High-Statistics Investigation of the Broad T and U Peaks in Antiproton Interactions*

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We observed broad bumps at 2193 and 2359 MeV in the elastic, inelastic, and annihilation $\bar{p}p$ cross sections. We find that the positions and widths of the structures are invariant to changes in the multiplicity and degree of nonperipheralism. Multiplicity distributions indicate that the structure at 2193 has no contribution from single π production, while as much as 40% of the structure at 2359 could be due to this process.

An ambiguity has long existed in the interpretation of the broad structures observed in $\sigma_{\text{tot}}(\bar{p}p)$ in the mass region greater than two nucleon masses.[1] The masses of these structures are in good agreement with those of the T and U mesons first observed in the CERN missing-mass spectrometer,[2] but the corresponding widths are considerably broader. Are the $\sigma_{\text{tot}}(\bar{p}p)$ structures to be identified as resonances (T and U or other states), or are they merely due to the onset of N^* production at the same total c.m. energy? Several investigations of $\bar{p}p$ interactions have tried to resolve this question, but none has been conclusive.[3]

The present experiment has investigated these structures by measuring the mass spectrum of the $\bar{p}p$ system with the Rutgers Annihilation Spectrometer (RAS)[4,5] as a function of the following two quantities:

(a) The nonperipheralism of the event. This is the forward cone angle, θ, within which *no* charged particles are emitted in the final state. We experimentally define four degrees of nonperipheralism: 2.5°, 5°, 10°, and 20°—all being measured simultaneously and each accurate to ±1°.

(b) The number of detected charged particles in the final state, N_c, as detected by 32 counters surrounding the target. We differentiate all multiplicities 0 to 6 and group together all events with $N_c \geq 7$.

Our measured multiplicity, N_c, deviates from the true charge multiplicity mainly because of three effects[6]: (1) Two particles passing through the same multiplicity counter register as one; (2) slow particles are stopped in the target—thus, elastic scattering below 20° registers as $N_c = 1$; (3) γ's from final-state π^0's often convert in the target and register as one particle.

This is entirely a counter experiment and has very high statistics. Our sample contains 1.6×10^9 incident $\bar{p}$'s with 20% interacting with $\theta > 2.5°$. Seven incident momenta were measured simultaneously by dividing the momentum bite of $\simeq 6\%$ into seven bins with momentum hodoscopes. Thus, the mass resolution, including ionization losses in the target, was ±5 MeV at 2.0 GeV/c. In addition, overlapping consecutive momentum settings allowed a check on run-to-run normalization.[7] Contamination of the incident $\bar{p}$ beam was monitored by time of flight (TOF) and found to be $\leq 0.1\%$ for all momenta. The empty-target cross section was found to be a smooth function of incident $\bar{p}$ momentum, and equal to $\simeq 11\%$ of the full-target cross section. No "point by point" subtraction of the empty-target background was made—this smooth contribution was absorbed by the background function during fitting. Triton TOF indicates a mass scale uncertainty of ±3 MeV.

We performed two series of fits to our data:

(1) When the widths and central masses of two Breit-Wigner forms with energy-dependent widths were free parameters, we found that *there was no significant correlation of the angular or multiplicity cuts with the fitted positions and widths of the Breit-Wigner forms.* Thus, these results do not support the hypothesis that the broad structures at 2193 or 2359 MeV are the sum of several narrow effects of different origins. Nor was significant narrow structure observed at any other mass.

(2) Next, the position and width of each Breit-Wigner was fixed at the best-fit values (listed in Table I) obtained from the above fit to our uncut data sample. The results of this series are those used in further analysis. We also fitted the

TABLE I. Best-fit values for structures above background extrapolated to 0°. Listed errors are statistical only. See Ref. 9 for a discussion of the results we list for Abrams *et al.*

	T region			*U* region		
	Mass (MeV)	Width (MeV)	Height (mb)	Mass (MeV)	Width (MeV)	Height (mb)
Rutgers	$2192.7^{+1.2}_{-1.5}$	$97.6^{+8.1}_{-5.9}$	$2.32^{+0.13}_{-0.08}$	$2359.4^{+1.4}_{-1.2}$	$164.9^{+17.9}_{-7.6}$	$2.06^{+0.20}_{-0.12}$
Abrams *et al.* (our fit)	2187 ± 3	56 ± 8	1.85 ± 0.25	2363 ± 2	171 ± 10	2.52 ± 0.28

data with the background function alone. Fits which included the two Breit-Wigners all had confidence levels greater than 5%, while fits with background only usually had confidence levels $<10^{-6}$.

Figure 1 shows our raw data summed over all multiplicities and summed over all angles >2.5°. Figure 1(a) shows the total data and a smooth fitted curve. Figure 1(b) shows what is obtained after subtracting the background. Fits with various cuts were all composed of a smooth third-order polynomial background in mass together with two Breit-Wigners. Other backgrounds gave Breit-Wigner amplitudes which agreed within 1 standard deviation with the results of the mass polynomial background when these backgrounds produced reasonable fits.

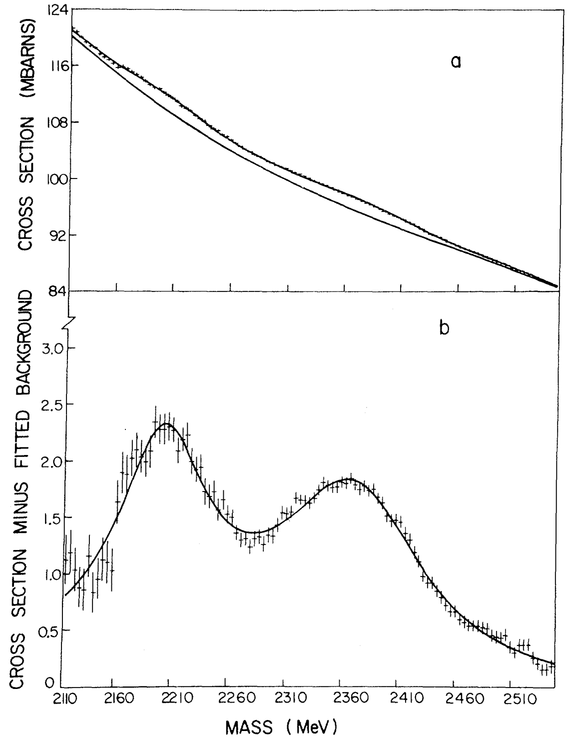

FIG. 1. (a) Our data sample summed over all values of measured multiplicity, N_c, and over all values of nonperipheralism, $\theta > 2.5°$. The solid lines are the best fit described in the text and the contribution of the background to the total fit. (b) The structure remaining after the background is subtracted.

To compare with the total cross-section measurement[1] we performed a linear extrapolation of our cross sections to 0° and compared (1) background away from peaks, and (2) the structures above the background. Background was found to agree to better than 5% and the widths, positions, and amplitudes of the structures above background were also in agreement[8] (see Table I).

Figure 2 shows plots of the dependence of the cross sections on nonperipheralism. The abscissa is θ, and the ordinate is the cross section for angles $>\theta$ normalized to the cross section for $\theta > 2.5°$. The solid lines are the results of a Monte Carlo calculation. One extreme is annihilation into 2π, and the other extreme is annihilation into 7π assuming isotropic distributions in the c.m. This defines a region of annihilation. Also shown with a solid line are the results of a Monte Carlo treatment of elastic scattering. The data points which are plotted are of two sorts: $N_c = 1$ is plotted as an open circle (we interpret this as mostly elastic scattering), and $N_c = 3-7$ is plotted as solid circles. For the background the data points for $N_c = 3-7$ fall within the annihilation region, and the $N_c = 1$ points fall along the elastic scattering prediction. This is true for the regions of both the T and the U.

When we do the same thing for the structure above background, we find that while $N_c = 3-7$ is consistent with annihilations,[9] $N_c = 1$ is falling faster than elastic scattering.[10]

The charge multiplicity, N_c, distributions of the structures above background are shown in Fig. 3(a). For the T region there are contributions for $N_c = 3-7$, no contribution at $N_c = 2$, a sizable contribution at $N_c = 1$, and a small contri-

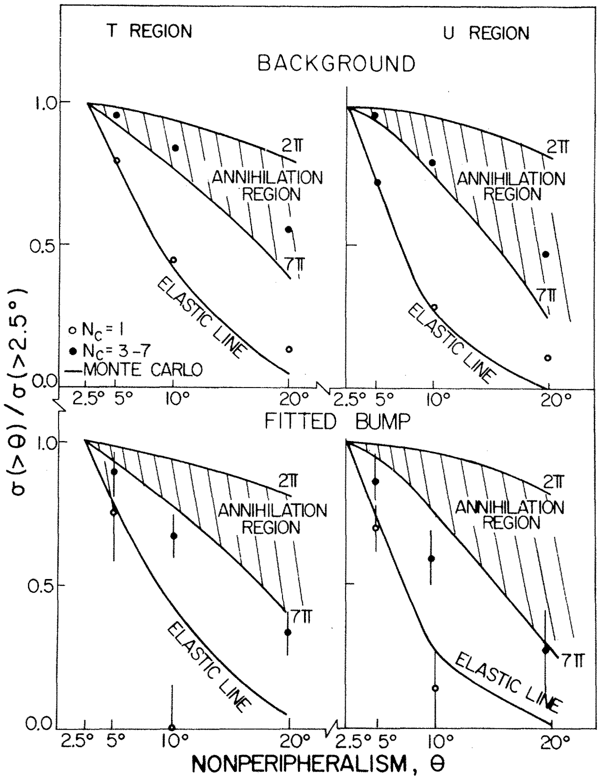

FIG. 2. Dependence of the cross section on nonperipheralism. Results are shown both for the background and for the structure above the background in the regions of the T and U mesons. The solid lines are Monte Carlo results for annihilation and for elastic scattering.

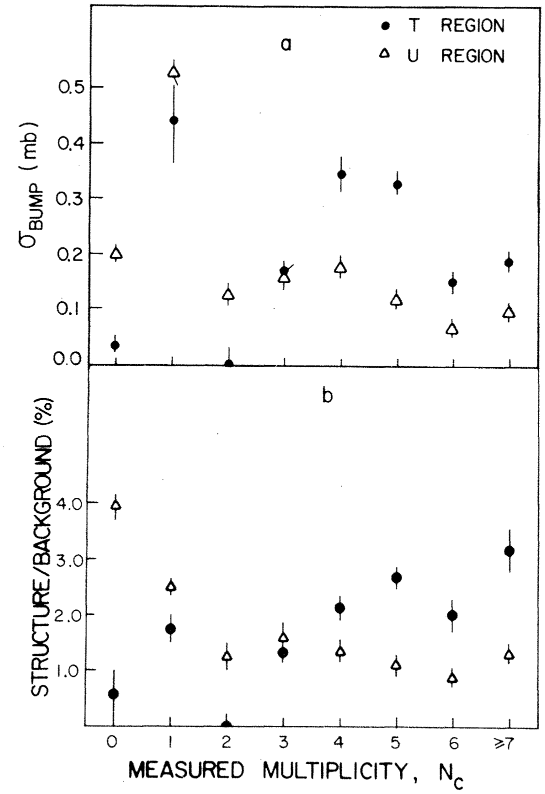

FIG. 3. (a) Height above background of the fitted structures in the regions of the T and U mesons as a function of measured multiplicity, N_c, for $\theta > 2.5°$. (b) The ratio of the height of the Breit-Wigners and the background for the structures in the regions of the T and U mesons as a function of measured multiplicity, N_c, for $\theta > 2.5°$.

bution at $N_c = 0$. Because the T is below threshold for multi-π production, we interpret the enhancements in $N_c = 3-7$ as $\bar{p}p$ annihilation. The simplest explanation for these enhancements is resonance formation, although we have not measured all quantum numbers and therefore cannot exclude the possibility that the rise and fall of different annihilation channels could conspire to give the observed structures. Because of the limits imposed by multiplicity smearing, no statement can be made about a preferred decay mode although the signal/noise seems to peak in $N_c = 4-6$ [Fig. 3(b)]. Monte Carlo studies which include the effects of multiplicity smearing on all possible $\Delta(1236)$ final states accessible to $\bar{p}p$ show that $\Delta(1236)$ production should be distributed with approximately equal probability over $N_c = 0$, 1, and 2. Thus, the enhancement in the T region for $N_c = 1$ cannot be attributed to the onset of this process.[11] Although the interpretation of the enhancement in $N_c = 1$ as the elastic decay of a resonance would predict an equal contribution in the charge-exchange mode, the near absence of an $N_c = 0$ contribution in the T region could be explained as a destructive interference between the charge-exchange amplitude and the same final state in the background.

The N_c distribution in the region of the U meson has contributions at $N_c = 0$, 1, and 2 and seems to follow the background distribution more closely than the enhancement in the T region [Fig. 3(b)]. Since $\Delta(1236)$ production is expected to be distributed with approximately equal probability in $N_c = 0$, 1, and 2, an upper limit of ~40% can be set for the contribution of single π production to the broad structure in $\sigma_{\mathrm{tot}}(\bar{p}p)$ in the U region by normalizing this distribution to the observed enhancements in this region. However, it should be be noted that Abrams *et al.*[1] found an isospin-1 enhancement at 2350 MeV and an isospin-0 enhancement at 2375 MeV when they made a $\bar{p}p - \bar{p}d$ subtraction. This would imply that our enhancement in the U region is a mixture of states and perhaps not amenable to the same analysis as the structure in the T region.

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[1] R. J. Abrams *et al.*, Phys. Rev. D 1, 1917 (1970).

[2] G. Chikovani *et al.*, Phys. Lett. 22, 233 (1966).

[3] Some of these experiments are reviewed by L. Montanet, in *Proceedings of the Fifth International Conference on Elementary Particles, Lund, Sweden, 1969*, edited by G. von Dardel (Berlingska Boktryckeriet, Lund, Sweden, 1970), p. 191.

[4] J. Alspector *et al.*, Nucl. Instrum. Methods 103, 239 (1972).

[5] B. Maglich and F. Sannes, Nucl. Instrum. Methods 103, 245 (1972).

[6] The last two effects are aggravated because the target is surrounded by an outer jacket of liquid hydrogen to maintain a constant target density. Multiplicity distributions were checked by tracing measured bubble-chamber events at 1.5 GeV/c through our apparatus with a computer. Taking the above effects into account, good agreement was obtained between our experimental results and the simulated distribution. This study also showed that "smearing" of the measured multiplicity by effects (1)–(3) above had a full width at half-maximum of ~ 2 for charge multiplicity =4 for the final states composing the background.

[7] Each mass bin has contributions from 12 different momentum settings of the spectrometer and represents between 20 and 30 independent measurements of the cross section. This allowed us to verify that each of the measurements agreed within errors with their average for every mass bin, multiplicity, and peripheralism cut. We conculde that there are no time variations in systematic errors (e.g., accidentals) comparable in magnitude to our statistical errors.

[8] To compare with the results of Abrams *et al.*, we performed our own fit to their published $\bar{p}p$ data. The fit results they published were the result of a $\bar{p}p - \bar{p}d$ subtraction.

[9] The tendency of $\sigma(\theta)/\sigma(2.5)$ to fall somewhat faster than expected for isotropic annihilation is perhaps consistent with a high-spin resonance preferentially giving small-angle decay products.

[10] This is consistent with the optical-theorem requirement of an enhancement in *forward* elastic scattering when there is an enhancement in the total cross section.

[11] This conclusion has qualitative support from bubble-chamber results for single π production in $\bar{p}p$ interactions. These studies show a smooth cross section in the region of the T meson and a break in the cross section in the region of the U meson. See, for example, R. Donald *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published), Paper No. 265.

Baryon Mass Differences in a Gauge Model of Strong and Electromagnetic Interactions*

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We calculate the baryon mass differences in a model of strong and electromagnetic interactions based on a spontaneously broken U(3)⊗U(1) gauge invariance. Good agreement with experimental values is obtained.

The criteria for calculability of a mass or mass difference in a field-theory model with spontaneously broken gauge symmetry are now well understood.[1,2] Several authors have used these newly developed ideas in an attempt to calculate the proton-neutron mass difference in models of electromagnetic or weak and electromagnetic interactions.[3] Such models invariably give the wrong sign for the mass difference. The problem is not hard to find: Models which make no reference to SU(3) cannot distinguish the proton-neutron doublet from the anticascade doublet.[4] Since the mass differences in the two systems are very different, SU(3) must be play-