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Boson Masses. III*

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Empirical boson assignments on the baryon-antibaryon model are used to analyze exhaustively the masses for 13 out of 16 expected P orbitals; on this basis search areas can be predicted for the missing three states, all having $I=0$ and $J^P=1^+$. The mass analysis alone does not necessarily require much SU_3 singlet-octet mixing. Extrapolation to D states appears to pose a contradiction between this model and exchange degeneracy of normal boson trajectories. The situation can be resolved empirically by determining accurate J^P values for the prominent $I=1$ bosons in the R-S region of missing-mass spectrometer assignments. Tentative evidence for a first radially excited octet with $J^P=0^-$ places it in a mass region consonant with the model.

1. INTRODUCTION AND SUMMARY

THE following is a continuation of empirical boson assignments in accord with the baryon-antibaryon model.[1] Although the model has some fundamental differences of statistics (see I) from the quark model,[2] these do not affect the discussion below. The present situation allows almost complete assignment of the S and P orbitals: to 21 out of 24 states. The remaining three unidentified states can be specified with enough accuracy for experimental search.

The observed pattern of masses for the P orbitals directly suggests a type of SU_3 failure in which there is little octet-singlet mixing. The strong spin-orbit and spin-spin terms apparent in the masses are assumed to break down according to $8\rightarrow 7+1$. Considerations based on mass alone cannot resolve this interpretation from the conventional one of large octet-singlet mixing angles.

Extrapolation of the model to D states is considered. The natural way of doing this in terms of the model runs counter to some current theoretical ideas on boson Regge trajectories. Most serious is the fact that although abnormal boson trajectories would be exchange-degenerate, normal ones would not be; moreover, they would have different slopes, at least in the region $\lesssim 4$ BeV^2. Experimental resolution of this dilemma requires establishment of firm J^P values in the R and S regions of missing-mass spectrometer assignments.

Some possible additional resonances not included in the primary assignment are discussed. Chief among these compose what might be a 0^- octet around 1.3 BeV, which would represent a first radial excitation on the simple baryon-antibaryon model. Its Regge slope agrees with the basic orbital value for the present model.

2. S AND P ASSIGNMENTS

The current situation is described in Table I. Masses in BeV are taken from the Particle Properties Tables[3] with the exception[4,5] of $K^*(0^+)$ and ϵ. The P states still unidentified are labeled F, G, and H.

The orbital assignments are argued as follows: All members of the first column have $I=S=0$ and decay modes predominantly (>50%) consisting of $[K\bar{K}\pi^n+\eta(2\pi)^m]$. The η is a trivial exception because of threshold limitations. In all other columns these modes are <10% in relative proportion,[6] so that this empirical separation is based on an order-of-magnitude distinction. We take the S^* as a genuine resonance, and infer[7] $J^P=1^+$ as the most likely assignment for the D.

All the K^* states in Table I have fairly definite J^P, but it remains to distinguish the $^3P_1$ and $^1P_1$ assignments. We do this on two bases: The $K^*(1.33)$ is the only K^* in this group that appears in the $K\omega$ channel,[8] and $K\rho$ decay is not apparent.[9] This makes it different

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[1] R. W. King and D. C. Peaslee, Phys. Rev. **143**, 1321 (1966); D. C. Peaslee, *ibid.* **159**, 1335 (1967); referred to as I and II in the text.

[2] See R. H. Dalitz, *Meson Spectroscopy* (W. A. Benjamin, Inc., New York, 1968), p. 497, and earlier references cited there.

[3] N. Barash-Schmidt, G. Conforto, A. Barbaro-Galtieri, L. R. Price, M. Roos, A. H. Rosenfeld, P. Söding, and C. G. Wohl, Rev. Mod. Phys. **41**, 109 (1969).

[4] B. French, rapporteur's talk in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN, Geneva, 1968), pp. 91 ff.

[5] T. G. Trippe, C. Y. Chien, E. Malamud, J. Mellema, P. E. Schlein, W. E. Slater, D. H. Stork, and H. K. Ticho, Phys. Letters **28B**, 203 (1968); D. Carmony and L. J. Gutay (private communication); D. J. Crennell, U. Karshon, K. W. Lai, J. S. O'Neall, and J. M. Scarr, Phys. Rev. Letters **22**, 487 (1969).

[6] The X^0 appears exceptional because it is practically stable against strong decays, like other member of the lowest 0^- nonet: Witness the high probability (~30%) of electromagnetic decay by ρ^0.

[7] C. D'Andlau, A. Astier, L. Dobrzynski, J. Siaud, J. Barlow, L. Montanet, L. Tallone-Lambardi, A. M. Adamson, J. Duboc, M. Goldberg, R. A. Donald, D. N. Edwards, and J. E. A. Lys, Nucl. Phys. **85**, 693 (1968).

[8] J. Bartsch, M. Deutschmann, E. Keppel, G. Kraus, R. Speth, C. Grote, J. Klugow, D. Pose, H. Schiller, H. Vogt, M. Baradin-Otwinowska, V. T. Cocconi, P. F. Dalpiaz, E. Flaminio, J. D. Hansen, H. Hromadnik, G. Kellner, D. R. O. Morrison, S. Nowak, N. C. Barford, D. P. Dallmann, S. J. Goldsack, M. E. Mermikides, N. C. Mukherjee, A. Fröhlich, G. Otter, I. Wacek, and H. Wahl, Phys. Letters **22**, 357 (1966).

[9] G. Bassompierre, Y. Goldschmidt-Clermont, A. Grant, W. P. Henri, I. Hughes, B. Jongejans, R. L. Lander, D. Linglin, F. Muller, J. M. Perreau, I. Saitov, R. L. Sekulin, G. Wolf, W. de Baere, J. Debaisieux, P. Dufour, F. Grard, J. Heughebaert, L. Pape, P. Peeters, F. Verbeure, R. Windmolders, M. Jobes, and W. Matt, Phys. Letters **26B**, 30 (1967).

TABLE I. Boson resonance assignments.

Iso-state / Orbital	$\mathbf{8}_0$	$\mathbf{8}_{1/2}$	$\mathbf{8}_1$	$\mathbf{1}_0$
$^1S_0$	$\eta(0.55)$	$K(0.50)$	$\pi(0.14)$	$X^0(0.96)$
$^3S_1$	$\phi(1.02)$	$K^*(0.89)$	$\rho(0.76)$	$\omega(0.78)$
$^1P_1$	G	$K^*(1.32)$	$B(1.22)$	H
$^3P_2$	$f'(1.51)$	$K^*(1.42)$	$A_2(1.30)$	$f(1.26)$
$^3P_1$	$D(1.28)$	$K^*(1.24)$	$A_1(1.07)$	F
$^3P_0$	$S^*(1.07)$	$K^*(1.1\text{–}1.2)$	$\delta(0.96)$	$\epsilon(0.7\text{–}0.9)$

from $K^*(1.42)$ and $K^*(1.24)$, hence the ^1P candidate. Moreover, direct analysis of the $K^*(1.24)$ decay modes[10] indicates $J^P=1^+$ and a C assignment consonant with ^3P.

Assignments in the $(SU_3)_I=\mathbf{8}_1$ column seem to be well agreed upon by now. The singlet column $\mathbf{1}_0$ is rather sparsely populated. Only two entries (ω and f) are well established, two others (F and H) being quite unknown; the remaining two (X and ϵ) appear to be gaining general acceptance, however.

Peak splitting—e.g., of the A_2 and f—is neglected in Table I on the grounds that at least one of the peaks has the conventional J^P assignment; the other represents at most an additional resonance, about which some remarks are appended in Sec. 5.

In Table I the SU_3 octet assignments are all but complete: 17 out of 18 entries. Accordingly, we restrict mass considerations to this portion of Table I. For each orbital value L and either spin S, let

$$\langle m^2\rangle=(2S+1)^{-1}(2L+1)^{-1}\sum_J m_J^2. \qquad (1)$$

Then define the octet parameters

$$M^2=\tfrac{1}{8}\sum_I(2I+1)\langle m_I^2\rangle, \qquad (2a)$$

$$\Delta=\langle m_{1/2}^2\rangle-\langle m_1^2\rangle, \qquad (2b)$$

$$\xi=\langle m_0^2\rangle-\langle m_{1/2}^2\rangle-\tfrac{1}{3}\Delta. \qquad (2c)$$

Here M^2 is the octet median mass, Δ specifies the spread of the octet pattern, and ξ is a measure of deviation from the octet. To determine ξ, the observed m_0^2 is taken from the first column of Table I; the results are given in Table II, with allowance for the one missing ^1P entry.

Table II invites the following remarks:

(i) The mean octet mass shows a strong triplet-singlet difference for S orbitals, but none for P.

(ii) The octet symmetry-breaking parameter Δ is not very spin-dependent but seems to increase with higher orbitals, contrary to one's naive expectations.

(iii) The deviation appears, when uncertainties of order ±0.1 BeV^2 for the P states are considered, to be perhaps as small for ^3P as for ^1S.

To see further into this last remark, we analyze the m_I^2 values of ^3P for spin-orbit and tensor terms according to

$$m_I^2=m_{IJ}^2+s\begin{Bmatrix} L \\ -1 \\ -(L+1) \end{Bmatrix}+t\begin{Bmatrix} -L/(2L+3) \\ 1 \\ -(L+1)/(2L-1) \end{Bmatrix}$$

$$\text{for}\quad J=\begin{Bmatrix} L+1 \\ L \\ L-1 \end{Bmatrix}. \qquad (3)$$

The tensor terms are not significantly different from zero[11]: $t=0.05$, -0.01, and -0.02 BeV^2 for $I=0, \frac{1}{2}$, and 1; the corresponding spin-orbit terms are $s=0.35$, 0.23, and 0.26 BeV^2. This shows a breakdown of SU_3 octet symmetry as $\mathbf{8}\rightarrow\mathbf{1}+\mathbf{7}$ with s being ~40% larger for $\mathbf{8}_0$. Thus, even if ξ is small for the triplet as a whole, the disparity in s parameters can yield values of large magnitude for individual orbitals ^3P_J, as has long been observed for $^3P_2$.

The argument could be repeated exactly for the ϕ meson as well. Suppose the singlet-triplet mass difference for the even orbitals to be, like the spin-orbit parameter s, some 40% larger for $\mathbf{8}_0$ than for the remainder of the octet. This would cause an m_0^2 increment of about 0.22 BeV^2; when this is removed, the effective m^2 $(\phi)\approx0.82$ BeV^2, and $\xi=-0.04$ BeV^2 for the ^3S octet.

These cases supply concrete examples of SU_3-symmetry breaking in a way that can yield substantial ξ values without invoking any SU_3 singlet-octet mixture. The true situation is no doubt some linear combination of the two possibilities and cannot be fixed by mass consideration alone.

3. THREE MISSING P STATES

The systematic behavior shown in Tables I and II encourages some predictions about the still absent entries labeled F, G, and H.

The F meson has $I^GJ^P=0^+(1^+)$. Its mass is intermediate between the ϵ and f, but this allows some latitude. It was suggested in II that the $\mathbf{1}_0$ and $\mathbf{8}_1$ states with triplet spin should lie rather close together in principle but that the observed positions are subject to downwards pulling proportional to the width of the resonance. On this basis one would guess that $m(F)\approx1.1$ BeV, since its width is likely to be small, while those of f and especially ϵ are enormous. The decay modes of the F generally resemble those of the X^0: $\eta\pi\pi$ and $\gamma\pi\pi$ are possible, but $\gamma\gamma$ is forbidden the F since $J=1$; on the other hand, this mode has been reported[12] for the X^0. Also, a little study of possible decay configurations satisfying Bose statistics shows that $F\rightarrow4\pi$ is less inhibited than $X^0\rightarrow4\pi$.

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[10] A. Astier, J. Cohen-Ganouna, M. Della-Negra, B. Marechal, L. Montanet, J. Zoll, M. Baubiller, J. Duboc, F. Levy, R. James, D. N. Edwards, and R. Donald, Nucl. Phys. **B10**, 65 (1969).

[11] This difference from the conclusions reached in II arises mainly from dropping the $\kappa(735)$ as a candidate and correcting the assignment of $D(1285)$.

[12] D. Bollini, A. Buhler-Broglin, P. Dalpiaz, T. Massam, F. Navack, F. L. Navarria, M. A. Schneegans, and A. Zichichi, Nuovo Cimento **58A**, 289 (1968).

One can cite some hints for the F, but nothing more. In a $(\bar{K}p)$ study[13] that gave good evidence of $X^0 \to \eta\pi\pi$, there is a second possible peak around 1.04 BeV. Further analysis[14] of the same pictures compares states of the type $\pi\pi(\mathrm{mm})$, where the missing mass (mm) satisfies $0.25 \leq (\mathrm{mm})^2 \leq 0.36$ BeV^2 (η region) on the one hand and $0.15 \leq (\mathrm{mm})^2 \leq 0.25$ BeV^2 or $0.36 \leq (\mathrm{mm})^2 \leq 0.49$ BeV^2 on the other. In the non-η region a small peak appears for $M(\pi\pi\ \mathrm{mm}) \approx 1.1$ BeV; it might be present but weaker in the η regions, which shows a strong signal at $M(\pi\pi\ \mathrm{mm}) = 0.96$ BeV. Although no single piece of evidence is very strong, this is all consistent with a neutral state at ~ 1.1 BeV that decays mainly by $\pi^+\pi^-$ (neutrals), where the neutrals do not equal any resonance below 0.7 BeV and hence are most likely $2\pi^0$. Weaker decay modes appear to be $\pi^+\pi^-\gamma$ and $\pi^+\pi^-\eta$.

The G meson has $I^G(J^P) = 0^-(1^+)$. If we allow $|\xi| < 0.2$, which encompasses all known cases, then $m(G) = 1.37 \pm 0.07$ BeV. The G lies in the column where $K\bar{K}\pi^n$ decay modes are prominent, and its mass range includes the E meson at about 1.4 BeV.[15] The most likely parameters for the E are $I^G(J^P) = 0^+(0^-)$, however; if the G is a separate resonance near by, it may prove difficult to disentangle from the E.[16] Among $K\bar{K}\pi^n$ decay modes for the G, the least inhibited appears to be $(\phi\pi\pi)$, and there is not much phase space available. For $\eta\pi^m$ decay modes it is necessary to go to at least $m=3$: perhaps $G \to \eta\omega$? It seems probable that the G will be narrow.

The H meson has $I^G(J^P) = 0^-(1^+)$ but is not expected to have any appreciable $K\bar{K}\pi^n$ decay mode; in fact, the $\rho\pi$ channel should swamp all other decays. Since the H is an SU_6 super-singlet like the X^0, we can give only a very poor estimate of its mass, say, $m(H) \approx 1.2-1.6$ BeV.[17] Because of Bose statistics, the $\rho\pi$ final state must have a momentum dependence characteristic of $l=2$ for the first pion, so that the H width should not be too large for ready identification. If it overlaps the G at all, it might enhance by interference the weak $\rho\pi$ decay mode of that resonance.

TABLE II. Octet mass parameters (BeV^2).

Orbital	M^2	Δ	ξ
^1S	0.17	0.23	-0.02
^3S	0.75	0.22	0.18
^1P	(1.67)	0.31	( )
^3P	1.67	0.36	0.05

4. EXTRAPOLATION TO D STATES

We now try extrapolation to the leading boson D states, following the $N\bar{N}$ model to the greatest possible extreme. Thus, we assume from the outset that L is a reasonably good quantum number for the masses and expect a basic trajectory depending on this quantum number, with systematic small differences in the slope to reflect spin-orbit coupling. The S, P comparison of Sec. 2 suggests that exchange degeneracy must also be abandoned in at least some cases; this is more serious, but we accept it for the present in the spirit of an empirical approach.

The most direct extrapolation from Sec. 2 is by assuming ^1L_L as the basic exchange-degenerate trajectory. In accordance with previous authors,[18,19] for $I=1$ this is

$$L(^1L_L) \approx 0.7t. \tag{4}$$

For $^3L_{L\pm 1}$ the trajectory slopes are approximately $[(0.7)^{-1} \pm s]^{-1} \approx 0.65,\ 0.85$ BeV^{-2}, where s is the spin-orbit parameter of Sec. 2. Hence,

$$\left.\begin{aligned} L(^3L_{L+1}) &\approx 0.65t \\ L(^3L_L) &\approx 0.7t + 0.1 \\ L(^3L_{L-1}) &\approx 0.85t + 0.2 \end{aligned}\right\} \quad (\text{odd } L), \tag{5a}$$

where the constants are evaluated for the P states. For even L we have only the $^3S_1$ state, which suggests a constant displacement of -0.35 from Eq. (5a):

$$\left.\begin{aligned} L(^3L_{L+1}) &\approx 0.65t - 0.35 \\ L(^3L_L) &\approx 0.7t - 0.25 \\ L(^3L_{L-1}) &\approx 0.85t - 0.15 \end{aligned}\right\} \quad (\text{even } L). \tag{5b}$$

From relations (4) and (5b), we obtain for the $I=1$ resonances,

$$m(^3D_1, {}^1D_2, {}^3D_2, {}^3D_3) \approx 1.6,\ 1.7,\ 1.7,\ 1.9 \text{ BeV}. \tag{6}$$

The identification is immediate with the most prominent missing-mass states: R_1, R_2, R_3, and S. A similar pattern has been observed[20] in $K\pi\pi$ resonances produced by Kp reactions at 5 BeV, with masses $m = 1.66$, 1.76, 1.85, and[21] 1.98 BeV.

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[13] R. Davis, R. Ammar, J. Mott, S. Dagan, M. Derrick, and T. Fields, Phys. Letters **27B**, 532 (1968).

[14] J. Mott, R. Ammar, R. Davis, W. Kropac, D. Slate, B. Werner, S. Dagan, M. Derrick, T. Fields, J. Loken, and F. Schwengruber, Phys. Rev. **177**, 1966 (1969).

[15] The $\eta\pi\pi$ display of Ref. 13 shows peaks at 1.28, 1.36, and 1.5 BeV, presumably the D, E, and f' mesons.

[16] In a study of E production from $\bar{p}p$ annihilation, by means of a substantial subtraction the $(K_1{}^0K_2{}^0\pi^0)$ mode was displayed; this is a possible decay channel for the G, though without any enhancement due to intermediate resonances. This mode showed a gap at the E mass, but a 1–2 standard deviation peak in the next lower mass bin [see P. Baillon, D. Edwards, B. Maréchal, L. Montanet, M. Tomas, C. d'Andlau, A. Astier, J. Cohen-Ganouna, M. Della-Negra, S. Wojcicki, M. Baubillier, J. Duboc, F. James, and F. Levy, Nuovo Cimento **50A**, 393 (1967)].

[17] The H is no longer believed to exist at 1 BeV—See, e.g., Ref. 13.

[18] D. G. Sutherland, Nucl. Phys. **B2**, 157 (1967).

[19] A. Ahmadzadeh and R. J. Jacob, Phys. Rev. **176**, 1719 (1968).

[20] M. Jobes, W. Matt, G. Bassompierre, Y. Goldschmidt-Clermont, A. Grant, V. P. Henri, I. Hughes, B. Jongejans, R. L. Lander, D. Linglin, F. Muller J. M. Perreau, I. Saitov, R. Sekulin, G. Wolf, W. de Baere, J. Debaisieux, P. Dufour, F. Grard, J. Heughebaert, L. Pape, P. Peeters, F. Verbeure, and R. Windmolders, Phys. Letters **26B**, 49 (1967); see also W. Matt, Diplomarbeit Max-Planck-Institut, München, 1968 (unpublished).

[21] W. Matt (private communication).

The chief experimental difficulty with assignment (6) is the indication[22,23] of $J^P=3^-$ for the g $(=R_1)$ meson, although no determination is entirely free from objection. As a sort of calibration, it should be of interest to compare the $\pi^+\pi^0$ distribution from the S region, which is supposed to be $J^P=3^-$ on either basis, whether $^3D_3$ or $^3G_3$ being a secondary question.

In general, the measurements needed are positive identification of the entire J^P pattern of $^{1,3}D_{1,2,3}$ states for $I=1$ and $I=\frac{1}{2}$, as in Table I. Equation (6) signalizes the R and S mesons as immediate targets for J^P study.

It is curious to note that if the trajectories really depend on L[24] as in Eqs. (5), they will have a region of crossing for t values on the order of -1 BeV. Qualitatively, three crossing trajectories in this region have been discussed[25] for p-p elastic scattering, the most thoroughly measured reaction. Both πp and $\bar{p}p$ elastic scattering have dips around -0.5 BeV^2 that might be interpreted as interference associated with trajectory crossing. This gross interpretation is very limited and can account for at most one or two dips in the t and u channels, however.

Some support the fundamental slope of 0.7 BeV^{-2} may come from identification of the $A_{1.5}$ as a 0^- state on the first daughter trajectory: on the $N\bar{N}$ model, a first "radial excitation" $^1S_0$. Coherent production of a peak that did not resolve A_1 and $A_{1.5}$ showed[26] a constant fraction of about 10% J^P-0^- along with the predominant $J^P=1^+$. Coherent production[27] of $K\pi\pi$ resonances shows not only the 1.23-BeV peak assigned $^3P_1$, but a larger one at 1.35 BeV. This should not be $^1P_1$ for coherent production but could be $^1S_0$, and the oldest of the extra mesons is the $E(1.42)$ with a prominent $K\bar{K}\pi$ decay mode and most probable $I^G(J^P)=0^+(0^-)$. It is very tempting to regard this complex as a pseudoscalar octet, even though no individual identification is incontestable. Then for the ordinal number of the trajectory, we have

$$n_\pi(^1S_0)\approx 0.72t-0.01\,, \tag{7}$$

essentially the same as Eq. (1). If spacings of daughter trajectories are all equal, the first 1^- radial excitation or ρ would be at

$$m^2(\rho')=m^2(\rho)+m^2(A_{1.5})-m_\pi^2\approx 1.95\ \mathrm{BeV}^2\,, \tag{8}$$

which is within error of the $A_2{}^H$.

5. CRITIQUE

The extrapolations of Sec. 4 can be readily extended to F and G orbitals and good agreement found with the location of boson states so far observed. This seems premature, however, in view of the serious objections that the principal Regge trajectories involved do not appear quite parallel nor exchange-degenerate. A set of trajectories largely satisfying these requirements leads to D state predictions in the 1.4–1.6-BeV region[28] instead of in the R-S region as here and in similar models.[29,30] Experimental decision between these alternatives will clearly be of great significance.

In other respects, conclusions from the $N\bar{N}$ model are very like those from the hypothesis of parallel, degenerate trajectories.[28] The missing P states discussed in Sec. 3 would be predicted in the same places by the procedures of Ref. 28. In particular, it is interesting to note that both approaches lead to quite different but in each case natural arguments that the masses themselves need not imply very much SU_3 singlet-octet mixing.

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[22] T. F. Johnson, J. D. Prentice, N. R. Steenberg, T. S. Yoon, A. F. Garfinkel, R. Morse, B. Y. Oh, and W. D. Walker, Phys. Rev. Letters **20**, 1414 (1968).

[23] D. J. Crennell, U. Karshon, K. W. Lai, J. M. Scarr, and I. O. Skillicorn, Phys. Letters **28B**, 136 (1968).

[24] This could be true of a scheme like that of H. Harari, Phys. Rev. Letters **22**, 562 (1969), suitably modified to the $N\bar{N}$ instead of the quark model. Then all diagrams look like Fig. 1(a) of that reference (with zero, one, or two loops removed) and randomization of the fermion spins is the most primitive assumption, i.e., major trajectory dependence on L.

[25] A. D. Krisch, Phys. Rev. Letters **19**, 1149 (1967).

[26] A. M. Cnops, P. V. C. Hough, F. R. Huson, I. R. Kenyon, J. M. Scarr, I. O. Skillicorn, H. O. Cohn, R. D. McCullock, W. M. Bugg, G. T. Condo, and M. M. Nussbaum, Phys. Rev. Letters **21**, 1609 (1968).

[27] A. Pevsner, Ref. 2, p. 249; D. Denegri (private communication).

[28] D. C. Peaslee, Phys. Rev. **187**, 1948 (1969).

[29] B. T. Feld, *Models of Elementary Particles* (Blaisdell Co., Waltham, Mass., 1970).

[30] L. Dubal, M. N. Focacci, W. Kienzle, C. LeChanoine, B. Levrat, B. C. Maglic, M. Martin, P. Schubelin, G. Chikovani, M. Fisher, P. Grieder, H. A. Neal, and C. Nef, Nucl. Phys. **B3**, 435 (1967).