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THE ARGUS COLLABORATION

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ABSTRACT

Using the ARGUS detector at DORIS II, we have obtained evidence for a new charmed resonance which decays into $D^{*\pm}(2010)\pi^{\mp}$. The observed mass and width are (2420 ± 6) MeV/c^2 and (70 ± 21) MeV/c^2 respectively. The fragmentation function is found to be hard, as expected for a state containing a leading charm quark produced by non-resonant e^+e^- annihilation.

Analogous to the excited states of mesons composed of a strange quark and lighter u or d quarks, excited states of charmed mesons are expected and explicit predictions for the masses of these states have been made[1]. In this letter, we report evidence for a new charmed meson with a mass of 2420 MeV/c^2 decaying into $D^{*+}(2010)\pi^-$.† This is the first candidate for an orbitally excited state of the $c\bar{u}$ system.

The data presented here were collected at centre-of-mass energies around 10 GeV using the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. A short description of the detector, trigger conditions and multihadron selection criteria is given in reference 2. The event sample used for this analysis consisted of 82.4 pb^{-1}, comprising 21.6 pb^{-1} on the $\Upsilon(1S)$, 36.2 pb^{-1} on the $\Upsilon(2S)$, 11.5 pb^{-1} on the $\Upsilon(4S)$ and 13.1 pb^{-1} obtained in nearby continuum or during scanning. Particle identification was made on the basis of measurements of specific ionization in the drift chamber and of time-of-flight[3].

The search for excited charm states, D^{*0}, has been made in the decay channel:

$$D^{*0} \rightarrow D^{*+}(2010)\pi^-$$

where $D^{*+}(2010) \rightarrow D^0\pi^+$, and:

$$D^0 \rightarrow K^-\pi^+ \quad (1)$$

$$D^0 \rightarrow K^-\pi^+\pi^+\pi^- \quad (2)$$

Together, these channels represent about 17% of all D^0 decays. Furthermore, the $D^{*+}(2010)$ can be easily isolated from background with good efficiency by taking advantage of the low Q value for the decay $D^{*+}(2010) \rightarrow D^0\pi^+$, which results in excellent resolution for the mass difference, $\Delta = M[D^{*+}(2010)] - M[D^0]$. Figure 1a shows the distribution of Δ for particle combinations with $M(K^-\pi^+)$ $[M(K^-\pi^+\pi^+\pi^-)]$ lying within ± 45 $[\pm 25]$ MeV/c^2 of the D^0 mass and with $x_p[D^{*+}(2010)] = p[D^{*+}(2010)]/p_{max} > 0.45$. The last requirement corresponds approximately to the region populated by D^{*0} decays with $x_p[D^{*0}] > 0.6$. For further analysis, a clean $D^{*+}(2010)$ sample was obtained by requiring, in addition to the cuts around the D^0 mass, that the mass difference, Δ, lie in the interval 144 to 147 MeV/c^2.

Mass combinations of selected $D^{*+}(2010)$'s with all other π^- candidates in the event were then studied. Additional cuts were made on the scaled momentum of the $D^{*+}(2010)\pi^-$ system, requiring $x_p[D^{*0}] > 0.6$, and on the angle, θ, between the $D^{*+}(2010)\pi^-$ line of flight and the $D^{*+}(2010)$ momentum vector in the $D^{*+}(2010)\pi^-$ rest frame, requiring $\cos\theta < 0$. The first cut is motivated by the nature of charm quark fragmentation, which results in a hard momentum spectrum for the leading heavy meson[4], while light hadronic background is concentrated at lower x_p. The second cut reduces background which peaks at forward angles, due to the combination of the $D^{*+}(2010)$ with random low momentum pions.

The mass difference spectrum, $\Delta^* = M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, for combinations passing these cuts, is shown in figure 2a. A prominent peak is seen around 410 MeV. A Breit-Wigner for the signal, plus a threshold factor times a second order polynomial for the background, were fitted to the mass difference distribution, yielding the results listed in Table 1. All sources of systematic error, including that introduced by the assumed mass dependence of the background, are negligible in comparison with the statistical uncertainties. Monte Carlo study shows the detector resolution to be 15 MeV/c^2 in this mass region, while the observed width is much larger, indicating that this new state decays strongly. The statistical significance of the enhancement is 3.9 standard deviations. In the following we refer to this state as the $D^{*0}(2420)$. It is now clear that at least part of the enhancement near 2.44 GeV/c^2 in the recoil spectrum to $D^0 \rightarrow K^-\pi^+$ reported by MARK II at SPEAR[5] was due to production of this excited charm state.

Supporting evidence for the observation was obtained using a third D^0 decay channel:

$$D^0 \rightarrow K^-\pi^+(\pi^0) \quad (3)$$

When the usual cut on the mass difference, $M(K^-\pi^+\pi^+) - M(K^-\pi^+)$, is applied, this channel produces a satellite peak in $K^-\pi^+$ mass distributions, shifted to lower masses by the missing π^0 [6]. Figure 1b shows the mass difference distribution for 1540 MeV/c^2 $< M(K^-\pi^+) <$ 1700 MeV/c^2, where again $x_p[D^{*+}(2010)] > 0.45$ was required. Events containing $D^{*+}(2010)$ candidates decaying into this channel were selected by requiring, in addition to the noted restriction on $M(K^-\pi^+)$, that $\Delta = M(K^-\pi^+\pi^+) - M(K^-\pi^+) < 152$ MeV/c^2. The momentum and decay angle cuts described above were then applied to the $D^{*+}(2010)\pi^-$ combinations. The resulting mass difference plot for Δ^* is shown in figure 2b. A fit to this distribution using a Breit-Wigner plus background polynomial yields the values listed in Table 1. The effect of the missing π^0 increases the detector resolution to 25 MeV/c^2, but this is still smaller than the natural width of the state. Monte Carlo studies show that there is negligible shift in the mass difference due to the missing π^0. Masses and widths for the three channels are

†References in this paper to a specific charged state are to be interpreted as implying the charge conjugate state also.

consistent: the combined significance of the effect is 4.9 standard deviations (figure 3).

Two different studies have been made in order to confirm that the enhancement is not an artifact of the employed kinematic selection criteria. These were made using (a) a sideband of the $D^{*+}(2010)$, and (b) wrong charge combinations, that is $D^{*+}(2010)\pi^{+}$. No significant enhancement was found in either approach.

The fragmentation function for the $D^{*0}(2420)$ was extracted by fitting a Breit-Wigner plus a background polynomial to mass distributions of events selected in different $x_p[D^{*0}(2420)]$ bins with the same $\cos\theta < 0$ cut. Only the channels 1 and 2 were used for this purpose. The result, corrected for acceptance, is shown in figure 4. Also shown are the results of fits made with two commonly used theoretical models, that of Peterson et al.[7] where:

$$s\frac{d\sigma}{dx_p} \sim \frac{1}{x_p\left(1-\frac{1}{x_p}-\frac{\epsilon}{1-x_p}\right)^2} \qquad \text{(I)}$$

and that of Kartvelishvili et al.[8] where:

$$s\frac{d\sigma}{dx_p} \sim x_p{}^{\alpha}\,(1-x_p) \qquad \text{(II)}$$

The fitted values for the parameters of the models were $\epsilon = 0.12 \pm 0.05$ with χ^2 probability of 0.7 (1 degree of freedom), and $\alpha = 1.4 \pm 0.8$ with χ^2 probability of 0.12. No attempt has been made to adjust these results for the effects of photon or gluon initial state radiation. Either form describes the distribution adequately.

The production cross section for the $D^*(2420)$ meson decaying to $D^{*+}(2010)\pi^-$ has been estimated by comparison with the rate observed for $D^{*+}(2010)$ production. The efficiency for observing the decay $D^{*0}(2420) \to D^{*+}(2010)\pi^-$, where the $D^{*+}(2010)$ decays through channels 1 and 2, and with the requirement that $\cos\theta < 0$ and $x_p[D^{*0}(2420)] > 0.6$, was found to be 0.107 ± 0.032, using a detector Monte Carlo study. The error is dominated by the uncertainty in extrapolating the observed cross section to $x_p[D^{*0}(2420)] = 0$.

The total number of observed $D^{*+}(2010)$ decays to the same channels with $x_p[D^{*+}(2010)] > 0.45$ is 1010 ± 40 events. Correcting this number also for the unseen low $x_p[D^{*+}(2010)]$ portion of the fragmentation distribution and for acceptance, we conclude that $(24^{+8}_{-6} \pm 8)\%$ of observed $D^{*+}(2010)$ are produced from $D^{*0}(2420)$, where the first error is statistical and the second systematic.

The production cross section, $\sigma[D^{*0}(2420)]$, is estimated by correcting for the neutral decay channel $D^{*0}(2420) \to D^{*0}(2008)\pi^0$ using isospin symmetry, so that:

$$\sigma[D^{*0}(2420)] \cdot Br[D^{*0}(2420) \to D^*\pi] = 0.24 \cdot \sigma[D^{*+}(2010)] \cdot \frac{3}{2}$$

Based on results quoted in references 3,9 and 10, we calculate that $\sigma[D^{*+}(2010)] = (940 \pm 150 \pm 270)$ pb at $\sqrt{s} \approx 10$ GeV. Using this value, we find that $\sigma[D^{*0}(2420)] \cdot BR[D^{*0}(2420) \to D^*\pi] = (340^{+190}_{-180})$ pb.

The resonance reported here is most likely one of the 1P states of c and ū quarks[1], since these are expected to be the lowest lying of the orbitally excited charmed states and would be more easily produced than higher angular momentum states in e^+e^- annihilation. The possible assignments are $^3P_J(0^+,\ 1^+,\ 2^+)$ and $^1P_1(1^+)$. As in the case of excited strange mesons, the $^3P_1$ and $^1P_1$ states can, and probably do mix, complicating predictions of masses and widths. All model calculations[1] have predicted P states lying within 100 MeV/c^2 of our observed value. Because the 0^+ state cannot decay strongly to a vector and a pseudoscalar meson owing to parity conservation, this assignment can be excluded. Of course the possibility exists that more than one resonance contributes to the observed signal, because the mass splittings of some of these states are less than their natural widths.

In summary, we have observed a resonance in the $D^{*+}(2010)\pi^-$ invariant mass distribution which we associate with a P state of c and ū quarks. Its production and decay characteristics support some of the theoretical predictions. The mass of the object is (2420 ± 6) MeV/c^2, corresponding to a mass difference $\Delta M = M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$ of (410 ± 6) MeV/c^2, and the width is (70 ± 21) MeV/c^2.

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TABLE 1. Properties of $D^{*0}(2420)$ determined from fits to the distribution of mass difference, $M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$.

Channel	$D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^0$	Combined Result
Mass difference [MeV/c^2]	411 ± 7	410 ± 11	410 ± 6
$M[D^{*0}(2420)]$ [MeV/c^2]	2421 ± 7	2420 ± 11	2420 ± 6
Full width Γ [MeV/c^2]	64 ± 26	75 ± 36	70 ± 21
Number of events	82^{+28}_{-21}	52^{+24}_{-18}	135^{+34}_{-29}
χ^2/degree of freedom	20.4/25	13.2/25	16.7/25

FIGURE CAPTIONS

Figure 1a Distribution of the mass difference, Δ, for channels 1 and 2, with $x_p[D^{*+}(2010)] > 0.45$, not corrected for acceptance.

Figure 1b Distribution of the mass difference, Δ, for channel 3, with $x_p[D^{*+}(2010)] > 0.45$, not corrected for acceptance.

Figure 2a Distribution of the mass difference, $M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, with $x_p[D^{*0}(2420)] > 0.6$ and $\cos\theta < 0$ for channels 1 and 2.

Figure 2b Distribution of the mass difference, $M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, with $x_p[D^{*0}(2420)] > 0.6$ and $\cos\theta < 0$ for channel 3.

Figure 3 Distribution of the mass difference, $\Delta^* = M[D^{*+}(2010)\pi^-] - M[D^{*+}(2010)]$, for the combined result shown in figures 2a and b.

Figure 4 Number of $D^{*0}(2420)$ events in channels 1 and 2 as a function of $x_p[D^{*0}(2420)]$, corrected for acceptance. The error bars are statistical only. The solid curve is the result of a fit to the data using expression I (Peterson), and the dashed curve using expression II (Kartvelishvili). The plot has been normalized so that the integral of the Peterson fit is unity.

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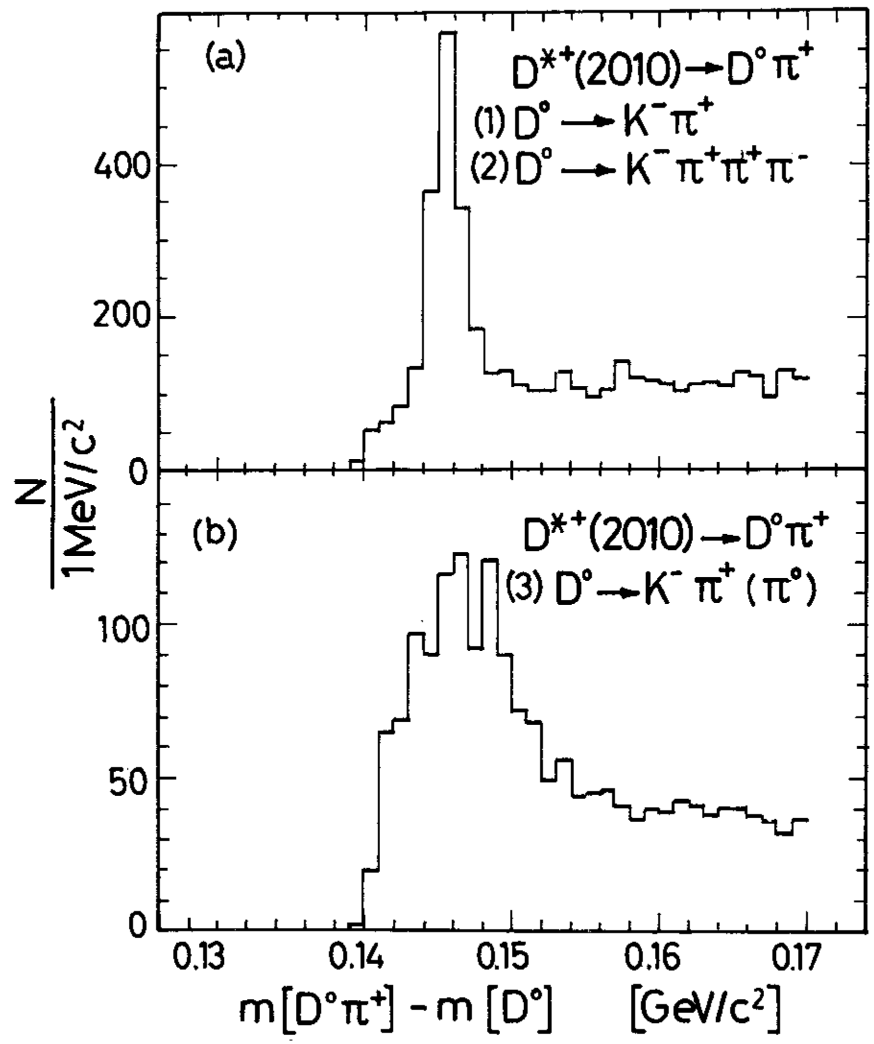

Figure 1

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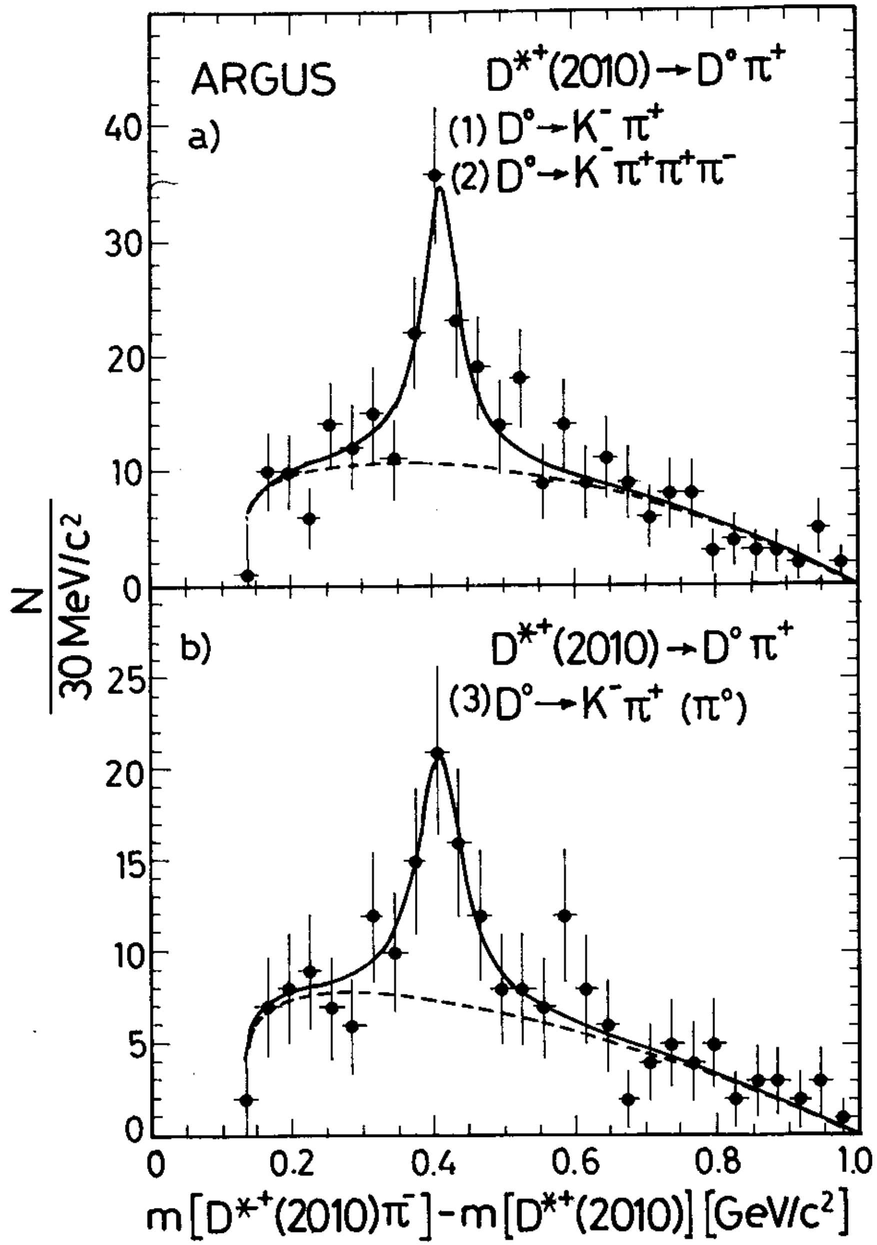

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Figure 2

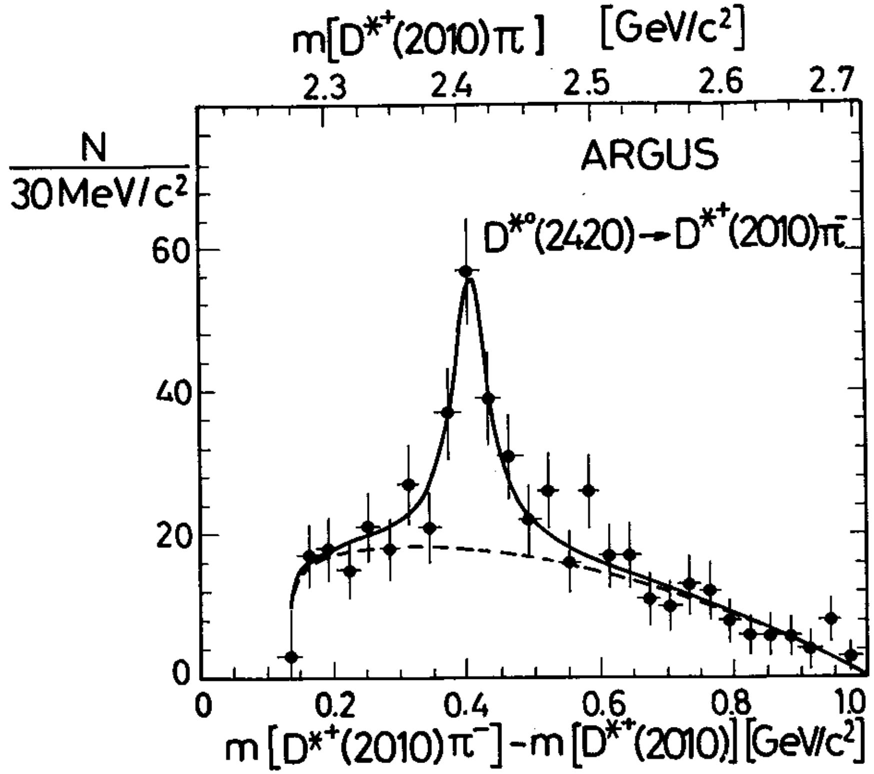

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Figure 3

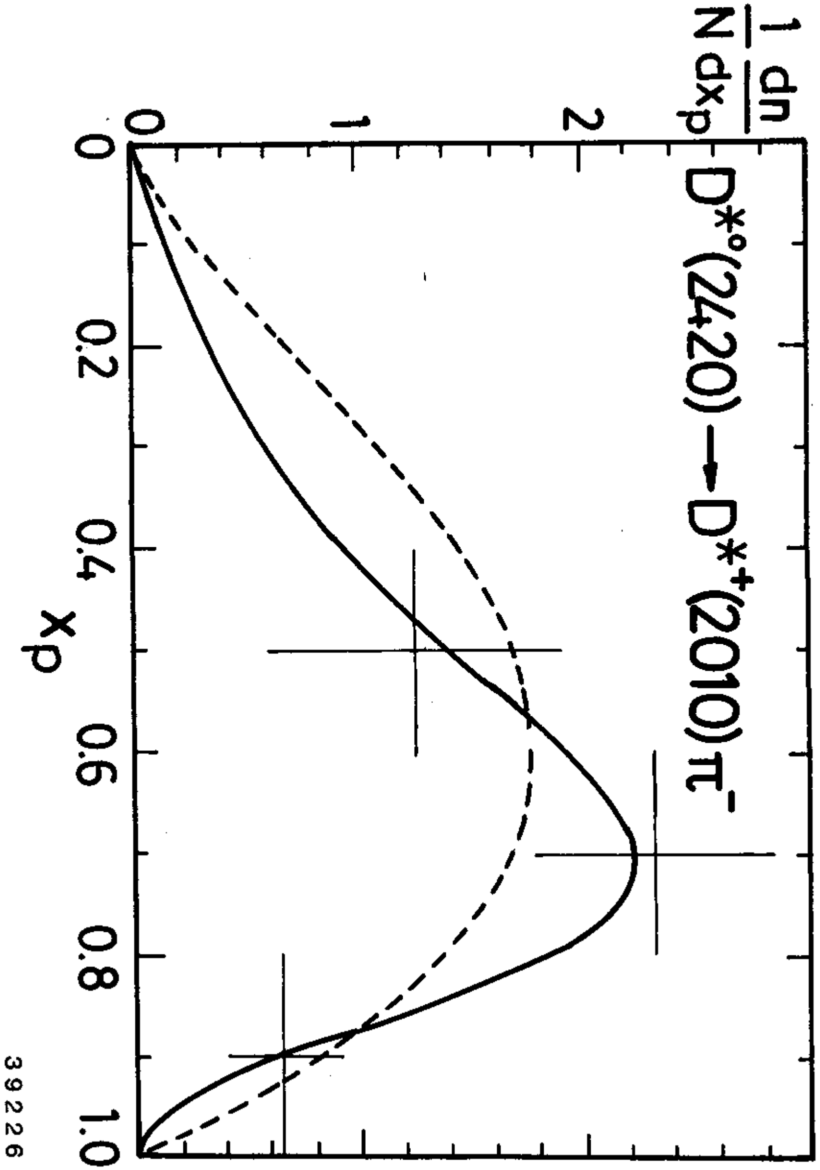

Figure 4

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