C$.

(2) Two broad showers penetrating into the first or second layer of the K calorimeter counters with energy greater than 1% of the total A, B, and C shower energy.

(3) Three or more broad showers with tracks in the drift chambers are also considered. A typical event is shown in Fig. 2(b).

The energy spectrum of the events passing the cut is shown as the hatched area of Fig. 3. The energy spectrum of beam-gas events, which are defined by a chamber track pointing at least 15 cm from the intersection point, is shown as the nonhatched area in Fig. 3. A comparison of those two spectra (which were taken simultaneously) shows that the real hadron events can be readily separated from beam gas by requiring the total energy of the event to be larger than 10 GeV for $\sqrt{s} = 17$ GeV (the cut is 8 GeV for $\sqrt{s} = 13$ GeV data). This cut will exclude from our sample most of the τ-lepton decay. The τ contribution is estimated to contribute 0.1 unit to R.

The acceptance for $e^+e^- \to$ hadrons via one-photon annihilation was computed using the Monte Carlo program. The program generates two jet events according to the Feynman-Field *Ansatz*[5] which includes only u, d, and s quarks. Each final-state track is then traced through a simulated representation of the detector which includes all the geometric details [as shown in Figs. 1(a) and 1(b)] of the magnet, scintillation counters,

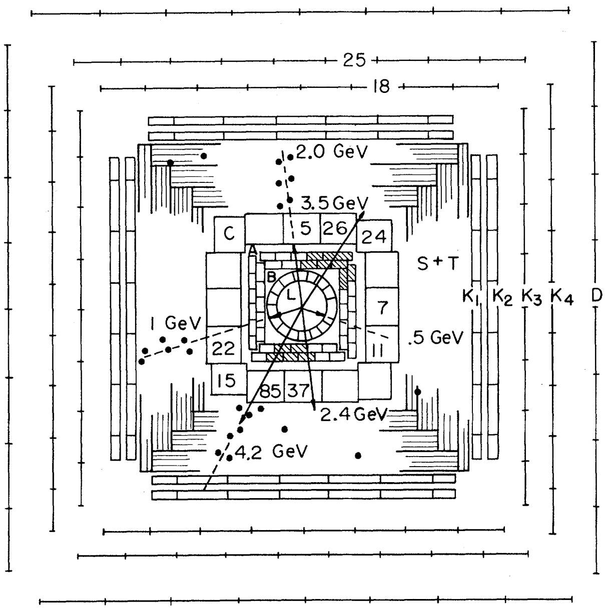

FIG. 2. A typical hadronic event as seen from the end view. The vectors which are drawn are along the direction of the identified showers in the A, B, C, and K counters. The numbers on the counters are proportional to the measured energy. The total energy seen in this event is 13.6 GeV. The circles are hits in the S and T chambers. Three tracks are visible and they point to the vertex.

and drift chambers. The digitized drift times in the chambers are generated after considering the nonlinearities of the relation between the position in the chamber and the drift time and effects of multiparticle hits in the chamber on the digitizing electronics. The pulse heights in each scintillation counter are produced using tables of the penetration probability of hadrons as a function of momentum and absorber depth as well as matrices representing the mean value and rms fluctuation of energy deposited in each counter as a function of incoming hadron energy and angle. The tables were produced using our test-beam data obtained at CERN as well as of an experiment by Sander[6] and the results of the Monte Carlo program (CALOR).[7] The resulting counter pulse heights and digitized chamber hits are then subjected to a set of cuts approximating those of the analysis program. With use of these methods, and of Feynman-Field jet events with average $p_\perp$ = 350 MeV, the acceptance as a fraction of 4π is 0.79 both at $\sqrt{s}$ = 17 GeV and at $\sqrt{s}$ = 13 GeV. Changing the average $p_\perp$ to 600 MeV increases these numbers by less than 5% which is included in the systematic errors of our results. The two-photon contribution has been calculated and found to be < 5% in this experiment.[8]

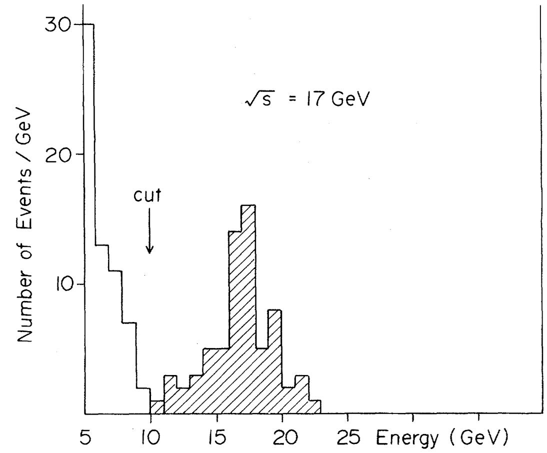

FIG. 3. Hatched area: energy spectrum of the events passing the criteria as defined in the text. Nonhatched area: energy spectrum of the beam-gas events.

We have obtained the following:

	$\sqrt{s}$ = 17 GeV	$\sqrt{s}$ = 13 GeV
$\int L dt$ (nb^{-1})	60	53
Events	68	98
R	4.9±0.6	4.6±0.5

where

$$R = \frac{\sigma(\text{hadrons})}{\sigma(\mu\mu)} = \frac{\text{events}}{\int L dt} \cdot \frac{1}{\text{acceptance}} \cdot \frac{1}{\sigma(\mu\mu)}.$$

We have assigned a rather conservative systematic error of ± 0.7 on R at each energy for the following reasons: (1) uncertainties due to models used in the Monte Carlo calculation of acceptance (± 10%), (2) the error in luminosity measurement (± 6%), and (3) the possibility of confusion in event selection (± 5%).

The ratio of R, which is insensitive to systematic errors, is then

$$R(\sqrt{s} = 17\ \text{GeV})/R(\sqrt{s} = 13\ \text{GeV}) = 1.08 \pm 0.18.$$

Our relative ratio R implies that there is no high-yield production of new particles in this energy region.

We wish to thank Professor H. Schopper and Professor G. Voss, who made this experiment possible. We are grateful for the cooperation of the German Ministry of Science, the Joint Research Program of FOM and ZWO of the Netherlands, the United States Department of Energy, and the Institute of High Energy Physics of the Chinese Academy of Science in this endeavor. We especially thank Dr. F. J. Eppling, Dr. M. Deutsch, Dr. H. Feshbach, Dr. G. Soehngen, and Dr. G. Weber for their valuable advice and support. We thank Miss I. Schulz, Miss S. Marks, Mr. P. Berges, and Mr. D. Osborne for technical and administrative help.

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Cosmological Constraints on New Stable Hadrons

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Possible new hadrons containing massive stable quarks (e.g., color-sextet quarks) surviving as relics of the early stages of the big bang should be present in $Z>1$ nuclei at levels accessible to experiment ($\sim 10^{-10}$). Grand unified theories that explain the observed baryon asymmetry of the universe should not contain these new stable quarks unless they are prevented from evolving asymmetrically. Otherwise, the new hadrons would be as common as nucleons, which is clearly not the case.

Existing bounds on anomalously heavy stable isotopes of hydrogen are exceedingly low, $\sim 10^{-18}$ relative to ordinary hydrogen for masses less than 16 GeV.[1] In contrast, bounds on anomalous stable isotopes of nuclei with $Z>1$ are much less severe.[2] A new heavy quark prevented from decaying by a new conserved quantum number would, along with the usual light quarks, form a stable heavy hadron. In terrestrial material, such heavy hadrons may reside preferentially in $Z>1$ nuclei. There is, moreover, no reason to expect that a nucleus containing such a new, heavy object would have an integral atomic mass.

The limit on anomalous nuclei of arbitrary mass comes simply from comparisons of the masses of elements determined chemically with those determined physically by averaging the known isotopes.[2] In contrast, techniques to detect specific stable isotopes[3] can have sensitivities as great as one nucleus in 10^{16}. Experiments designed specifically to search for anomalous heavy nuclei should therefore easily eliminate the new heavy hadrons—or find them if they exist.

The possibility that there exist new, heavy, stable quarks (for our purposes the lifetime should exceed the age of the Universe $\sim 10^{10}$ yr) has been suggested recently by several authors.[4-7] The negative results of searches at accelerators[8] suggest that it is unlikely that the ~5-GeV b quark (constituent of the upsilon)[9] is stable as was originally suggested by Cahn.[5] Indeed, these experiments eliminate long-lived ($\tau \gtrsim 5\times 10^{-8}$ sec) hadrons (production cross section $>\frac{1}{10}\sigma_T$) with mass $\lesssim$5–10 GeV. There is, however, no evidence at present against the existence of a stable hadron with mass $\gtrsim$10 GeV. There is, however, no evidence at present against the existence of a stable hadron with mass $\gtrsim$10 GeV. For example, the color-sextet quark of charge $+\frac{1}{3}$ that arises naturally in the theory of supergravity[6] based on SO(8) could be sufficiently massive to have escaped detection. A color-sextet quark would be

