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Photoproduction of Y^* Resonances above 1800 MeV*

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The photoproduction of K^+ mesons and hyperons with strangeness $S=-1$, in reactions of the type $\gamma+p \rightarrow Y^*+K^+$, has been studied in the Y^* mass range 1800–2600 MeV with a missing-mass spectrometer by analyzing the structures in the K^+ yield as a function of the end point bremsstrahlung energy. The K^+ yield was observed at the laboratory angle of $\theta_K=10°$ and at the K^+ momenta of 2.5 and 2.0 BeV/c. A fit to the K^+ yield curve suggests, in addition to a smooth background, resonancelike structure at 1820±20, 2025±20, 2250±20, and 2530±25 MeV. Widths and photoproduction cross sections for these states were measured.

I. INTRODUCTION

THE photoproduction of K^+ mesons and hyperons with strangeness $S=-1$, in reactions of the type $\gamma+p \rightarrow Y^{*0}+K^+$, has been studied in the past in several experiments using the bremsstrahlung beams from high-energy electron accelerators. In these experiments, the momentum and the laboratory production angle of the K^+ meson were measured, usually by a spectrometer, and the mass of the Y^{*0} resonance was determined from the kinematics of the two-body reaction and the energy of the incident photon. The selection rule for the photoproduction process further requires the Y^{*0} to have isospin $I=0$, 1, or 2.

Early experiments on K^+ meson photoproduction were performed at the 1.2-BeV Cornell synchrotron.[1] The results bore evidence for the photoproduction of Λ and Σ^0, demonstrating the validity of the hypothesis of the associated production of strange particles in photoproduction reactions. Extension of these experiments[2] to 2.0-BeV photon energy gave evidence for the production of $Y_1^*(1385)$ and $Y_0^*(1405)$ and indicated the dominance of two-body final-state production. Cross sections for these reactions were measured; no evidence for the production of the $Y_0^*(1520)$ was found. Studies on Λ and Σ^0 production were carried out also at the California Institute of Technology[3] and at Frascatti.[4]

In an earlier experiment at the Cambridge Electron Accelerator (CEA), the photoproduction of K^+ mesons and Y^{*0} resonances was studied at photon energies up to 6.0 BeV.[5] The higher photon energy allowed us to search for the existence of Y^* resonances in the mass range above 2.0 BeV which had been hitherto unexplored. The data gave the first evidence for the presence of a Y^* resonance at 2022 MeV and also one at 2245 MeV.[5] Although the statistics of the data was rather limited, the measured masses proved to be in good agreement with the values reported shortly afterwards from an experiment at the Brookhaven National Laboratory on the K^-p and K^-d total cross sections.[6] The BNL experiment established that the isospin of both of these resonances is $I=1$.

The present paper reports a later experiment at the CEA with a much improved K-meson spectrometer. The resonances found earlier are again observed with much better statistical accuracy, and the search for higher mass resonances has been extended to a mass of 2600 MeV. The relative contribution of photoproduction reactions with many-body final states compared to those with two-body final states is found to increase with photon energy. A brief report of our experiment has been published.[7] The data provided the earliest evidence for several of the $Y=0$ hyperon states.[8,9] The purpose of the present report is to give a more complete description of the experimental method used, the instrumentational problems involved, the counting rates, signal-to-background ratio, and the nature of the background which one encounters in this approach to study Y^* photoproduction in this energy range. The significance of the data obtained will be discussed in Sec. III. In addition to the search for higher-mass

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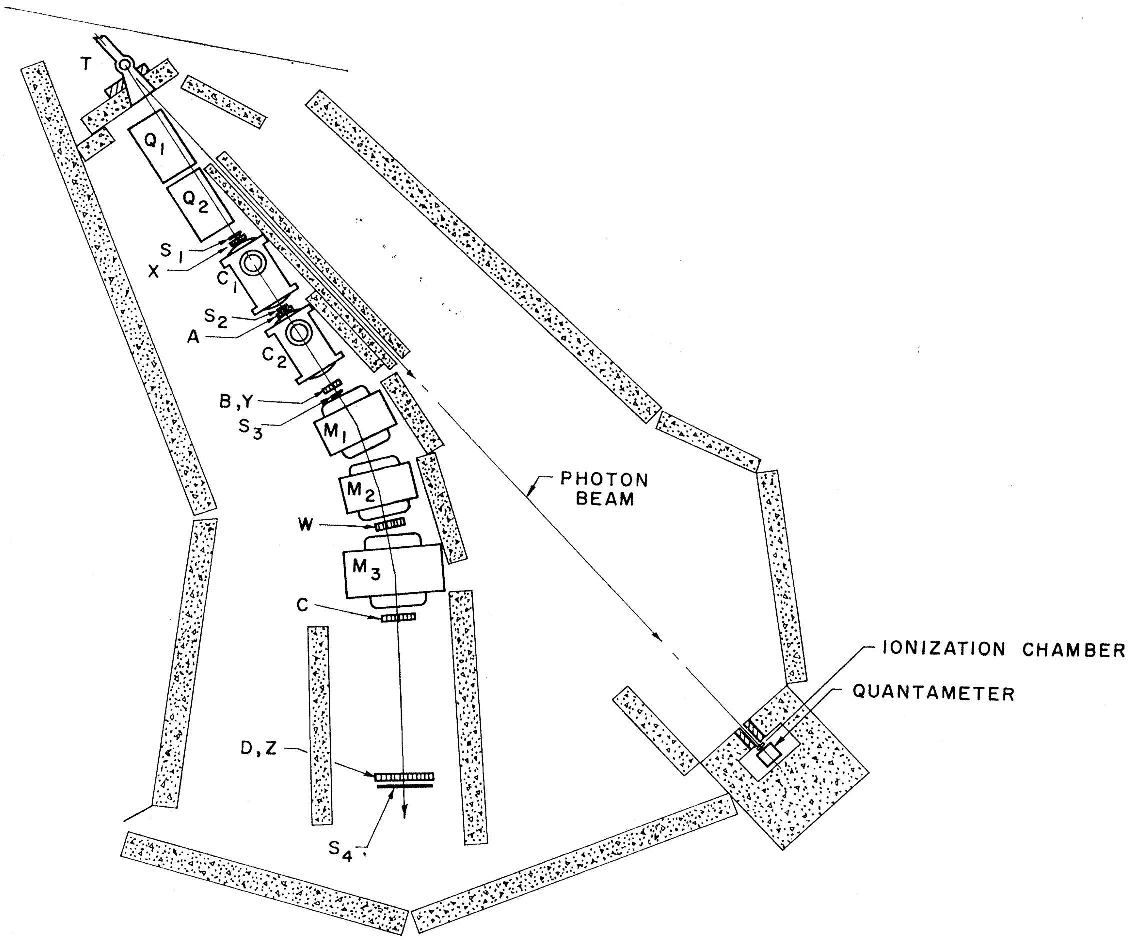

FIG. 1. Experimental layout: T, liquid hydrogen target; $Q1$, $Q2$, 12-in. half-quadrupole magnets; $M1$, $M2$, $M3$, bending magnets; $C1$, $C2$, differential gas Čerenkov counters; $S1$, $S2$, $S3$, $S4$, scintillation trigger counters; A, B, C, D, X, Y, W, Z, scintillation counter hodoscopes.

hyperons which is discussed here, the earlier publication[7] gave data on and the implications of the ratio of Λ and Σ^0 photoproduction cross sections. A related research in which we studied the photoproduction cross sections. A related research in which we studied the photoproduction of K^- mesons from protons in a search for baryon resonances with strangeness $+1$ has been completely reported.[10,11]

II. EXPERIMENTAL METHOD AND PROCEDURE

A. General Method

The photoproduction reaction studied is the following:

$$\gamma+p \rightarrow K^+ + (\text{other particles})\,. \tag{1}$$

Only the K^+ meson is detected, and its production angle and momentum are measured with a spectrometer. The reaction with a two-body final state is

$$\gamma+p \rightarrow K^+ + Y\,, \tag{2}$$

in which Y includes Λ, Σ, and higher mass Y^*. In addition there can be many reactions with three- or more-body final states, some of which are listed below:

$$\gamma+p \rightarrow K^{*+,(0)} + Y^{0,(+)} \rightarrow K^+ + Y + \pi\text{'s}\,, \tag{3}$$

$$\gamma+p \rightarrow K^+ + Y + \pi\text{'s}\,, \tag{4}$$

$$\gamma+p \rightarrow p \text{ (or } N^*) + \phi \rightarrow p + K^+ + K^- + (\pi\text{'s})\,, \tag{5}$$

$$\gamma+p \rightarrow p \text{ (or } N^*) + K^+ + K^-\,, \tag{6}$$

$$\gamma+p \rightarrow K^- + Z^{*++} \rightarrow K^- + K^+ + p + \pi\text{'s}\,. \tag{7}$$

The general method and apparatus used in this experiment are identical with those used in the experiment on photoproduction of K^- mesons and already described in detail.[11] We will briefly summarize our previous description. The experimental layout is shown

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TABLE I. Experimental parameters.

Beam: Bremsstrahlung from 0.1-radiation-length tungsten ribbon.	
Duty cycle:	~1-msec pulses at 60 cps.
Dimensions:	7/16 in. height, 13/16 in. width at hydrogen target.
End point energy (k_0):	3–6.1 BeV
Energy accuracy:	±0.25%
Dosage monitor:	Wilson-type quantameter, ±2% accuracy.
Secondary monitors:	Ionization chamber, pion flux.
Target: Liquid hydrogen, 6-in.-diam vertical cylinder.	
Čerenkov counters: C_1 and C_2, differential gas Čerenkov counters.	
C_1 acceptance:	(2.0 or 2.5) BeV/c±8%, K^+.
C_2 acceptance:	(2.0 or 2.5) BeV/c±10%, π^+(anticoincidence).
Angular acceptance:	±1° from optical axis.
Aperture:	~6-in. diam circular.
Spectrometer (over-all):	
Angular acceptance:	~1° polar angle (0.8° horizontal, 7° vertical).
Solid angle:	1.5 msr for central momentum.
Angular accuracy:	±0.1° for mean production angle.
Momentum acceptance:	16% for K^+; 20% for π^+.
Momentum resolution:	~1%.
Momentum accuracy:	~±0.5% for mean momentum.
Integral acceptance:	integral of $(\Delta P/P)\times$(solid angle), 0.25 msr.
Transmission efficiency:	0.14.

in Fig. 1. A collimated bremsstrahlung beam from the 6-BeV electron synchrotron at the CEA struck a 6-in.-long liquid-hydrogen target T and was monitored by a quantameter and an ionization chamber placed inside a concrete hut. K^+ mesons produced in the target were identified and their momenta analyzed by a K-meson spectrometer which consisted of two half-quadrupole magnets Q_1 and Q_2, two differential gas Čerenkov counters C_1 and C_2, three bending magnets M_1, M_2, and M_3, scintillation trigger counters S_1, S_2, S_3, and S_4, and scintillation counter hodoscopes A, B, C, D, X, Y, W, and Z. Some relevant parameters on the apparatus are summarized in Table I.

In this experiment, the spectrometer was set to observe the K^+ mesons produced at a polar angle of $\theta_K=10°$ with a central momentum of 2.5 or 2.0 BeV/c. The K^+-meson yield observed at a given production angle θ_K and kaon momentum P_K in the laboratory system is contributed by all the reactions listed in Eqs. (2)–(7) which are kinematically possible (as well as other unlisted reactions with many-body final states).

For reactions with a two-body final state [Eq. (2)], the energy of the incident photon is uniquely related to m_p, m_K, and m_Y—the rest mass of the proton, K^+ meson, and Y^*—by the kinematic relation

$$E(P_K,\theta_K)=\frac{m_Y{}^2-m_p{}^2-m_K{}^2+2m_pE_K}{2(P_K\cos\theta_K-E_K+m_p)}, \qquad (8)$$

where $E_K=(m_K{}^2+P_K{}^2)^{1/2}$. The number of photons with energy $E(P_K,\theta_K)$ per equivalent quantum (EQ) of the bremsstrahlung beam is independent of the end point energy k_0 of the bremsstrahlung provided $k_0>E(P_K,\theta_K)$. Thus if the K^+-meson yield per equivalent quantum is plotted against k_0, the resulting excitation curve for a two-body final-state reaction will be a step function rising at the point $k_0=E(P_K,\theta_K)$, corresponding to the onset of this reaction, whereas for reactions with many-body final states the excitation curves probably rise smoothly with k_0. Therefore, the composite excitation curve is expected to be a series of step functions superposed on a smoothly rising background. Each of the steps occurs at a value of $E(P_K,\theta_K)$ corresponding to the onset of a two-body final-state reaction involving a particular Y^*. The mass of this Y^* can then be deduced through Eq. (8) from the observed values of $E(P_K,\theta_K)$, P_K, and θ_K, and the known rest masses. The natural width of the Y^* resonance can be determined from the width of the observed step and the resolution of the spectrometer, which is about 20 MeV for the missing mass.

B. Adjustment and Calibration of Spectrometer

The spectrometer was set for the desired momentum by first adjusting the bending magnets for the appropriate fields, and then adjusting the quadrupole magnets to maximize the K^+ counting rate. Details on the procedure used to study the spectrometer and its momentum acceptance have been reported previously.[11] An accuracy of about ±0.5% in particle momentum determination could be achieved in the calibration of the spectrometer by observing the K^+ excitation for Λ and Σ^0 production which are clearly separated on the excitation curve by virtue of the 20-MeV missing-mass resolution of the instrument. The bremsstrahlung

TABLE II. Typical counting rates: $\theta_{K^+}=10°$, $P_{K^+}=2.5$ BeV/c, $k_0=5.08$ BeV, and total incident photon beam $=0.559\times10^{14}$ equivalent quanta in 63 min.

Counter or coincidence[a]	Counts
S_1 (single)	246.1×10^6
S_2 (single)	107.3×10^6
S_3 (single)	27.36×10^6
S_4 (single)	···
C_1 (single)	222.8×10^6
C_2 (single)	28.43×10^6
$3S$ (S_1, S_2, S_3 triple coincidence)	1 044 851
$4S$ ($3S$, S_4 coincidence)	349 084
$4SC_1$ ($4S$, C_1 coincidence)	30 600
$4SC_2$ ($4S$, C_2 coincidence)	253 051
$4SA$ ($3S$, S_4 accidental)	3 455
$4SC_1\bar{C}_2$ ($4SC_1$, C_2 anticoincidence)	16 277
$4SAC_1\bar{C}_2$ ($4S$ delayed, $C_1\bar{C}_2$ accidental)	149
$4SC_1A\bar{C}_2$ ($4S$, C_1 delayed, $\bar{C}_2$ accidental)	1 629
$4SC_1C_2A$ ($4SC_1$, C_2 delayed, accidental)	99
Master trigger ($4SC_1\bar{C}_2$, $4SAC_1\bar{C}_2$ and/or $4SC_1A\bar{C}_2$)	17 765
Event trigger (master trigger less dead time)	16 995

[a] For further explanation, see Ref. 9.

end point energy k_0 was known to an accuracy of $\pm 0.25\%$.

C. Data Collection and Reduction

The K^+-meson yield data were taken in four separate runs with overlapping missing-mass ranges which cover from 1800 to about 2600 MeV. In three of the runs, the spectrometer was set for a kaon momentum of 2.5 BeV/c. The bremsstrahlung end point energy was varied from 4.0 to 6.1 BeV. To reach the upper limit of the missing-mass range, the spectrometer setting was reduced to 2.0 BeV/c in the fourth run. The missing-mass range from 2400 to 2560 MeV was studied at both kaon-momentum settings, providing a check on the kinematic shifts of the steplike structures in the excitation curve associated with two-body final-state reactions. The spectrometer parameters, such as the Čerenkov counter gas pressure, were adjusted slightly from run to run to optimize the experimental conditions.

The measurements were made typically with synchrotron energy steps of 60 MeV and each energy point consisted typically of two (or more) measurements, one with the synchrotron energy being increased and the other with its energy being decreased. The typical collimated bremsstrahlung beam intensity was 1.5×10^{10} EQ/sec. A sample of the single, coincident, and accidental counting rates in a measurement is given in Table II.

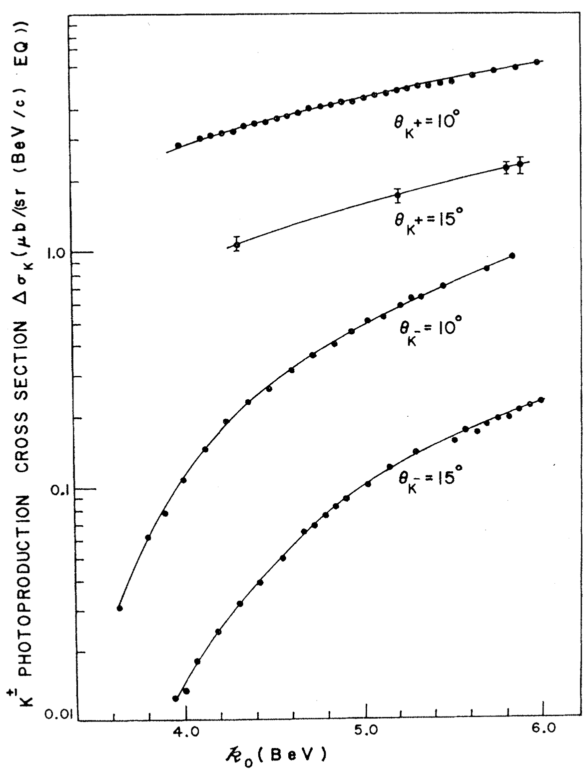

FIG. 2. Photoproduction cross section $\Delta\sigma_K$ for K^+ mesons of 2.5 BeV/c, in units of μb/[sr (BeV/c) EQ]: $\Delta\sigma_K$ is the differential cross section integrated over the bremsstrahlung spectrum and averaged over the angular and momentum acceptances of the spectrometer. The target thickness is 6.8×10^{23} protons/cm^2; the integral of the solid-angle acceptance times the fractional momentum acceptance for kaons at $\theta_{K^+}=10°$ is about 0.25 msr; the integral acceptance for $\theta_{K^+}=15°$ is about 15% less than the value for $\theta_{K^+}=10°$; the transmission efficiency for 2.5 BeV/c kaons is about 0.14.

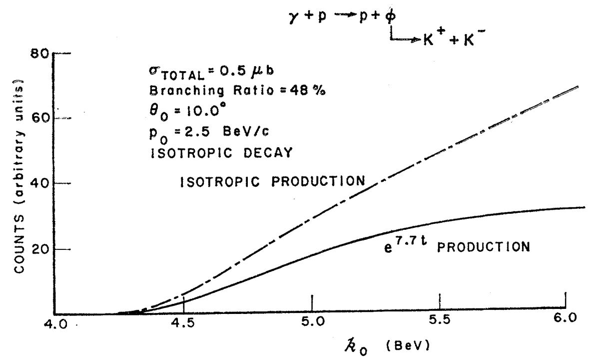

FIG. 3. The shape of K^+ yield background from ϕ production, estimated by Monte Carlo computations.

Information for each accepted event was recorded on magnetic tape and includes trigger type, hodoscopic pattern, Čerenkov pulse height, and other identification numbers. For details of the data reduction process and the absolute normalization of the K^+ yields, we again refer to our previous paper.[11]

III. RESULTS AND DISCUSSION

A. K^+-Meson Yields

The photoproduction cross section $\Delta\sigma_K$ for K^+ mesons of 2.5 BeV/c at a laboratory angle of $\theta_K=10°$ is shown as a function of bremsstrahlung end point energy k_0 in Fig. 2. The quantity $\Delta\sigma_K$ is the differential cross section for production of K^+ mesons integrated over the bremsstrahlung spectrum and averaged over the angular and momentum acceptances of the spectrometer. Some limited amount of data for $\theta_K=15°$ are also included. The cross sections for K^- mesons[11] are also included to illustrate the difference between K^+ and K^- mesons.

B. Photoproduction of Y^{*0}

Photoproduction of higher-mass Y^{*0} states in reactions with two-body final states were observed as steplike structures in the K^+ excitation curve at higher bremsstrahlung energies. Unlike in the cases of Λ and Σ^0, however, these steplike structures at higher energies must be discerned in the presence of a substantial background. This background is contributed by all the processes of the types given by Eqs. (3)–(7) in which K^+'s are produced directly or indirectly in three- or more-body final states. In addition, each of the steplike structures for a two-body process [Eq. (2)] occurring at a lower incident photon energy con-

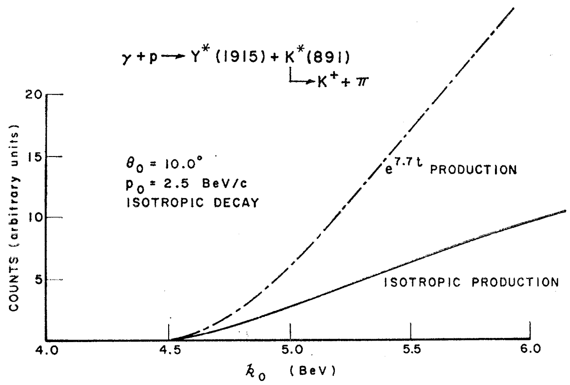

FIG. 4. The shape of K^+ yield background from K^* production, estimated from Monte Carlo computations.

tributes a flat background for the steplike structures at higher energies.

A detailed analysis of the background was carried out for the present K^+ experiment similar to that reported for the K^- data.[11] Some of the reactions contributed identically to the K^+ background as to K^-, i.e., Eqs. (5) and (6). The shapes of the background contributed by these reactions have been estimated by Monte Carlo computations, using known cross sections, widths, and branching ratios wherever available. Figure 3 shows the background due to ϕ production, Eq. (5). The dot-dash line in Fig. 3 assumed the production to be isotropic, and the solid line assumed the production to have an $e^{7.7t}$ dependence on t, the square of four-momentum transfer. A second category of reactions which probably contributes significantly to the K^+ background are those involving K^* production, i.e.,

$$\gamma+p \to (\Lambda, \Sigma^0, \text{ or } Y^{*0})+K^{*+}, \quad K^{*+} \to K^+ + \pi^0$$
$$\gamma+p \to (\Sigma^+ \text{ or } Y^*)+K^{*0}, \quad K^{*0} \to K^+ + \pi^-.$$

A typical example shown in Fig. 4 is the background estimated for the reaction

$$\gamma+p \to Y^*(1910)+K^*(891) \to Y^*(1910)+K^+ + \pi.$$

Again the production is assumed to be isotropic or to have an $e^{7.7t}$ dependence on t. The K^* decay is assumed to be isotropic. Reactions involving Z^* production, if present, are expected to be unimportant in background contribution due to their much lower cross sections.[11]

From the curves, it is apparent that the background contributions from reactions with three- (or more-) body final states are all quite smooth and exhibit no abrupt rises which may appear as steplike structures associated with two-body final states. This is particularly true in the higher bremsstrahlung-energy range of the present study which lies far above the threshold of the background processes. In fact, in the high-energy range, the composite shape of the K^+ background appears approximately linear and can be represented by a straight line of adjustable slope for χ^2 fitting in data analysis.

As mentioned in Sec. II C, the data on K^+ mesons were obtained in four separate runs. In order to avoid systematic errors, the data from each run were analyzed separately and converted to the missing-mass scale. The results from separate runs were then combined, assuming a normalization such that the excitation curves on the missing-mass scale matched smoothly between runs in the overlapping regions. The result is shown in Fig. 5, and a summary of the results from the least-squares fits for the four separate runs is given in Table III.

In the χ^2 fitting, the resonances were assumed to have Breit-Wigner shapes, with the masses, widths, and cross sections as free parameters. The number of resonances used in the analysis is suggested by the appearance of the excitation curve. In sections of the curve where the appearance is ambiguous, different numbers of resonances were tried. The quality of the χ^2 fits and the assignments of the masses of the resonances were found to be quite insensitive to the slope and magnitude of the linear background. However, substantial uncertainties resulted in the determinations of the cross sections and widths of the resonances due to the uncertainties in the background.

C. Conclusions of Photoproduction of Y^{*0} Resonances

In the present experiment, we have observed indications of the photoproduction of Y^{*0} resonances in the mass range 1800–2600 MeV. The indications appear

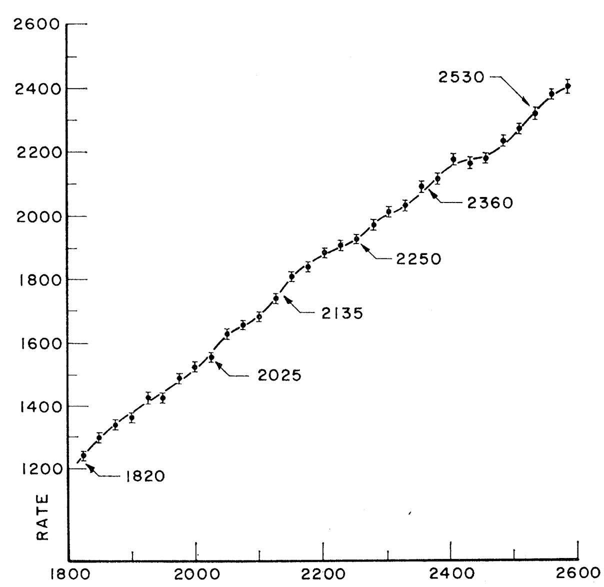

FIG. 5. The total yield of K^+ mesons at $\theta_K = 10°$ for synchrotron energies up to 6.1 BeV. Data taken with spectrometer set for 2.5 or 2.0 BeV/c and combined on missing-mass scale. The errors are statistical. The solid curve is the sum of a linear background and Breit-Wigner resonances fitted by least squares.

TABLE III. Summary of results on photoproduced Y^* resonances.[a]

Mass (MeV)	Width (MeV)	Cross section (μb/sr)	$\theta_{c.m.}$ (deg)
1820±20	55	0.07±0.035	33.0
2025±20	80	0.10±0.05	34.9
2135±20	40	0.09±0.045	35.9
2250±20	125	0.14±0.07	37.0
2360±20	55	0.14±0.07	38.1
2530±25	150	0.14±0.07	39.8

[a] The errors associated with the mass measurements are estimated overall errors, about equally contributed by statistical errors and by systematic errors. The errors in widths are generally quite large, about 30–40%, due mainly to the uncertainties in background. For the same reason, the error in cross-section measurements is about 50%.

as steplike structures in the K^+ photoproduction yield curve, superimposed on a smooth background. If one adopts the interpretation that such steps are the result of two-body reactions of the type $\gamma+p\rightarrow K^++Y^{*0}$, then a χ^2 fit, in which the mass, width, and yield of each Y^{*0} resonance are left as free parameters, whereas the number of resonances are suggested by the steplike structure, gives Y^{*0} mass values of 1820, 2025, 2135, 2250, 2360, and 2530 MeV. It is significant that, except for the resonance at 2530 MeV, these values are in substantial agreement with those determined from total cross-section measurements[6,12] and with other reported evidences.[8,13,14] From a purely statistical point of view, it is quite likely that the data could be fitted equally well by some other χ^2 analysis, assuming some arbitrary form for the yield curve; it is thought, however, that the assumption of two-body reactions in addition to a smooth background due to many-body reactions is more plausible physically. This latter point of view is strengthened by the clearly steplike structures observed with this apparatus for Σ^0 and Λ production at lower energies,[7] and by the observation of similar steplike structures at lower energies in earlier experiments.[2] It is only natural to assume that such steplike structures are also present at this higher-energy range although they become less discernable from the dominant background due to many-body reactions.

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The resonance mass values of 2025 and 2250 MeV are in agreement with what we have first reported in an earlier experiment.[5] The 2135-MeV resonance was not observed in the earlier experiment due to the statistical quality of our data. The resonance at 1820 MeV is probably the unresolved $\Lambda(1815)$ and $\Lambda(1830)$.[8] The widths determined for these states from photoproduction, while basically in agreement with those measured from other processes, show a general tendency to be narrower.

There is no evidence in our data for the photoproduction of the $\Sigma(1915)$ state.[8] If a resonance with fixed mass at 1915 MeV is introduced in our χ^2 fitting, the quality of the fit does not improve, and the cross section so obtained is at least a factor of 5 smaller than those for the other states.

The higher-mass region studied in this experiment gave indication for the existence of a new Y^* resonance at 2530 MeV with a width of about 150 MeV. The photoproduction cross section for this state was determined to be about 0.14 μb/sr, which is comparable to those for the other Y^* resonances. It is interesting to note, however, that two resonances at 2433 and 2595 MeV have been observed in the BNL K^-p and K^-d experiment.[6,12] An attempt was made to fit the upper part of our data with two resonances with fixed masses at 2455 and 2595 MeV. The quality of the fit does not differ significantly from that with one resonance at 2530 MeV.

During the last few years, the spins and parities of most of the Y^* resonances observed below 2200 MeV have become known,[8] and some of them can be assigned to $SU(3)$ multiplets. The 1820-MeV Y^* observed in this experiment may be either (or both) the $\Lambda(1815)$ or the $\Lambda(1830)$.[8] The former belong to the $(\frac{5}{2}, +)$ Regge recurrence of the baryon octet. The latter has $(J,P)=(\frac{5}{2}, -)$, and its interpretation is less clear. The Y^* observed at 2025 MeV is most likely the $\Sigma(2035)$,[8] and belongs to the $(\frac{7}{2}, +)$ recurrence of the $(\frac{3}{2}, +)$ decuplet.[9] The 2135-MeV Y^* may be the $\Lambda(2100)$, which has $(J,P)=(\frac{7}{2}, -)$.[8] The (J,P) assignment of Y^*'s above 2200 MeV are at the moment not known.

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