STUDY OF Y_1*(1660) AND Y_1*(1695) PRODUCTION IN K^-p INTERACTIONS*

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In this note we report information on $I=1$ hyperon resonances (Y_1*'s) in the mass range 1600-1750 MeV, made in K^-p collisions at 4.6 and 5.0 BeV/c. Significant Y_1*(1660) production is noted, primarily in the $\Sigma^0\pi^+$ and $(\Sigma\pi\pi)^+$ states. Estimates of branching ratios are given. Evidence is presented which strongly supports the existence of a new Y_1* at 1700 MeV in the $\Lambda\pi^+$ system as first reported by Derrick et al.[1] There are no unambiguous indications of other decay modes. A compilation of high-energy experiments[1,2] yields the values $M=1695\pm8$ MeV, $\Gamma=108\pm20$ MeV for the new Y_1*.

We have examined a data sample consisting of five events/μb from our 80-in. Brookhaven National Laboratory hydrogen-bubble-chamber K^-p exposures at 4.6 and 5.0 BeV, where $\sim\frac{2}{3}$ of the total comes from the 4.6-BeV/c sample. For present purposes, we consider only the following final states[3,4]: (1) $\Lambda^0\pi^+\pi^-$, (2) $\Sigma^0\pi^+\pi^-$, (3) $\Sigma^+\pi^+\pi^-\pi^-$ and $\Sigma^-\pi^+\pi^+\pi^-$, (4) $\Sigma^+\pi^0\pi^-$, (5) $p\bar{K}^0\pi^-$, and (6) $\Lambda^0\pi^+\pi^-\pi^0$. Identification of events is made on the basis of both kinematical and ionization information.[5] Among the single-V^0 candidates [(1), (2), (5), and (6) above], there is virtually no Λ^0-vs-K^0 confusion. The only significant source of potential misidentification[6] is "Σ^0-vs-Λ^0 ambiguity," i.e., competition between (1) and (2) or (2) and (6). For either of these ambiguities, if one hypothesis is five times more probable than the other, the event is considered uniquely identified. If the χ^2 probabilities are comparable, the best fit is accepted unless it is $\Sigma^0\pi^+\pi^-$ in competition with the $\Lambda^0\pi^+\pi^-$ hypothesis. In this case, the $\Sigma^0\pi^+\pi^-$ identity is retained only if the hyperon missing mass MM_Y (e.g., $K^-+p\to\pi^++\pi^-+MM_Y$) is closer to the Σ^0 than the Λ^0 mass. Direct checks on the "Λ^0" and "Σ^0" samples so obtained indicate that the identification procedure is reliable. These checks will be described later. For the topologies with one charged decaying prong, the only appreciable ambiguity concerns the $\Sigma^+\pi^-\pi^0$ vs $\Sigma^+\pi^-$+neutral missing mass (MM). Here we employ criteria[7] limiting our acceptance of $\Sigma^+\pi^-\pi^0$ to those events which achieve a fit with a χ^2 probability of $\geq0.5\%$ and also have $MM=m_{\pi^0}$ to within 1.5 standard deviations.[8] For $\Sigma^\pm$ and $\Sigma^+\to p\pi^0$ in particular, there is a severe scanning bias against small angle decays. Corrections are made on the basis of the observed decay angular distribution in the Σ rest frame for a sample in which the Σ length is ≥0.5 cm.[9]

We turn now to our study of Y_1*(1660) production. Examination of the data reveals no statistically significant difference between the fraction at 4.6 and 5.0 BeV/c; so both momenta are considered as a unit in the ensuing analysis. The mass spectra relevant to the search for the Y_1*(1660)$^+$ in the final states listed above are shown in Fig. 1. In all cases appropriate subtractions of copiously produced two-particle resonances and/or two-body production channels have been carried out in order to reduce reflection effects. Specifically, peripheral ρ^0 and ρ^- have been removed from the final states (2) and (4), respectively,[10] N*(1238) and K*(890) have been omitted from (5), and the reactions $\Lambda+(\eta^0$ or ω^0 or $X^0+\varphi)$ and Y*(1385)$^{\pm,0}+\rho^{\mp,0}$ have been removed from (6).

In the spectra of Figs. 1(a) and 1(b), clear signals are observed near 1660 MeV corresponding to $\Sigma^0\pi^+$ and Y_0*(1405)π^+ decay modes. (These signals become even more pronounced relative to background if a peripheral cut[11] is made.) Furthermore, the control distributions, such as $M(\Sigma^-\pi^0)$ and $M(Y_0$*(1405)$\pi^-)$, contain no "1660" signals and in fact have a phase-space shape [see dashed curve of Fig. 1(h)]. Thus, there is very little question that the peaks are

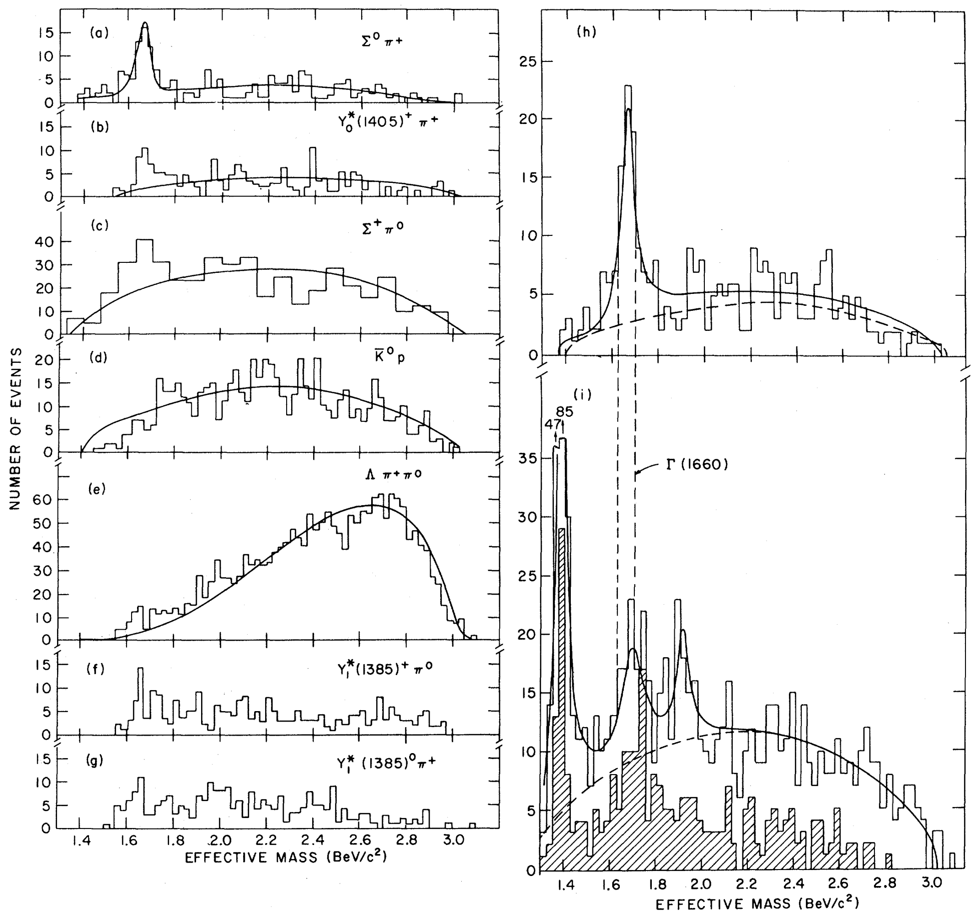

FIG. 1. (a)-(g) Effective mass plots. See text for selection criteria. (h) Sum of Figs. 1(a) and 1(b). Solid line is best fit curve. Dashed line is a smoothed "control" spectrum from $\Sigma^0\pi^-$ and $1405\pi^-$. (i) $\Lambda\pi^+$ mass spectrum with best fit curve. Shaded area represents data with $M^2(\pi\pi) > 1.75$ $(\text{BeV})^2$, to eliminate ρ^0 and f^0.

real. The combined data of Figs. 1(a) and 1(b) are shown in Fig. 1(h). The solid curve is a "best fit," yielding the values $M = 1661 \pm 9$ MeV, $\Gamma = 60 \pm 20$ MeV, in agreement with the accepted[12,13] mass and width. Consequently it is virtually certain that these signals represent $Y_1^*(1660)$ decay modes.

Other potential "1660" signals are small and/or less susceptible to unambiguous interpretation. The broad excess at 1550-1750 MeV in the $M(\Sigma^+\pi^0)$ spectrum [Fig. 1(c)], is compatible with a "1660" interpretation. The breadth is probably due to the poor resolution in the channel (±35 MeV). Considering this and background uncertainties due to $Y_0^* \rightarrow \Sigma^\pm\pi^\mp$ reflection effects,[10] one finds that the $\Sigma^0\pi^+/\Sigma^+\pi^0$ ratio is compatible with unity, as expected. No significant $p\bar{K}^0$ signal is observed, in agreement with the currently accepted, very small branching fraction for this mode. An excess of events is also noted in the $\Lambda\pi^+\pi^0$ mass spectrum near the 1660 region [Fig. 1(e)]. This signal persists if one selects $Y_1^*(1385)^{+,0}\pi^{0,+}$ events, as shown in Figs. 1(f) and 1(g). Note, however, that a single event often appears in both the $Y^*(1385)^+\pi^0$ and $Y^*(1385)^0\pi^+$ spectra because the two Y_1^* bands happen to overlap in the center of the "1660" decay Dalitz plot. The peaking may thus be a kinematical effect unrelated to any Y^* decay.[14] Moreover, the peak could be interpreted[1] as being partially due to $Y_1^*(1700)$ decay. Considering these sources of ambiguity, together with the severe "$Y_1^*(1385)+\rho$" background subtraction which must be made here, no firm conclusion can be drawn regarding the nature of the $\Lambda\pi^+\pi^0$ peak. All branching-ratio estimates are systematically uncertain as a result.

Finally, we turn to the $M(\Lambda\pi^+)$ spectrum from channel 1 [Fig. 1(i)]. The $Y^*(1385)$ peak is adequately fitted with the accepted values $M = 1382$ and $\Gamma = 35$. In addition, there is an enhancement of five standard deviations in the region 1625-1750 MeV relative to a phase-space background drawn under the excess at approximately 1900 MeV, the latter being consistent with a $Y_1^*(1910)$ interpretation. (The 1700-MeV enhancement is peripheral.) Although both the ρ^0 and f^0 are also produced here,[4] their incoherent subtraction does not alter the significance of the "1700" enhancement [see shaded area of Fig. 1(i)], so that the latter cannot be due to reflection or interference. Standard fitting gives the values $M = 1694 \pm 24$ MeV, $\Gamma = 105 \pm 35$ MeV, which are one standard deviation in Γ and 1.5 standard deviation in mass from the values obtained for the $Y_1^*(1660)$, as described above. In addition, as noted in Ref. 1, if the $\Lambda\pi^+$ enhancement were interpreted as a decay mode of the $Y^*(1660)$, its $\Lambda\pi^+/\Sigma^0\pi^+$ branching fraction would be 1.8 ± 0.6, in contrast to the previous determination of 0.3 ± 0.15, due to Huwe.[15] Similarly, if the enhancement were interpreted as due to $Y_1^*(1765)$ decay, the observed $\bar{K}^0p/\Lambda\pi^+$ branching fraction would be in disagreement with the accepted value[16] by six standard deviations. Thus it is very likely that the $\Lambda\pi^+$ excess should be associated with a new Y_1^*, hereafter referred to as $Y_1^*(1695)$.

Assuming this, and carrying out all necessary fiducial and Clebsch-Gordan coefficient corrections,[17] the information of Figs. 1(a)-1(f) yields the $Y^*(1660)$ branching ratios given in Table I. Errors include estimates of systematic uncertainties. It should be noted that virtually all investigations[12,18] agree that "1405π" and "$\Sigma\pi$" modes exist. Furthermore, in experiments where large samples are available,[13,15] the masses and widths of the two modes are found to be indistinguishable. However, the "1405π"/"$\Sigma\pi$" ratio appears to vary[19] between $\frac{1}{2}$ and 3 at various momenta between 1.5 and 5.5 BeV/c. Thus the possibility exists that more than one resonance is involved. In our opinion, no firm conclusion on this point can be drawn as yet because the errors are rather large and because there exist several potential sources of systematic uncertainty, such as the Σ^0-vs-Λ^0 ambiguity, complex interference phenomena,[13] severe Σ^+ scanning bias, etc.

Since the evidence for existence of a $Y^*(1695)$ in this experiment (and others) rests almost entirely on the relative characteristics of the $\Sigma^0\pi^+$-vs-$\Lambda^0\pi^+$ signals, it is of obvious importance to establish the reliability of the identification of channels (1) and (2). Several checks have been made toward this end. Firstly, we have taken accepted $\Lambda\pi^+\pi^-$ events and refitted them as $\Sigma^0\pi^+\pi^-$'s. The resultant (hyperon-π^+) mass distribution (not shown), reveals that the $Y^*(1385)$ peak is shifted in mass by 65 MeV, and there is no excess at 1660 MeV. Secondly, the inverse procedure, i.e., refitting accepted $\Sigma^0\pi^+\pi^-$'s as $\Lambda\pi^+\pi^-$, yields a hyperon-pion mass spectrum with no significant peaking whatsoever (for the small number of events which achieved any refitting at all). A third check comes from a comparison of the two-body channels $\Sigma^0\rho^0$ and $\Sigma^+\rho^-$ contained within the final states (2) and (4). The appropriate (peripheral) $M(\pi\pi)$ spectra (not shown), with all requisite corrections included, yield a $\Sigma^+\rho^-/\Sigma^0\rho^0$ ratio of 3.6 ± 1.3. This is in agreement with the value of 4.0 predicted by an $(I = \frac{1}{2})$ meson exchange model, evidence for the validity of which is found in many K^-p experiments in this energy range.[20] On the basis of these checks and others,[21] we believe that the observed $\Sigma^0\pi^+$ and $\Lambda^0\pi^+$ enhancements cannot be the result of Σ^0 vs Λ^0 misidentification.

An examination of the usual decay angular distributions of the $Y_1^*(1695)$ reveals no significant anisotropies and thus gives no useful information on possible spin-parity values.

A compilation of high-energy K^-p data on

Table I. $Y_1^*(1660)$ branching ratios.

Mode	Events in 1660 region[a] above background: Raw	Fully corrected[b]	Branching ratio[c]
$\Sigma\pi$			$\Sigma\pi$/all
$\Sigma^0\pi^+$	33 ± 8	49 ± 12	0.63 ± 0.20
$\Sigma^+\pi^0$	20 ± 7	55 ± 19	
$Y_0(1405)^0\pi^+$			1405π/all
$\Sigma^+\pi^-\pi^+$	6 ± 3	18 ± 9	0.37 ± 0.15
$\Sigma^-\pi^+\pi^+$	11 ± 3	24 ± 6	
$\Sigma^0\pi^0\pi^+$	...	18 ± 9	
$\bar{K}^0p$	0 ± 5	0 ± 15	$\bar{K}^0p$/all <0.15
$(Y^*\pi)^+$	30 ± 11	...[d]	...[d]
$(\Lambda\pi^+)$	60 ± 11	...[e]	...[e]

[a]Region adjusted for experimental resolution.
[b]Including analyzed film fraction correction.
[c]Ref. 18.
[d]Assuming that this signal is not due to 1660 decay (see text).
[e]This signal is due to 1695 decay (see text).

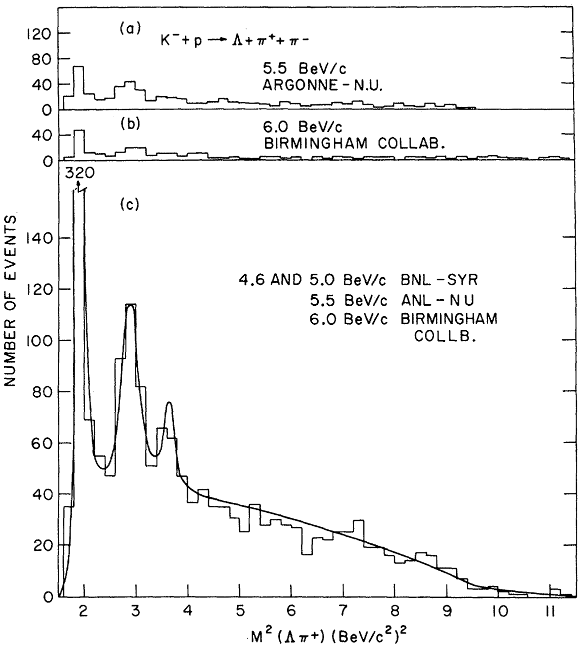

FIG. 2. (a)-(c) $\Lambda\pi^+$ mass spectra from Refs. 1, 2, and world data, respectively. Solid curve is best fit (Ref. 22).

$M(\Lambda\pi^+)$ is shown in Fig. 2(c). Such a compilation appears justified by the internal consistency of the data, as is manifest from a comparison of Figs. 2(a), 2(b), and 1(i). The combined data exhibit a clear enhancement of eight standard deviations at 1700 MeV, the excess at 1900 MeV most probably arising from the decay of the $Y_1^*(1915)$.[22]

In summary, our major conclusions are that the $Y_1^*(1660)$ is produced in the usual final states at ~4.7 BeV/c and that the existence of an $I=1$ $Y_1^*(1695)$ is firmly established.

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[1]M. Derrick et al., Phys. Rev. Letters 18, 266 (1967); M. Derrick and R. Ammar, private communication containing 50% more $\Lambda\pi^+\pi^-$ data than originally published.

[2]D. C. Colley et al., Phys. Letters 24B, 489 (1967).

[3]The final states (1)-(6) contain 921, 262, 266, 310, 519, 1356, and 2786 events, respectively. However, different effective fractions of the film were analyzed for each final state. Thus only fully corrected numbers may be meaningfully compared.

[4]Certain general characteristics of the channels (1), (2), (5), and (6) have been discussed by P. Dornan et al., Phys. Rev. Letters 18, 680 (1967), and V. Barnes et al., Phys. Rev. Letters 19, 964 (1967).

[5]Events are accepted provided at least one fitted hypothesis has a χ^2 probability >0.2%.

[6]Contamination from rare channels such as $\Lambda K^+K^-(\pi^0)$, $\Lambda K^\pm\pi^\mp(K^0)$, $\Xi^0K^+\pi^-$, etc. is negligible after ionization information is taken into account.

[7]To reduce contamination from decaying π's and K's we reject all events with times of flight ≥ 3.5 Σ lifetimes and correct appropriately.

[8]This underestimates the number of $\Sigma^+\pi^-\pi^0$ events by approximately 10%; appropriate correction is made in branching-ratio analyses.

[9]The total correction amounts to approximately 30% for $\Sigma\to n\pi^\pm$ and approximately 60% for $\Sigma^+\to p\pi^0$ decays.

[10]For the $\Sigma^+\pi^-\pi^0$ sample we make an additional (crude) subtraction of an observed low-mass peak in $\Sigma^+\pi^-$ due to production of $Y_0^*(1405)$, $Y_0^*(1520)$, and other possible $I=0$ Y^*'s, in order to avoid reflection effects in the high-mass end of the $M(\Sigma^+\pi^0)$ spectrum.

[11]Defined by cos(production angle of 1660 decay products) ≤ -0.8. These data are not shown.

[12]References can be found in the compilation of A. H. Rosenfeld et al., University of California Radiation Laboratory Report No. UCRL 8030 (revised), 1967 (unpublished).

[13]P. Eberhard et al., Phys. Rev. 163, 1446 (1967).

[14]See G. London et al., Phys. Rev. 143, 1034 (1966), for a discussion of this point (p. 1070).

[15]D. Huwe, University of California Radiation Laboratory Report No. UCRL 11291 (unpublished).

[16]$\bar{K}^0p/\Lambda\pi^+ = 2.9\pm0.4$ from Ref. 12.

[17]For the $(\Sigma\pi\pi)^+$ system, we assume that the unobservable mode $\Sigma^0\pi^0\pi^+$ is identical to $\Sigma^+\pi^-\pi^+$ because in both states the $Y_0^*(1405)$ can be formed. On the other hand, we ignore the $\Sigma^+\pi^0\pi^0$ rate because it cannot proceed through a $Y_0^*(1405)\pi$ intermediate state. Our estimate of the "total 1660 signal" should certainly be increased to account for the fact that there are $(\Sigma\pi\pi)$ decays not included in our $Y_0^*(1405)\pi$ signal (see Ref. 13). We have not done this because our sample size is insufficient to study interference effects, the knowledge of which is needed to make such a correction.

[18]The private communication of Ref. 1 indicates that the $\Sigma^0\pi^+$ and $(\Sigma\pi\pi)^+$ modes $Y_1^*(1660)$ are observed at 5.5 BeV/c.

[19]It is of interest to note that such uncertainties in the "1660" 1405π vs $\Sigma\pi$ branching ratios do not affect the generally accepted contention that the $Y_1^*(1660)$ is a member of an SU(3) octet also containing the $N^*(1525)$, $Y_0^*(1700)$, and $\Xi^*(1815)$. If mixing with the $Y_0^*(1520)$

SU(3) singlet is taken into account, the "unbroken"-SU(3) decay-rate predictions (well satisfied by established supermultiplets) are consistent with present crude experimental values for most resonances, provided only that the $\Sigma\pi/\Lambda\pi$ ratio from "1660" decay is large. The significant inconsistencies which do exist are due entirely to the $\Xi^*(1815)$ decay rates. See M. Goldberg et al., Nuovo Cimento 45A, 169 (1966); N. Masuda and S. Nukomo, to be published.

[20]See P. Schlein, in Lectures in Theoretical Physics, edited by Wesley E. Brittin et al. (University of Colorado Press, Boulder, Colorado, 1965), Vol. VIIB, p. 111; J. Leitner, ibid., p. 43.

[21]For example, the observation of a $Y_1^*(1385) \rightarrow \Sigma^0\pi^+$ signal of a size compatible with the accepted $\Sigma^0\pi^+/\Lambda\pi^+$ branching ratio, etc.

[22]Using the accepted M and Γ parameters of the $Y^*(1385)$ and $Y^*(1910)$, the best "three-resonance" fit (χ^2 probability of 84%), which is shown as the solid curve of Fig. 2(c), yields the values $M = 1702 \pm 11$ MeV, $\Gamma = 108 \pm 24$ MeV for the $Y_1^*(1695)$. This is consistent with the world average given in our first paragraph, obtained by averaging out best values of M and Γ with those quoted by the other experiments.

MEASUREMENT OF THE LOW-ENERGY END OF THE μ^+ DECAY SPECTRUM*

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Precise measurements[1-4] above 25 MeV have shown that with appropriate radiative corrections,[5,6] the Michel formula[7]

$$N(y;\rho,\eta) = 4(1+2\eta y_0)^{-1}(y^2-y_0^2)^{1/2}[3y(1-y) + (\tfrac{2}{3})\rho(4y^2-3y-y_0^2) + 3y_0\eta(1-y)] \quad (1)$$

(where $y = E/E_{\mathrm{max}}$, E = total electron energy, $E_{\mathrm{max}} = 52.83$ MeV, and $y_0 = m_e/E_{\mathrm{max}}$)[8] gives an excellent fit to the upper half of the μ-decay spectrum when the parameters ρ and η are given the values $\rho = \frac{3}{4}$, $\eta = 0$ corresponding to a $V-A$ theory. For experiments in the 25- to 53-MeV range, however, the correlation between the parameters is such[2] that η can be derived only by assuming a precise value (e.g., $\frac{3}{4}$) for ρ, and ρ can be derived only by assuming a precise value (e.g., zero) or a range of possible values (e.g., $-\frac{1}{2}$ to $+\frac{1}{2}$) for η. By contrast, in our energy range (1-7 MeV) ρ and η are almost decoupled, so that we can make a significant two-parameter fit.

The significance of the low-energy yield becomes evident if we analyze the decay process in the charge-retention ordering. The ν-$\bar{\nu}$ correlation then plays the same role as the e-$\bar{\nu}$ correlation in β decay and the parameter η of Eq. (1) is a measure of that correlation through the electron "recoil" spectrum.

Our spectrometer was a 10-liter hydrogen bubble chamber in a 21-kG field exposed to a beam of stopping μ^+ and π^+ from the Chicago synchrocyclotron. The film was scanned so as to produce two distinct samples. Sample 1 covered the whole spectrum as seen in every hundredth frame and sample 2, taken from all other frames, consisted of events with projected radius $r < 2.5$ cm. This radius corresponds, for zero dip-angle events scanned at 2× magnification, to ~7 MeV/c. The spectrum from sample 2 is shown in Fig. 1.

The calibration of the chamber as a low-momentum electron spectrometer is described elsewhere.[9] Briefly, the standards used were the following: (a) two internal-conversion electron lines of energies ~$\frac{1}{2}$ and 1 MeV (momenta of 0.875 and 1.414 MeV/c) from a Bi^{207} source deposited in a thin layer on 1-mil polyester strips stretched through the chamber, (b) the high-energy cutoff of the μ-decay spectrum

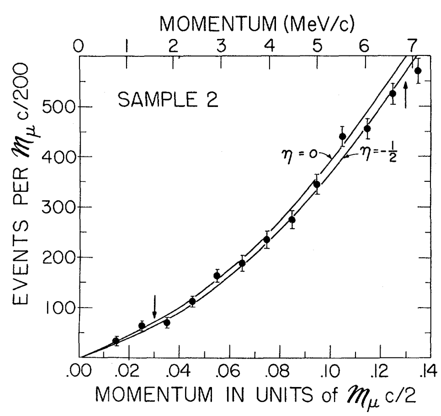

FIG. 1. Low end of spectrum. Points show distribution of events below 7.4 MeV/c found among 530 000 decays of all momenta. Curves show spectra calculated for $\eta = 0$ and $\eta = -0.5$ assuming $\rho \equiv \frac{3}{4}$, radiative corrections as in Ref. 5, and spectrometer resolution as given by Eq. (2). Arrows show limits of momentum range used in analysis (2444 events in this range).