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[1]G. Cocconi, E. Lillethun, J. P. Scanlon, C. A. Stahlbrandt, C. C. Ting, J. Walters, and A. M. Wetherell, Phys. Letters 8, 134 (1964).

[2]G. Belletini, G. Cocconi, A. N. Diddens, E. Lillethun, J. P. Scanlon, A. M. Shapiro, and A. M. Wetherell, Phys. Letters 18, 167 (1965).

[3]C. M. Ankenbrandt, A. R. Clyde, B. Cork, D. Keefe, L. T. Kerth, W. M. Layson, and W. A. Wenzel, Nuovo Cimento 35, 1052 (1965).

[4]E. W. Anderson, E. J. Bleser, G. B. Collins, T. Fujii, J. Menes, F. Turkot, R. A. Carrigan, R. M. Edelstein, N. C. Hien, T. J. McMahon, and I. Nadelhaft, Phys. Rev. Letters 16, 855 (1966).

[5]I. M. Blair, A. E. Taylor, W. S. Chapman, P. I. P. Kalmus, J. Litt, M. C. Miller, D. B. Scott, H. J. Sherman, A. Astbury, and T. G. Walker, Phys. Rev. Letters 17, 789 (1966).

[6]H. L. Anderson and A. Barna, Rev. Sci. Instr. 35, 492 (1964); H. L. Anderson et al., CERN Report No. CERN 64-30, 1964 (unpublished).

[7]H. L. Anderson et al., in Proceedings of the International Conference on Instrumentation for High Energy Physics, Stanford (1966), to be published; Rev. Sci. Instr. (to be published).

[8]We are indebted to Dr. Ellis Steinberg for calibrating the proton beam intensity from the radioactivity induced in standard gold foils.

[9]N. P. Samios, A. H. Bachman, R. M. Lea, T. E. Kalogeropoulos, and W. D. Shephard, Phys. Rev. Letters 9, 139 (1962); J. Kirz, J. Schwartz, and R. D. Tripp, Phys. Rev. 130, 2481 (1963); R. Del Fabbro, M. De Pretis, R. Jones, G. Marini, A. Odian, G. Stoppini, and L. Tau, Phys. Rev. Letters 12, 674 (1964); F. S. Crawford, Jr., R. A. Grossman, L. J. Lloyd, LeRoy R. Price, and E. C. Fowler, Phys. Rev. Letters 11, 564 (1963); J. B. Kopelman, D. D. Allen, J. Godden, L. Marshall, E. Urvater, R. E. Juhala, and J. I. Rhode, Phys. Letters 22, 118 (1966).

[10]L. M. Brown and P. Singer, Phys. Rev. 133, B812 (1964); H. Faier and L. M. Brown, Bull. Am. Phys. Soc. 10, 467 (1965).

[11]C. Lovelace, R. M. Heinz, and A. Donnachie, Phys. Letters 22, 332 (1966).

[12]E. L. Hart, R. I. Louttit, and T. W. Morris, Phys. Rev. Letters 9, 133 (1962); G. Alexander, O. Benary, G. Czapek, B. Haber, N. Kidron, B. Reuter, A. Shapira, E. Simopoulou, and G. Yekutieli, in Proceedings of the Thirtheenth International Conference on High Energy Physics, Berkeley, California, 1966 (unpublished). C. Caso, G. Tomasini, L. Mosca, S. Ratti, I. Bloodworth, L. Lyons, and A. Norton, ibid.

[13]H. Hinterberger and R. Winston, Rev. Sci. Instr. 37, 1094 (1966).

OBSERVATION OF THE B MESON IN THE REACTION $\bar{p}+p\rightarrow\omega^0+\pi^++\pi^-$†

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The B meson, decaying into $\omega^0+\pi^\pm$, has been observed in $\bar{p}p$ annihilations at rest in the reaction $\bar{p}+p\rightarrow\omega^0+\pi^++\pi^-$. The mass and width of the B meson as observed in this reaction are $M=1200\pm20$ MeV and $\Gamma=100\pm30$ MeV.

Evidence for an $\omega\pi$ resonance at 1220 MeV, called the B meson, was first reported by Abolins et al.[1] in 1963. Since then evidence for both charged states of the B meson, decaying via $\omega^0\pi^\pm$, has been obtained in a number of experiments.[2] Recently, however, the interpretation of the enhancement in the $\omega\pi$ mass spectra as a resonant state has been questioned.[3,4]

The purpose of this note is to present evidence for the production of the $B^\pm$ meson in the annihilation of antiprotons at rest in hydrogen. The details of the experimental procedure and analysis have been published.[5]

The present study is based on 16 934 events of the type

$$\bar{p}+p\rightarrow\pi^++\pi^++\pi^-+\pi^-+\pi^0. \tag{1}$$

Figure 1 shows a fit of a Gaussian plus a second-order polynomial for background to the $\pi^+\pi^-\pi^0$ effective-mass spectrum from Reaction (1) in the region 650 to 950 MeV. The best fit, centered at $M_\omega=783.4\pm0.7$ MeV, with $\sigma=19.9$ MeV, corresponds to 3221 events of the two-step process

$$\bar{p}+p\rightarrow\omega^0+\pi^++\pi^-,\quad \omega^0\rightarrow\pi^++\pi^-+\pi^0. \tag{2}$$

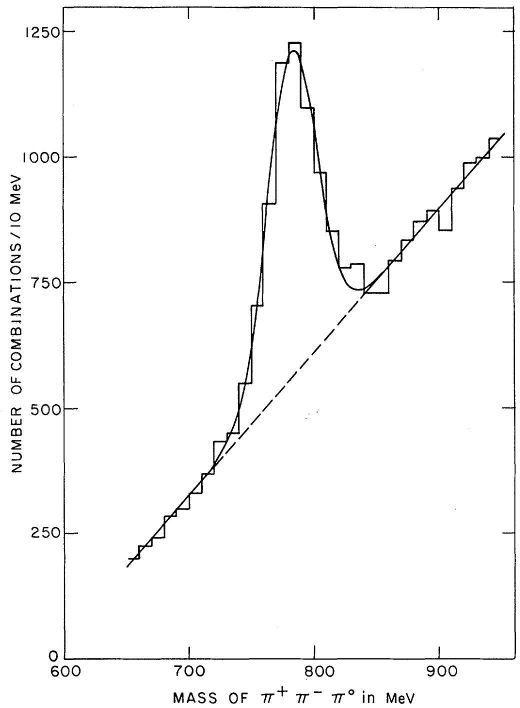

FIG. 1. Fit to the $\pi^+\pi^-\pi^0$ mass distribution in the reaction $\bar{p}+p\to\pi^++\pi^++\pi^-+\pi^-+\pi^0$ near the ω^0 mass region. The curve represents the best fit to a Gaussian plus a second-order polynomial for background, with $M_\omega=783.4\pm0.7$ MeV and $\sigma=19.9$ MeV.

For further study, events of Reaction (1) were selected with neutral pion triplets in the mass range from 765 to 805 MeV. This region included ~2200 $\omega^0\pi^+\pi^-$ events and ~2300 events of the 5π background. The mass spectrum of these neutral pion triplets combined with an additional $\pi^\pm$ in each event is shown in Fig. 2(b). For comparison, the same mass spectra are shown in Figs. 2(a) and 2(c) using pion triplets from control regions outside of the ω^0 region, with $705\le M_{3\pi}\le745$ MeV and $825\le M_{3\pi}\le865$ MeV, respectively. There is a peak in the $\omega^0\pi^\pm$ mass spectrum near 1200 MeV in Fig. 2(b), which is not apparent in either of the two control regions in Figs. 2(a) and 2(c). We interpret this peak as evidence for the production of the $B^\pm$ meson followed by its decay into $\omega^0+\pi^\pm$, via the three-step process

$$\bar{p}+p\to B^\pm+\pi^\mp$$
$$\quad\hookrightarrow\omega^0+\pi^\pm$$
$$\quad\quad\hookrightarrow\pi^++\pi^-+\pi^0. \qquad (3)$$

The significance of this effect depends on the knowledge of the $\omega\pi$ mass spectrum of the background events. Phase space alone does not adequately predict the effective-mass distributions in $\bar{p}p$ annihilations at rest. A detailed analysis of the $\omega^0\pi^+\pi^-$ final state in terms of Lorentz-invariant matrix elements corresponding to annihilation from the $^1S_0$ and $^3S_1$ states of the $\bar{p}p$ system has been carried out and the results have been presented in a previous publication.[6] In the present study the number of $\omega^0\pi^+\pi^-$ events is somewhat more than two and a half times the number used in the previous analysis (Ref. 6). A two-dimensional fit of the $\omega\pi\pi$ Dalitz plot to the distribution functions derived in Ref. 6 has been redone, excluding the two bands on the Dalitz plot which corre-

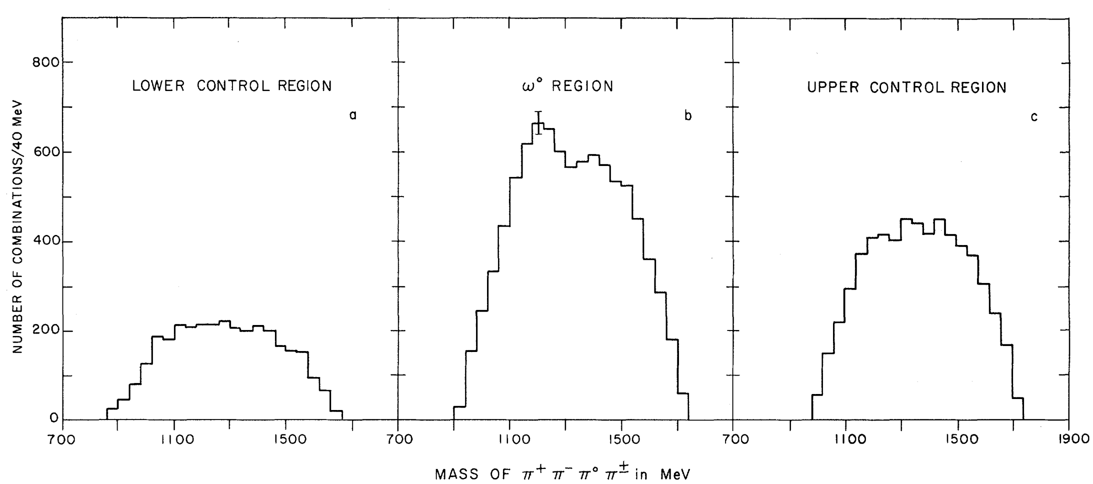

FIG. 2. Distribution in the effective mass of a neutral pion triplet combined with one of the remaining charged pions in $\bar{p}+p\to\pi^++\pi^++\pi^-+\pi^-+\pi^0$. Selection was made on the mass of the neutral pion triplet: (a) $705\le M(\pi^+\pi^-\pi^0)\le745$ MeV, (b) $765\le M(\pi^+\pi^-\pi^0)\le805$ MeV, and (c) $825\le M(\pi^+\pi^-\pi^0)\le865$ MeV.

spond to B-meson production ($1120 \leq M_{\omega\pi^\pm} \leq 1280$ MeV). The form of the distribution function used is

$$M^2 = a + b(\vec{P}_+ \times \vec{P}_-)^2 + c(E_+E_- - \vec{P}_+ \cdot \vec{P}_-) + d(E_+E_- - \vec{P}_+ \cdot \vec{P}_-)^2 + e\frac{(\vec{P}_+ \times \vec{P}_-)^2}{(M_{+-} - M_\rho)^2 + (\frac{1}{2}\Gamma_\rho)^2} \quad (4)$$

where E_+, E_-, $\vec{P}_+$, and $\vec{P}_-$, are the total energies and momenta of the π^+ and the π^-, respectively; M_{+-} is the $\pi^+\pi^-$ effective mass; and M_ρ and Γ_ρ are the mass and width of the ρ meson ($M_\rho = 760$ MeV and $\Gamma_\rho = 120$ MeV were used). The coefficients a, b, c, d, and e were determined by the fit. The last term in the distribution function was needed to take $\omega^0\rho^0$ production into account.

For each event of Reaction (1), it is possible to choose the neutral pion triplet in four different ways. Of all the events with pion triplets in the ω^0 mass region ($765 \leq M_{3\pi} \leq 805$ MeV), 91.1 % had only one triplet in the ω^0 mass region while 8.9 % had two triplets in the ω^0 mass region. Events with two triplets in the ω^0 mass region were removed from the sample used in the fit. Because of the relatively small number of events involved (8.9 %), the distribution was not substantially changed. The mass spectrum in Fig. 2(b) includes the "double-ω^0" events, while in the distributions of Fig. 3, they were removed. The significance of the peak is clearly unaffected by the inclusion or removal of these events. The position of the peak, however, is sensitive to the distortion introduced by the double-ω^0 events to the extent of ~20 MeV. The removal of these events was taken into account in the computation of the background by also removing the double-ω^0 events in the calculation of the distribution function (4), using Monte Carlo techniques.

The Dalitz plot was folded about the E_{ω^0} symmetry axis. After removing the B-meson bands, the remaining area was divided into 64 boxes. The χ^2 method was used to fit the number of events in these boxes to distribution function (4). The best fit had $\chi^2 = 55.3$ with the values of the coefficients b and c consistent with 0. The fit was redone forcing b and c to 0; the χ^2 for the three-parameter fit remained essentially unchanged.[7]

The projection of the distribution function on the $\omega^0\pi^\pm$ mass axis using the coefficients obtained from the best fit is shown by the dashed curve on Fig. 3(a). The curve is normalized to have the same area as the experimental distribution; the disagreement between this curve and the experimental distribution in the region 1100 to 1400 MeV is apparent. A χ^2 fit to the experimental $\omega^0\pi^\pm$ mass distribution was then performed using the background curve, plus a Breit-Wigner resonant amplitude multiplied by phase space for the B meson; the position and width as well as the magnitude of the Breit-Wigner contribution were free parameters. The best fit obtained had $\chi^2 = 34.4$ with 37 degrees of freedom and yielded a mass and width for the B meson of $M_B = 1200 \pm 20$ MeV and $\Gamma_B = 100 \pm 30$ MeV. The 20-MeV error on the mass of the B meson includes both the statistical error from the fit as well as the uncertainty in the B-meson mass connected with the removal of the double-ω^0 events. The area of the Breit-Wigner in the fit corresponds to 376 $\pm$ 75 events, which leads to an annihilation rate for B-meson production via process (3), corrected for the neutral decays of the ω^0, of (0.75 $\pm$ 0.25) % of all $\bar{p}$ stops. The fit is shown by the solid curve in Fig. 3(a).

To test whether the peak at 1200 MeV is actually associated with the ω^0, as is expected for the B meson, or with uncorrelated pion triplets in the background under the ω^0 peak, the data were divided into two parts, as suggested by Goldhaber et al.,[3] according to the position of the event on the ω^0 decay Dalitz plot. The true ω^0 events have a distribution given by $(\vec{P}_i \times \vec{P}_j)^2$ on the decay Dalitz plot, while in the present sample, the background pion triplets in the ω^0 mass region are experimentally consistent with a uniform distribution. Events were separated into "central" and "peripheral" events by a selection in $(\vec{P}_i \times \vec{P}_j)^2$ in such a way that the true ω^0 events were equally divided, while there were ~2 times as many background events in the peripheral region as in the central region. Both distributions were fitted to the background curve discussed above plus a Breit-Wigner, multiplied by phase space, with $M = 1200$ MeV and $\Gamma = 100$ MeV. The best fits correspond to 218 ± 49 B-meson events in the central region and 155 ± 54 in the peripheral region. These numbers are in agreement with the 1-to-1 ratio predicted for B-meson decay into $\omega + \pi$, and are in poor agreement with the ratio 1 to 2 predicted for B-meson decay into uncorrelated pions. The $\omega^0\pi^\pm$ mass distribution for events in the central region is shown in Fig. 3(b).

In order to test whether the enhancement in

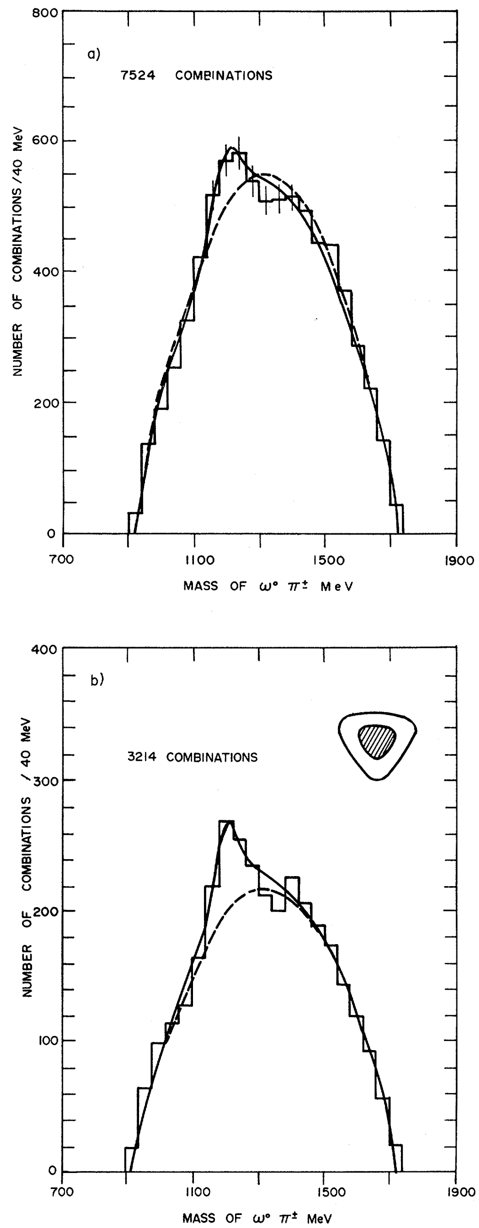

FIG. 3. (a) Distribution in the effective mass of the $\omega^0\pi^\pm$ in the reaction $\bar{p}+p\rightarrow\omega^0+\pi^++\pi^-$. The dashed curve represents the background expected from the fit to the $\omega^0\pi^+\pi^-$ Dalitz plot with the B-meson bands removed; the curve has been normalized to the total number of events in the distribution. The solid curve is the best fit including B-meson production, as described in the text. (b) $\omega^0\pi^\pm$ mass distribution selecting events in which the ω^0 lies in the central region of the ω^0 decay Dalitz plot. The solid curve is the best fit including B-meson production discussed in the text. The dashed background curve here has been normalized to the experimental distribution outside of the B-meson region.

the $\omega^0\pi^\pm$ mass spectrum near 1200 MeV could be a kinematic reflection of a $\pi^+\pi^-$ interaction near high $\pi^+\pi^-$ effective masses, the lower third of the $\omega\pi\pi$ Dalitz plot, corresponding to low ω^0 kinetic energies, was removed from the $\omega^0\pi^\pm$ mass plot. The remaining events still showed the B-meson enhancement clearly.

The reactions $\bar{p}+p\rightarrow\eta^0+\pi^++\pi^-$, $\bar{p}+p\rightarrow K^0+K^\pm+\pi^\mp$,[8] and $\bar{p}+p\rightarrow K+\bar{K}+\pi+\pi$[9] were examined for B-meson production. There was no evidence for the intermediate state $\bar{p}+p\rightarrow B^\pm+\pi^\mp$ in any of these reactions. This result leads to the following upper limits (90% confidence level) for alternative decay modes of the B meson:

$$\frac{B^\pm\rightarrow\eta^0+\pi^\pm}{B^\pm\rightarrow\omega^0+\pi^\pm}<25\,\%,$$

$$\frac{B^\pm\rightarrow K_1{}^0+K^\pm}{B^\pm\rightarrow\omega^0+\pi^\pm}<5\,\%,$$

$$\frac{B^\pm\rightarrow K_1{}^0+K^\pm+\pi^0}{B^\pm\rightarrow\omega^0+\pi^\pm}<4\,\%,$$

$$\frac{B^\pm\rightarrow K_1{}^0+K_1{}^0+\pi^\pm}{B^\pm\rightarrow\omega^0+\pi^\pm}<2\,\%,$$

$$\frac{B^\pm\rightarrow K_1{}^0+K_2{}^0+\pi^\pm}{B^\pm\rightarrow\omega^0+\pi^\pm}<6\,\%.$$

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[1]M. Abolins, R. L. Lander, W. A. W. Mehlhop, N.-h. Xuong, and P. M. Yager, Phys. Rev. Letters 11, 381 (1963).

[2]S. U. Chung, O. I. Dahl, R. I. Hess, G. R. Kalbfleisch, J. Kirz, D. H. Miller, and G. A. Smith, in

Proceedings of the Sienna International Conference on Elementary Particles, edited by G. Bernardini and G. P. Puppi (Società Italiana di Fisica, Bologna, Italy, 1963), p. 201; D. D. Carmony, R. L. Lander, C. Rindfleisch, N.-h. Xuong, and P. Yager, Phys. Rev. Letters 12, 254 (1964).

[3]G. Goldhaber, S. Goldhaber, J. A. Kadyk, and B. C. Shen, Phys. Rev. Letters 15, 118 (1965).

[4]S. U. Chung, M. Neveu-Rene, O. I. Dahl, J. Kirz, D. H. Miller, and Z. G. T. Guiragossián, Phys. Rev. Letters 16, 481 (1966).

[5]C. Baltay, P. Franzini, G. Lütjens, J. C. Severiens, D. Tycko, and D. Zanello, Phys. Rev. 145, 1103 (1966).

[6]C. Baltay, P. Franzini, G. Lütjens, J. C. Severiens, J. Steinberger, D. Tycko, and D. Zanello, Phys. Rev. 140, B1042 (1965).

[7]As a check on the background curve obtained by fitting the $\omega^0\pi^+\pi^-$ Dalitz plot to the distribution function (4), the $\omega^0\pi^+\pi^-$ Dalitz plot (with the B-meson bands removed) was refitted to a polynomial in x and y (with a Breit-Wigner contribution to take the ρ^0 meson into account) where $x=(T_{\pi^+}-T_{\pi^-})/\sqrt{3}Q$ and $y=T_{\omega^0}/Q$; the T's are kinetic energies and $Q=2M_p-2M_\pi-M_{\omega^0}$. The best fit, with a $\chi^2=54.4$ in 64 bins, produced a projection on the $\omega^0\pi^\pm$ mass axis essentially indistinguishable from the background curve obtained from the fit to the distribution function (4).

[8]N. Barash, P. Franzini, L. Kirsch, D. Miller, J. Steinberger, T. H. Tan, R. Plano, and P. Yeager, Phys. Rev. 139, B1659 (1965).

[9]N. Barash, L. Kirsch, D. Miller, and T. H. Tan, Phys. Rev. 145, B1095 (1966).

ELECTRIC DIPOLE OPERATORS IN THE CONFIGURATION MIXING SCHEME

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The phenomenological assumption is made that the electric dipole operators at infinite momentum have components both in the (8, 1) and (1, 8) representation of the collinear group and in the (3, 3*) and (3*, 3) representation. Under this assumption, the algebra of dipoles, in the usual configuration mixing scheme, provides very accurate relations for the baryon magnetic moments and charge radii. The over-all scheme seems thus capable of consistent predictions for all low-energy baryon parameters.

Satisfactory results for the axial couplings of the baryons have been recently obtained by saturating the commutators of the chiral algebra within a finite set of states.[1,2] For instance, a successful mixing scheme,[1] at least for describing the ground state, includes besides the octet and decuplet the negative parity SU(3) multiplets of a $(\underline{20}, L=1)$ representation of SU(6)⊗ O(3).[3] The anomalous magnetic moments can be obtained at $p_3=\infty$ from the electric dipole operators $D_i^{(1)}$ (i is a unitary index, 1 denotes the space direction).[4,5] For a behavior (1, 8) + (8, 1) of $D_i^{(1)}$ under the chiral algebra, as expected from the quark commutators, the decuplet dominance hypothesis leads to vanishing anomalous magnetic moments.[4,6] Such a result appears disturbing. In fact the quark model is capable, in terms of a single wave function for octet and decuplet baryons (i.e., in an apparently corresponding approximation) to reproduce the successful SU(6) prediction $\mu_p/\mu_n=-\frac{3}{2}$ for the total moments. No significant improvements are obtained for larger mixture.[7,8] On the other hand, a consistent over-all picture can be obtained by relating the total magnetic moments to the tensor charges through a strong form of partial conservation of tensor currents.[8,9] In such a scheme the electric dipole operators are expected to have a more complicated behavior than (8, 1) + (1, 8).[9] One can also adopt the following attitude: Saturation of the infinite-dimensional local current algebra is impossible within a finite set of states. Nevertheless, an approximate finite saturation may be possible for truncated algebras (for instance