dependence of the rise in α_{pair} vs $p_\perp$. We can, however, see significant species dependence of α at low dihadron $p_\perp$. The values of α are especially high for pK^- and $p\bar{p}$ states, which contain two particles, each with a single-hadron α value which reaches 1.3 at high $p_\perp$.

In conclusion, we find that the dihadron A dependence in the hard-scattering region exhibits a behavior as a function of $p_\perp$ similar to that observed for single hadrons. But, with integration over all $p_\perp$, the average α_{pair} is consistent with 1 for $m' > 4.5$ GeV/c. As was evident from single-hadron results,[1] the quantum numbers of the state produced play an important role.

We thank the many people from Fermilab, Nevis Laboratory, and the State University of New York at Stony Brook who helped us to carry out the experiment. We also thank J. W. Cronin for helpful discussions. This work was supported in part by the National Science Foundation and the U. S. Energy Research and Development Administration.

[a] Present address: CERN, 1211 Geneva 23, Switzerland.

[b] Present address: Foundation for Fundamental Research on Matter, Amsterdam, The Netherlands.

[1] L. Kluberg *et al.*, Phys. Rev. Lett. 38, 670 (1977).

[2] L. M. Lederman, in *High-Energy Physics and Nuclear Structure—1975*, AIP Conference Proceedings No. 26, edited by H. C. Wolfe (American Institute of Physics, New York, 1975), p. 303.

[3] U. Becker *et al.*, Phys. Rev. Lett. 37, 1731 (1976).

[4] J. Pumplin and E. Yen, Phys. Rev. D 11, 1812 (1975).

[5] G. Farrar, Phys. Lett. 56B, 185 (1975).

[6] P. V. Landshoff, J. C. Polkinghorne, and D. M. Scott, Phys. Rev. D 12, 3738 (1975).

[7] P. M. Fishbane and J. S. Trefil, Phys. Rev. D 12, 2113 (1976); P. M. Fishbane, John K. Kotsonis, and J. S. Trefil, Phys. Rev. D 16, 122 (1977).

[8] J. H. Kühn, Phys. Rev. D 11, 2948 (1976).

[9] M. L. Good, Y. Kazama, and C. N. Yang, Phys. Rev. D 15, 1920 (1977).

[10] G. Berlad, A. Dar, and G. Eilam, Phys. Rev. D 13, 161 (1976).

[11] S. Fredriksson, Nucl. Phys. B111, 167 (1976).

[12] A. Krzywicki, Phys. Rev. D 14, 152 (1976).

[13] R. D. Kephart *et al.*, Phys. Rev. Lett. 39, 1440 (1977).

[14] If $k \equiv (\mathrm{N/SEM}) \times [A/(\text{Avogadro's number} \times \text{density of target} \times \text{length of target})]$, then $C = k_W/k_{Be}$.

[15] We calculate α for hadrons (averaged over charge) using α values for π, K, and p from Ref. 1 and particle ratios from J. W. Cronin *et al.*, Phys. Rev. D 11, 3105 (1975).

Search for Fractionally Charged Tungsten Ions

R. N. Boyd, D. Elmore, A. C. Melissinos, and E. Sugarbaker
Department of Physics and Astronomy and Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
(Received 3 October 1977)

A search for W ions having an additional charge of $-\frac{1}{3}e$ has been conducted, using a Van de Graaff accelerator as an ultrasensitive mass spectrometer. The study investigated masses varying from 182 to 192 amu. No evidence was found for the existence of such ions to a limit of 1 part in 1×10^{12} over the mass range covered.

Since the original suggestion by Gell-Mann[1] and Zweig[2] that particles with fractional charge may exist, several groups have searched for such particles (quarks) either by attempting to produce them in accelerators,[3] or by detecting their presence in cosmic rays or in various materials in which they may be trapped.[4] Searches for integrally charged quarks[5] which would manifest themselves as stable particles of anomalous mass have also been reported.[6] All such searches have been negative except for a recent result from a magnetic levitation experiment reported by LaRue, Fairbank, and Hebard.[7] That result suggests[8] that the quarks are attached to W atoms or nuclei, producing fractionally charged W (hereafter denoted as W_f). A more recent result by Bland *et al.*[9] finds no evidence for fractional charge in W at a sensitivity of 1 part in 1.1×10^{12}.

The present experiment involves quite a different approach. The tandem Van de Graaff accelerator facility of the University of Rochester Nuclear Structure Research Laboratory was used as a double mass spectrometer followed by a detection system [see Fig. 1(a)]. The entire system was designed to accept W_f in a specific charge state, the $W_f^{+14/3}$ state, and to reduce the intensities of other ionic species as much as possible.

The accelerator injection system, consisting of a sputter ion source,[10] inflection magnet, and 150-kV preacceleration column, selects negative

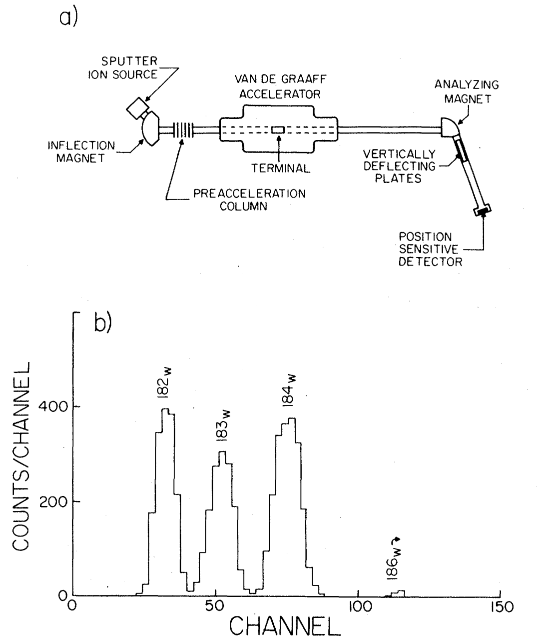

FIG. 1. (a) Layout of experimental apparatus; (b) position spectrum for 36-MeV $W^{(+5)}$ guide beam on the PSD.

ions of a specific charge-to-mass ratio. Thus injection of a ^{184}W beam of particles having charge $-\frac{1}{3}e$ is achieved by sputtering from a W cone (made from zone-refined W) in the source and setting the inflection magnet at the field setting equivalent to that for injection of an ion of mass 552 amu having a charge of $-1e$. The inflection-magnet field calibration was performed to an accuracy better than 1% by using calibration beams such as O_2, W, WO_3, Pb, Pb_2, and YbI_3. The mass resolution of the injection system is about 6 amu FWHM (full width at half-maximum) out of 184 amu. In addition, a ramp placed on the deflection plates just following the ion source extended this over another 4 amu.

Ions in several charge states are produced at the (N_2 gas) terminal stripper. Those with charge q and mass M have energy $E=(V_{ext}+V_{pa}+V_T)q_0M/M_0+V_Tq$, where V_{ext}, V_{pa}, and V_T are the source extraction, preacceleration, and terminal voltages respectively, M_0 is the mass of the injected molecule from which the (elemental) ion of mass M comes, and q_0 is the magnitude of the (negative) charge of the injected ion. After acceleration, ions with specific ME/q^2 are selected by the analyzing magnet. A pair of electrostatic vertically deflecting plates (ES plates) was placed just following the 70° exit port of this magnet. A 5-cm-long (collimated to 4 cm long by 1 mm high) semiconductor position-sensitive detector (PSD) was mounted horizontally 2 m after the exit port and 5.7 cm below the axis of the undeflected beam. The deflection of the ions by the ES plates determines their q/E, and the PSD gives their energy. Furthermore, all ions which originate in the source undergo charge exchange only at the terminal, and are selected by the analyzing magnet have sufficiently similar q/E values that they are accepted by the detector collimator. The ES plates thus distinguish between ions with the above properties and those originating elsewhere, e.g., from charge exchange in the accelerator tubes. Thus these three elements determine the q, E, and M of any ion which gets to the detector. The PSD also allows observation of the individual masses in its position spectrum; that for a 36-MeV W calibration beam, shown in Fig. 1(b), exhibits the approximate isotopic abundance of $^{182,183,184}W$.

Since in the W_f injection configuration only small beam currents could be observed out of the accelerator, tuning was done with guide beams. The low-energy steerers and lenses were optimized for a variety of beams injected at the accelerator terminal voltage of interest, and the differences in settings observed. Since, except for the inflection magnet, these steering and focusing elements are electrostatic, their optimum settings might be expected to depend only slightly on the beam-particle mass. This was confirmed, and so the low-energy parameters were set at those which optimized a $(WO_3)^{-1}$ beam.

The same $(WO_3)^{-1}$ beam was injected into the accelerator and the $W^{(+5)}$ beam emerging from the terminal stripper was used to tune the high-energy accelerator parameters. This tuning was performed at the same analyzing magnet (and, therefore, magnetic quadrupole) setting as that used to look for the $W_f^{+14/3}$ charge state. Since the $W^{(+5)}$ charge state observed at that magnet setting requires an accelerator terminal voltage of about 70 kV (out of 6.29 MV) less than that required for the $W_f^{+14/3}$ if the W_f mass is the same as the W mass, the $W^{(+5)}$ tuning also gave the terminal-voltage calibration for the W_f runs. Once set, that voltage was maintained at a constant value by a generating voltmeter system. The ES plate voltage required for the $W^{(+5)}$ beam is also close to that of the $W_f^{+14/3}$ particles; hence the $W^{(+5)}$ tune also provided that calibration. The source extraction voltage, inflection magnet field, accelerator terminal voltage, analyzing magnet field, and ES plate voltage were all monitored continuously throughout data collection. The stability of the entire system is documented by the fact that the transmission from source to PSD was essentially unchanged after 32 hours of data taking with identical accelerator parameters.

In order to encompass a larger range of W_f mass than the 4 amu spanned by the PSD, the terminal voltage, inflection magnet, and vertically deflecting plate voltage were scanned to produce a grid spanning a total W_f mass range of 10 amu. The PSD energy spectrum in Fig. 2(a) illustrates the extreme sensitivity of this technique to trace quantities of impurities in the beam produced at the source. Most of the ion masses which could possibly have been transmitted through the entire system were observed at the PSD. The charge-state separation in the PSD energy spectrum reflects the near constancy of q/E for all such ions. Also note that M/q for such ions is essentially constant; thus the higher-charge-state impurity peaks will contain the heavier-mass ions. For example, the 3+ peak was predicted[11] to contain isotopes of Sn at the terminal voltage of 6.29 MV, and these were identified in the position spectrum of that charge-state peak (by comparing the count rate with the natural abundances of the isotopes). Over the grid described above, the composition of the 5+ peak varied from isotopes of Au and Hg to those of Tl and Pb. Note that at no point in the grid were W ions expected to reach the PSD.

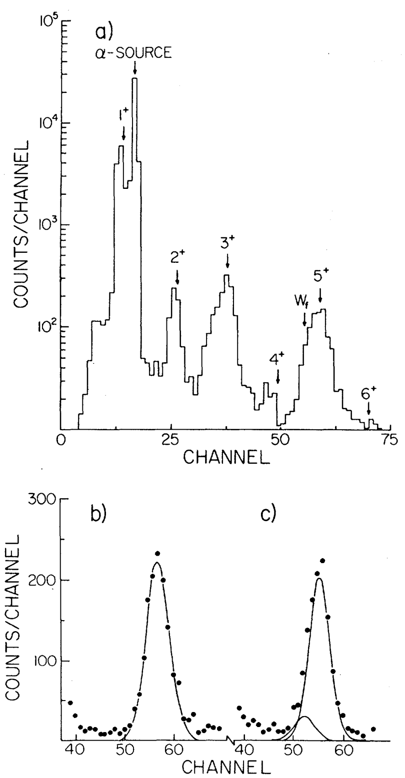

FIG. 2. (a) Energy spectrum seen in the PSD. The arrows indicate channel locations of the several charge-state peaks predicted from the energy calibration; (b) a 5^+ peak of average width and its Gaussian peak fit; (c) a two-peak fit to the 5^+ peak which gave the highest W_f count rate; the smaller peak is at the predicted $W_f^{+14/3}$ location.

The energy calibration of the PSD was accomplished by observing the locations of highly attenuated W and C beams of well-defined (by the accelerator and analyzing magnet) energies, and by using the formalism of Kaufmann *et al.*[12] to account for the pulse-height defects in the detector. The channel locations thus predicted for the peaks of the integral-charge states [indicated by the arrows in Fig. 2(a)] are in excellent agreement with those observed. With this calibration, the $W_f^{+14/3}$ peak is predicted to occur at about 6% (with a slight variation with terminal voltage) below the 5+ impurity peak in the energy spectrum; this was confirmed by observing the peak location produced by a $W^{(+5)}$ beam at the $W_f^{+14/3}$ energy.

The 5+ impurity peaks from each point in the grid over terminal voltage and inflection magnet were fitted with a Gaussian peak shape [see Fig. 2(b)], and the centroid and FWHM (about 10%) extracted. While the distributions of these two quantities did not indicate more than a single peak at the energy of the 5+ impurities, a small additional peak on the side at the $W_f^{+14/3}$ location would be difficult to detect. Thus these data were analyzed further as indicated below.

The addition of one quark to each of the four prominent W isotopes (which span 5 amu) could produce $W_f^{+14/3}$ satellites on the 5+ energy peaks in no more than half the spectra in the grid. Such a satellite at the predicted location would produce an increase in the FWHM and a decrease in the centroid of the composite peak. Thus averages of the smaller half of the FWHM's, $\overline{FWHM}$, and of the larger half of the centroids (after accounting for the variation with terminal voltage), $\overline{CH}$, were determined. The peaks were then fitted with a sum of two Gaussian peaks each having width $\overline{FWHM}$ and centroids fixed at $\overline{CH}$ and $\overline{CH}$ less the 6% difference given by the energy calibration. The amplitudes of the two Gaussians were adjusted for the best fit. Under this procedure, the maximum count rate for any grid segment which spans 5 amu in W_f mass was 0.15 counts/sec; the corresponding fit is shown in Fig. 2(c). Increasing this rate to 0.22 counts/sec (which is 10% of the 5+ impurity peak count rate) includes 1 standard deviation; this rate was taken to be the upper limit for the count rate of $W_f^{+14/3}$ ions.

The W atoms having a quark with charge of $-\frac{1}{3}e$ would be produced by the same mechanism as neutral W atoms in the source, i.e., by simple sputtering, but would be extracted at the rate for $W^{(-1)}$ ions. Since the sputtering process is not very dependent on nuclear charge,[13] the rate at which $W^{(-1/3)}$ ions leave the source was assumed to be

$$I_{-1/3} = \rho_{0-1} R I_{-1}, \tag{1}$$

where ρ_{0-1} is the ratio of the densities of neutral W to that of $W^{(-1)}$ ions in the source, R is the fraction of natural W which has a $-\frac{1}{3}$ quark, and I_{-1} is the particle current observed for $W^{(-1)}$. The value of ρ_{0-1} is estimated,[14] from secondary ion mass spectroscopy (SIMS) data,[15] to be between 1.6×10^4 and 6×10^5. We have measured the amount of W sputtered from the source cone in a 6-h period, and have compared that to the $W^{(-1)}$ beam current measured just after the exit aperture of the source. Since the sputtered mass[14] is nearly all neutral W, these results give an estimate of ρ_{0-1} which agrees with the lower SIMS limit. That value, together with the $W^{(-1)}$ beam current measured at the accelerator entrance to be 15 nA, gives a $W_f^{(-1/3)}$ intensity there of $I_{-1/3} = (1.5\times10^{15})R$ ions per second.

The yield of $W_f^{+14/3}$ at the detector is then given by

$$I_{-1/3} T_{+14/3}(6\text{ MV}) f_{+14/3}(6\text{ MV}) < 0.22 \text{ counts/sec}, \tag{2}$$

where $T_{+14/3}(6\text{ MV})$ is the accelerator transmission for the $W_f^{+14/3}$ beam and $f_{+14/3}(6\text{ MV})$ the fraction of the W_f in the +14/3 charge state at $V_T = 6$ MV. Since the energy of the $W_f^{(-1/3)}$ ions at the 6-MV terminal is only 2 MeV, the product $T_{+5}(6\text{ MV})f_{+5}(6\text{ MV})$ observed at regular intervals throughout the experiment for the WO_3 guide beam (which produces a W beam of 5 MeV at the terminal for a 6 MV terminal voltage) must be corrected for the energy dependence of accelerator transmission and charge-state population. The value of $f_{+14/3}(6\text{ MV})$ will lie between $f_{+4}(2\text{ MV})$ and $f_{+5}(2\text{ MV})$. The systematics of terminal stripping[16] suggest that the latter number leads to a more conservative W_f limit. Accordingly, the products $T_{+5}(2\text{ MV})f_{+5}(2\text{ MV})$ and $T_{+5}(5\text{ MV})f_{+5}(5\text{ MV})$ were measured for a gold beam and found to be 1.4×10^{-3} and 7.6×10^{-3}, respectively. Using the product of this ratio and $T_{+5}(6\text{ MV})f_{+5}(6\text{ MV})$ (conservatively 8×10^{-4} under running conditions) for the WO_3 beam in Eq. (2) we find that $R < 1\times10^{-12}$.

The systematics of the accelerator and detection system, the stability of the entire system, and the consistent choice of conservative estimates of numbers in the calculation lead us to conclude that $W_f^{(-1/3)}$ does not exist above a level of 1 part in 1×10^{12} in our W sample over the mass range from 182 to 192 amu. This result is essentially the same as that of Bland *et al.*[9]; the fundamental differences in the two experimental approaches make the mutual corroboration important. Since the limit imposed by the experiment of LaRue, Fairbank, and Hebard[7] is difficult to determine,[8] a definitive comparison with the present result cannot be made.

The authors are grateful to T. Lund, W. Sondheim, and the rest of the Nuclear Structure Research Laboratory staff for their assistance in the technical aspects of the experiment, and to M. McLaughlin for experimental assistance. W. P. Alford is thanked for allowing us to use his detector. Finally, we wish to acknowledge useful discussions with H. E. Gove, J. R. Birkelund, R. B. Liebert, R. Middleton, and C. Goldie. This work was supported in part by the National Science Foundation and by the U. S. Department of Energy.

[1]M. Gell-Mann, Phys. Lett. 8, 214 (1964).

[2]G. Zweig, CERN Report No. 8419/Th 412, 1964 (unpublished).

[3]D. Antreasyan *et al.*, Phys. Rev. Lett. 39, 513 (1977), and references therein.

[4]For a review, see L. W. Jones, Rev. Mod. Phys. 49, 717 (1977).

[5]M. Han and Y. Nambu, Phys. Rev. 139, B1006 (1965).

[6]R. Muller, L. Alvarez, W. Holley, and E. Stephenson, Science 196, 521 (1977).

[7]G. S. LaRue, W. M. Fairbank, and A. F. Hebard, Phys. Rev. Lett. 38, 1011 (1977).

[8]W. M. Fairbank, quoted by Wm. D. Metz, Science 196, 746 (1977).

[9]R. Bland, D. Bocobo, M. Eubank, and J. Royer, Phys. Rev. Lett. 39, 369 (1977).

[10]General Ionex Corp, Ipswich, Mass.

[11]D. Elmore, Program ELISE, University of Rochester, 1977 (unpublished).

[12]S. B. Kaufman, E. P. Steinberg, B. D. Wilkins, J. Unik, A. J. Gorski, and M. J. Fluss, Nucl. Instrum. Methods 115, 47 (1974).

[13]G. K. Wehner and G. S. Anderson, in *Handbook of Thin Film Technology*, edited by L. I. Maissel and R. Glang (McGraw-Hill, New York, 1970).

[14]P. Williams, University of Illinois, private communication. We are indebted to Dr. Williams for bringing the results of H. Storm (to be published) to our attention and for interpreting them. For a discussion of the SIMS techniques, see, for example, C. A. Anderson and J. R. Hinthorne, Anal. Chem. 45, 1431 (1973), and references therein.

[15]Storm, Ref. 14.

[16]H. D. Betz, Rev. Mod. Phys. 44, 465 (1972).

Will the Axion Be Found Soon?

T. Goldman and C. M. Hoffman
Theoretical and Meson Physics Divisions, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 28 November 1977)

We show that if the light isoscalar pseudoscalr meson (h) proposed by Wilczek and by Weinberg exists, it must be seen in the decay $K^+ \to \pi^+ h$. The theoretical lower bound and the present experiment upper bound differ by approximately an order of magnitude.

Recently, Wilczek[1] and Weinberg[1] have suggested that unless the mass of the "up" quark vanishes, in conflict with current-algebra estimates,[2] a *low-mass* isoscalar peseudoscalar meson (axion or h) must exist. It is required to prevent the appearance of strong-interaction CP-nonconserving effects in QCD (quantum chromodynamics) and gauge theories of the weak interactions.

We point out in this Letter, by two different arguments, that if the axion exists, it must appear in kaon decays $K^+ \to \pi^+ h$ at a level not much below the present experimental limits. The first argument is a variant of PCAC (partial conservation of axial-vector current) applied to an *isoscalar* axial current, the divergence of which should be dominated by the axion pole. The second argument uses a static quark model (SQM) for kaon decay which reproduces the dominant modes adequately.[3] Despite the wide differences of approach of these two arguments, they provide essentially the same parameter-independent lower bound for $K^+ \to \pi^+ h$. Finally, we examine the present experimental limits on this process in the light of these theoretical estimates.

The essential feature of the axion that is required for these arguments is the axion-fermion interaction Lagrangian density. We use Wilczek's[1] version, which we write as

$$L_I = 2^{1/4} G_F{}^{1/2} \Big\{ \sum_{Q=2/3,1/3;\,C} \left[\tilde{m}_q \tan\eta\, \bar{q}_{2/3,C} \gamma_5 q_{2/3,C} + \tilde{m}_q \cot\eta\, \bar{q}_{1/3,C} \gamma_5 q_{1/3,C} \right] + \textstyle\sum_l \tilde{m}_l \cot\eta\, \bar{l} \gamma_5 l \Big\} \times (h \cos\zeta - \pi^0 \sin\zeta), \quad (1)$$

where $q_{Q,C}$ is the field of the quark of charge Q and "color" C, $\tilde{m}_q$ is its current-algebra mass,[4] h is the axion field, l is the field of a charged lepton, and $\tan\eta$ is a parameter whose value is unknown.[5] We have included a description of h-π^0 mixing by means of the mixing angle ζ.

Our first argument is based on PCAC applied to axions. To implement it, we need to know the appropriate axial current containing the axion. A general discussion of this question for various Higgs structures has been developed by Bardeen and Tye.[6] The current we use below is consistent with their results for a simple four-quark version of the W-S (Weinberg-Salam) model with two Higgs doublets: the φ, which gives mass to the u and c quarks by means of its vacuum expectation value (VEV), and the χ, which does the same for d and s quarks.[7] (The ratio of the VEV's of χ and φ defines the parameter $\tan\eta$ which is therefore positive.) The structure of the current is constrained by the requirement that its divergence vanish in the limit $\tilde{m}_u \to 0$ since, in that limit, the axion should become massless, i.e., it should be the Goldstone boson of the current.

Using this constraint, we construct the current and find

$$A_\mu{}^h = i f_h \partial_\mu h \cos\zeta - \sum_C \bar{\psi}_C \left\{ \frac{(\tan\eta + 3\cot\eta)}{2\sqrt{6}} \lambda_8 + \frac{\tan\eta}{\sqrt{3}} \lambda_{15} \right\} \gamma_\mu \gamma_5 \psi_C, \quad (2)$$

