

### Observation of the Decay $D^{*+} \rightarrow D^0 \pi^+ \dagger$

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We have observed the decay  $D^{*+} \rightarrow D^0 \pi^+$  and have measured its  $Q$  value to be  $5.7 \pm 0.5$  MeV. The decay width of the  $D^{*+}$  is less than  $2.0 \text{ MeV}/c^2$ . The observation of  $D^{*+} \rightarrow (K^- \pi^+) \pi^+$  but not of  $D^{*+} \rightarrow (K^+ \pi^-) \pi^+$  sets an upper limit on the amount of  $D^0$ - $\bar{D}^0$  mixing.

When the  $D^+$  was discovered in  $e^+e^-$  annihilations at the center-of-mass energy ( $E_{c.m.}$ ) of 4.03 GeV, it was noted that it was produced primarily in association with a system of mass  $2010 \pm 20 \text{ MeV}/c^2$ .<sup>1</sup> This system was widely interpreted to be an excited state of the  $D^+$ , the  $D^{*+}$ , but its mass and width could not be determined precisely nor were any of its decay modes known. In this Letter we report the observation in higher-energy  $e^+e^-$  annihilations of the decay  $D^{*+} \rightarrow D^0 \pi^+$  and a precise measurement of its  $Q$  value.

The data on which this Letter is based come from about 160 000 hadronic events in the  $E_{c.m.}$  range 5.0 to 7.8 GeV collected with the Stanford Linear Accelerator Center-Lawrence Berkeley Laboratory magnetic detector at SPEAR.<sup>2</sup> The average  $E_{c.m.}$  for these data is 6.8 GeV and the integrated luminosity is  $17 \text{ pb}^{-1}$ .

The analysis techniques are substantially the same as those used previously.<sup>1,3</sup> Briefly, each particle in a multihadronic event is assigned a weight proportional to the probability that it is a  $\pi$ ,  $K$ , or  $p$ . These weights are determined from the measured momentum and time of flight over a 1.5–2.0-m flight path using a Gaussian time distribution with a 0.35-ns standard deviation. The  $\pi$ - $K$ - $p$  weights are normalized so that their sum is unity for each track. All possible combinations of tracks and particle hypotheses are made with each combination weighted by the joint probability that the tracks satisfy the particular hypotheses assigned to them.

If the  $Q$  value of the decay  $D^{*+} \rightarrow D^0 \pi^+$  is small, then the momenta of the  $D^0$  and  $\pi^+$  in the laboratory frame will be roughly proportional to their masses. Since the magnetic detector has low efficiency for the detection of charged particles

with momenta less than  $100 \text{ MeV}/c$ , the  $D^{*+}$  decay cannot be readily detected unless the  $D^0$  momentum is about  $1.5 \text{ GeV}/c$  or greater. With this in mind we plot in Fig. 1 the invariant-mass spectrum for  $K^\pm \pi^\mp$  combinations weighted in the manner explained above with the condition that the  $K\pi$  pair have a momentum greater than  $1.5 \text{ GeV}/c$ . A  $D^0$  peak with  $87 \pm 25$  weighted combinations, corresponding to about 250 events, is clearly visible. Its observed rms width of  $34 \text{ MeV}/c^2$  is consistent with that expected from experimental resolution. (To avoid unwieldy notation, reference to a state will always imply the sum of that state and its charge-conjugate state.)

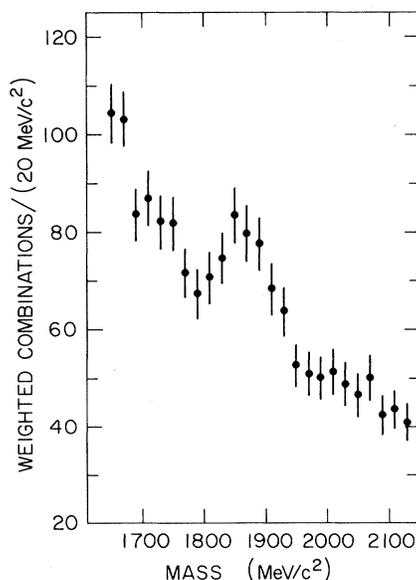


FIG. 1. Weighted invariant-mass spectrum for  $K^\pm \pi^\mp$  combinations with momenta greater than  $1.5 \text{ GeV}/c$  at  $\langle E_{c.m.} \rangle = 6.8 \text{ GeV}$ .

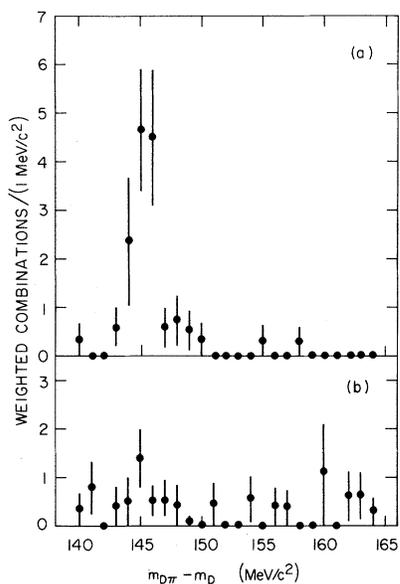


FIG. 2. Weighted  $D\pi$ - $D$  mass difference spectra for (a)  $D^0\pi^+$  and  $\bar{D}^0\pi^-$  (i.e.,  $K^\mp\pi^\pm\pi^\pm$ ) combinations and (b)  $\bar{D}^0\pi^+$  and  $D^0\pi^-$  (i.e.,  $K^\mp\pi^\pm\pi^\mp$ ) combinations.

We take  $K^-\pi^+$  combinations from Fig. 1 in the mass range 1820 to 1910  $\text{MeV}/c^2$  to be  $D^0$  candidates, combine them with an additional pion, and plot the  $D\pi$ - $D$  mass difference spectrum in Fig. 2. There is a clear  $D^{*+}$  peak in  $D^0\pi^+$  (i.e.,  $K^\mp\pi^\pm\pi^\pm$ ) combinations [Fig. 2(a)]. There is at most a small signal in  $D^0\pi^-$  (i.e.,  $K^\mp\pi^\pm\pi^\mp$ ) combinations [Fig. 2(b)] which is discussed below.

The restrictive kinematics of the  $D^{*+}$  decay give it a signal-to-background advantage over the  $D^0$  decay of two orders of magnitude, as can be seen from a comparison of Figs. 1 and 2(a). Since there is almost no background below the  $D^{*+}$  peak, the probability is high that each event in the peak is real. Thus, in Fig. 3 we gain statistically by replotting with unit weight each event which contributed at least 0.1 unit to Fig. 2.<sup>4</sup> The observed width of the  $D^{*+}$  peak in Fig. 3(a) is consistent with the calculated width expected from experimental resolution alone. At the 90% confidence level the decay (full) width of the  $D^{*+}$  is less than 2.0  $\text{MeV}/c^2$ .

Using the data from Fig. 3(a), we determine the  $D^{*+}$ - $D^0$  mass difference to be  $145.3 \pm 0.5$   $\text{MeV}/c^2$ , or equivalently the  $Q$  value of the decay to be  $5.7 \pm 0.5$   $\text{MeV}$ . The error is dominated by systematic uncertainties. Although the kinematics of this decay allow a precise determination of the  $D^{*+}$ - $D^0$  mass difference, the absolute  $D^{*+}$  mass cannot be determined from these data any

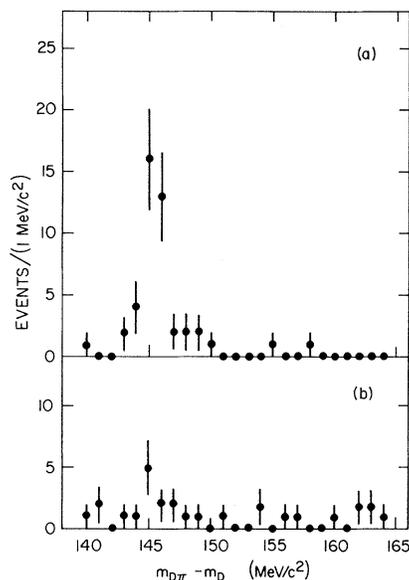


FIG. 3. Unweighted  $D\pi$ - $D$  mass difference spectra for (a)  $D^0\pi^+$  and  $\bar{D}^0\pi^-$  (i.e.,  $K^\mp\pi^\pm\pi^\pm$ ) combinations and (b)  $\bar{D}^0\pi^+$  and  $D^0\pi^-$  (i.e.,  $K^\mp\pi^\pm\pi^\mp$ ) combinations.

more accurately than the  $D^0$  mass is known. From Ref. 3, the  $D^0$  mass is  $1865 \pm 15$   $\text{MeV}/c^2$  which implies that the  $D^{*+}$  mass is  $2010 \pm 15$   $\text{MeV}/c^2$ .

Making corrections for geometrical, trigger, and time-of-flight inefficiencies and assuming isotropic production, we calculate that

$$\sigma_{D^{*+}} B\left(\frac{D^{*+} \rightarrow D^0\pi^+}{D^{*+} \rightarrow \text{all}}\right) B\left(\frac{D^0 \rightarrow K^-\pi^+}{D^0 \rightarrow \text{all}}\right) = 13 \pm 4 \text{ pb},$$

where  $\sigma_{D^{*+}}$  is the sum of cross sections for the production of  $D^{*+}$  and  $D^{*-}$  with momenta greater than 1.6  $\text{GeV}/c$  and the  $B$ 's are the indicated branching fractions. The error includes both statistical and systematic uncertainties; the latter are estimated to be 25%. Comparing Figs. 1 and 2(a) and making a correction for efficiencies we can also deduce that  $(25 \pm 9)\%$  of all  $D^0$ 's with momenta greater than 1.5  $\text{GeV}/c$  come from  $D^{*+}$  decay.

We now return to a consideration of the possible signal in  $D^0\pi^-$  near a mass difference of 145  $\text{MeV}/c^2$  [Figs. 2(b) and 3(b)]. These events could be caused by three effects: (1) double misidentification of a  $\pi$  as a  $K$  and a  $K$  as a  $\pi$ , (2)  $\Delta C = -\Delta S$  decays, which are expected to be suppressed by  $\tan^4\theta_C$  ( $\sim 2 \times 10^{-3}$ ), or (3)  $D^0$ - $\bar{D}^0$  mixing, a possibility which has received wide speculation in the literature.<sup>5</sup> To eliminate the first possibility as much as possible, we select the events from Figs. 3(a) and 3(b) within 2.5  $\text{MeV}/c^2$  of the center of

the peak and require that the ratio of the time-of-flight weights for the chosen combination to that for the combination in which the  $K$  and  $\pi$  have been interchanged be greater than 3.<sup>6</sup> Out of 38  $D^0\pi^+$  events 26 survive and out of 11  $D^0\pi^-$  events 3 survive. These latter 3 events are consistent with coming from backgrounds. We expect 1.4 events from uncorrelated combinations of particles and 0.6 events from  $K\pi$  double misidentification. Thus, at the 90% confidence level, the fraction of the time that a  $D^0$  decays as if it were a  $\bar{D}^0$  (e.g., to  $K^+\pi^-$  instead of  $K^-\pi^+$ ) is less than 16%.<sup>7</sup>

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<sup>4</sup>The threshold value of 0.1 units is not critical since backgrounds increase very slowly as the threshold value is decreased.

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<sup>6</sup>It should be noted that our  $D^0-\bar{D}^0$  discrimination comes from both the time-of-flight information and the requirement used in constructing Figs. 2 and 3 that the observed  $K\pi$  mass lie in the range 1820 to 1910 MeV/ $c^2$ .

<sup>7</sup>A similar upper limit on  $D^0-\bar{D}^0$  mixing has been deduced from a study of apparent strangeness conservation in events with an identified  $D^0$  produced in the  $E_{c.m.}$  region 3.9 to 4.6 GeV. G. Goldhaber, Bull. Am. Phys. Soc. **22**, 20(T) (1977).

## Large-Angle Neutron-Proton Elastic Scattering from 5 to 12 GeV/ $c^*$

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Neutron-proton differential cross sections have been measured with good statistics for four-momentum transfers  $0.14 < -t \leq 19.0$  (GeV/ $c$ )<sup>2</sup> at laboratory momenta ranging from 4.5 to 12.5 GeV/ $c$ . The experiment was carried out in a neutron beam at the Argonne National Laboratory zero-gradient synchrotron. These results in conjunction with previous  $n-p$  charge-exchange data provide almost complete elastic-scattering angular distributions in this momentum range.

We report measurements of neutron-proton elastic scattering which extend from small angles out to about 145° in the c.m. system. At the highest energies this corresponds to  $0.14 < -t \leq 19$  (GeV/ $c$ )<sup>2</sup>. The only previous  $n-p$  measurements above 1 GeV/ $c$  which extend to large angles were made by our group at the Lawrence Berkeley Laboratory Bevatron<sup>1</sup> some years ago. We have now extended these measurements to higher momenta and larger angles with greatly improved statistics. Our data in conjunction with the  $n-p$  charge-exchange data of Miller *et al.*<sup>2</sup> provide nearly complete elastic-scattering angular distributions in this momentum range.

A schematic diagram of the experimental layout is shown in Fig. 1. A neutron beam with a continuous spectrum of momenta up to 12.5 GeV/ $c$  was produced by steering the internal proton beam of the Argonne National Laboratory zero-gradient synchrotron onto a beryllium target. Collimators were used to define the beam and two sweeping magnets removed charged particles. Lead filters reduced the  $\gamma$ -ray contamination to a negligible value. The  $K^0$ 's and  $\bar{n}$ 's in the beam were also negligible. An intensity of  $2.3 \times 10^{12}$  circulating protons yielded  $\sim 3 \times 10^6$  neutrons over a spill length of 550 msec.

The neutron beam was incident on a liquid-hy-