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e^+e^--PRODUCTION OF CHARMED PARTICLES AT THE SPEAR MAGNETIC DETECTOR*

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I. INTRODUCTION

In this talk we will present some recent experimental results on charmed particles produced in e^+e^- annihilation. These results have been obtained with the SLAC-LBL magnetic detector MARK I at SPEAR. The detector is shown in Fig. 1.

We will first discuss in Section II some new properties of the charmed mesons D^o and D^+. We have studied them at the c.m. energy of 3.772 GeV where D^o and D^+ are copiously produced in the decay products of the resonance $\psi(3772)$ (see Fig. 2 for a plot of $R = \sigma_{had}/\sigma_{\mu\mu}$ showing the $\psi(3772)$ resonance). In Section III we will present some preliminary results on a search for the charmed meson F in $e^+e^- \to F^+F^-$. These results have been obtained at a c.m. energy of 4.161 GeV (see Fig. 2). Finally, in order to find an indication of production of charmed baryons we will look (Section IV) in the inclusive yields of antiprotons and of lambdas as a function of the c.m. energy (see Fig. 2).

Charmed particle decays involving leptons among the decay products will not be discussed here because they are presented by P. Lecomte and W. Slater at this conference. The results presented here are based on data collections obtained by two different collaborations using the MARK I detector: the SLAC-LBL collaboration[1] (experiment SP17, 1974 until June 1976), and the SLAC-LBL-Hawaii-Northwestern-Stanford collaboration[2] (experiment SP26, July 1976 until June 1977).

II. SOME PROPERTIES OF D^o AND D^+ MESONS

Properties of D mesons were studied in events produced at the $\psi(3772)$ resonance. The c.m. energy 3.772 GeV is slightly above the thresholds of 3.726 GeV for $e^+e^- \to D^o\bar{D}^o$ and of 3.736 GeV for $e^+e^- \to D^+D^-$. On the other hand the $\psi(3772)$ lies below the thresholds of $D\bar{D}^*$ (3.869 GeV) and $D\bar{D}\pi$ (3.861 GeV) production. Thus in the region of the $\psi(3772)$ resonance, D mesons can only be produced in the reaction $e^+e^- \to D\bar{D}$. The results given in this section are based on the analysis of about 25,000 hadronic events collected at $E_{c.m.} \approx$ 3.772 GeV with an integrated luminosity of 1.14 pb^{-1}.

A. MASSES OF D^o AND D^+

In the reaction $e^+e^- \to D\bar{D}$, two D mesons of equal masses are produced and therefore the energy of each D meson equals the beam energy $E_b = \frac{1}{2} E_{c.m.}$. The mass of the D meson can be calculated as

$$M = \sqrt{E_b^2 - p^2} \quad (1)$$

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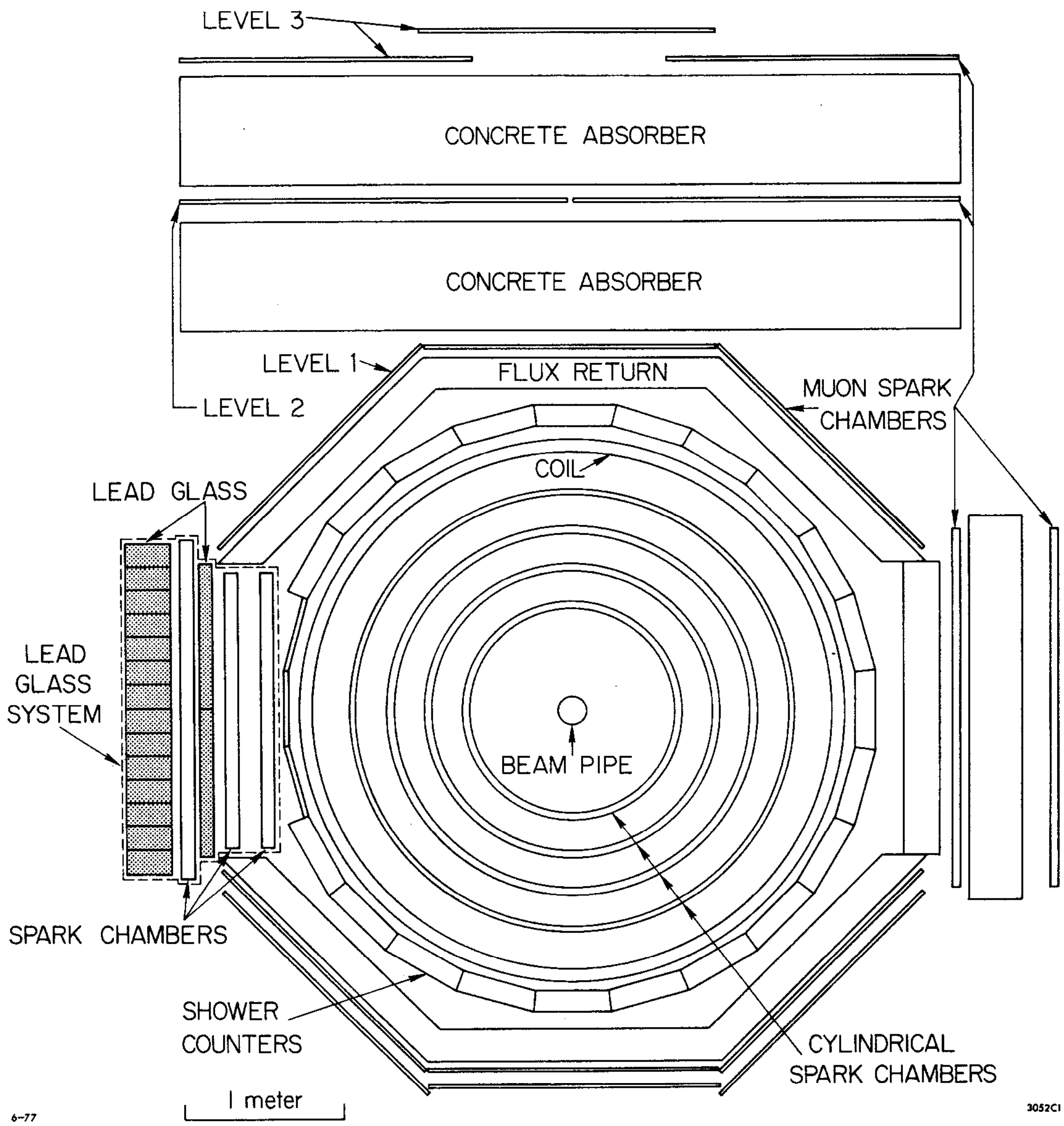

Fig. 1. The MARK I magnetic detector with the lead glass wall addition in a view along the beam line. The two proportional chambers around the beam pipe and the trigger counters inside the solenoid coil are not shown.

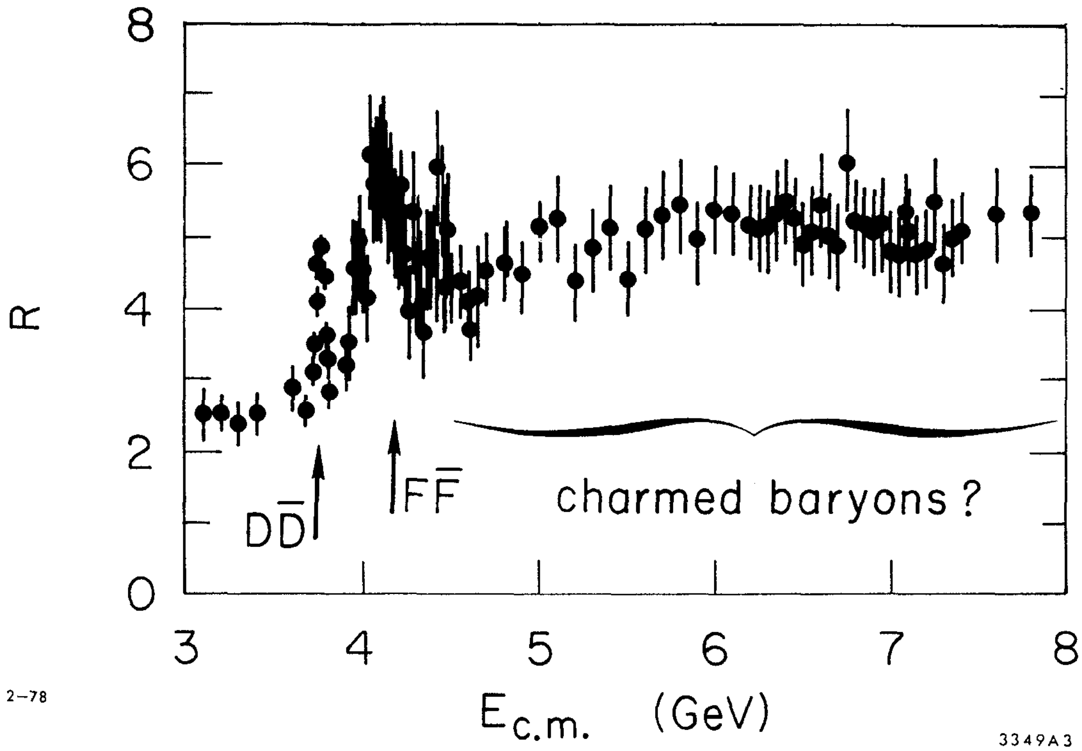

Fig. 2. $R = \sigma_{had} / \sigma_{\mu\mu}$ as function of the center of mass energy. The large peaks due to ψ and ψ' have been omitted.

where p is the momentum of the decay products. The beam energy is known very accurately; it has an rms spread of about 1 MeV which is due to quantum fluctuations in synchrotron radiation. For $D\bar{D}$ production at $E_{c.m.}$= 3.772 GeV the momentum p of the decay products is small compared to E_b($p^2 \approx 0.080$ GeV^2 compared to $E_b^2 \approx 3.557$ GeV^2). Therefore the uncertainty in the measured value of p has only a small effect on the uncertainty of the mass M. We measure M with an rms resolution of about 3 MeV. This resolution is a factor of 5 to 10 better than in the case when the D energy is not constrained to the beam energy.

In the MARK I detector charged kaons are identified by time-of-flight measurements[3,4]. Neutral kaons decaying into $\pi^+\pi^-$ are identified by measurement of the $\pi^+\pi^-$ invariant mass, reconstruction of the $\pi^+\pi^-$ vertex and by appropriate cuts on the vertex position.[5] For each particle combination, with a particle type assigned to each track, we require that the total energy E of the combination agrees with E_b to within 50 MeV. The invariant mass is then calculated from equ. (1) using the constraint $E = E_b$.

Fig. 3 shows the distribution of the invariant masses for five different decay modes of charged and neutral D mesons. Each of the five decay modes shows a clear D signal due to the reactions $e^+e^- \to D^o\bar{D}^o$ or $e^+e^- \to D^+D^-$. The mass difference between D^+ and D^o of about 5 MeV is clearly visible. The following mass values for the D^o and D^+ were obtained by a fit to the sum of all observed modes (see Fig. 4)[6]:

$$M\ (D^o) = 1863.3 \pm 0.9 \text{ MeV},$$

and

$$M\ (D^+) = 1868.3 \pm 0.9 \text{ MeV}.$$

The quoted uncertainties in the mass determination include statistical contributions (0.4 MeV) and systematics due to the momentum calibration (0.5 MeV) and the long term stability of the beam energy (0.5 MeV). Since the uncertainty due to the absolute energy calibration of SPEAR (2.4 MeV) is not included in the quoted errors, the D mass values are relative to the mass 3095.0 MeV of the ψ. The $D^+ - D^o$ mass difference is determined more accurately than the individual D masses because several systematic errors cancel when calculating the difference. We find $M(D^+) - M(D^o) = 5.0 \pm 0.8$ MeV. Different theoretical estimates vary between 2 and 15 MeV.

Using previous measurements from Refs. 7,8 we obtain for the D^* masses:

$$M\ (D^{*o}) = 2006.0 \pm 1.5 \text{ MeV},$$
$$M\ (D^{*+}) = 2008.6 \pm 1.0 \text{ MeV},$$

and a mass difference of $M(D^{*+}) - M(D^{*o}) = 2.6 \pm 1.8$ MeV. Thus all D and D^* masses are known with an uncertainty of 1.5 MeV or less.

The decay mode $D^o \to K^-\pi^+\pi^o$ has been observed[9] in events at 3.772 GeV c.m. energy where the $\pi^o \to \gamma\gamma$ decay was detected in the "lead glass wall" of the MARK I detector (see Fig. 1). The mass distribution in Fig. 5 shows a signal of 7.3 events above an estimated background of 1.7 events at the mass of the D^o.

For each of the observed D^o and D^+ decay modes the product $\sigma \cdot B$ is given in Table I where σ is the inclusive cross section for production of the corresponding D and $\bar{D}$ at 3.772 GeV and B is the corresponding branching ratio (e.g.$\sigma(D^o,\bar{D}^o)\cdot B(D^o \to K^-\pi^+)$ for the mode $K^-\pi^+$).

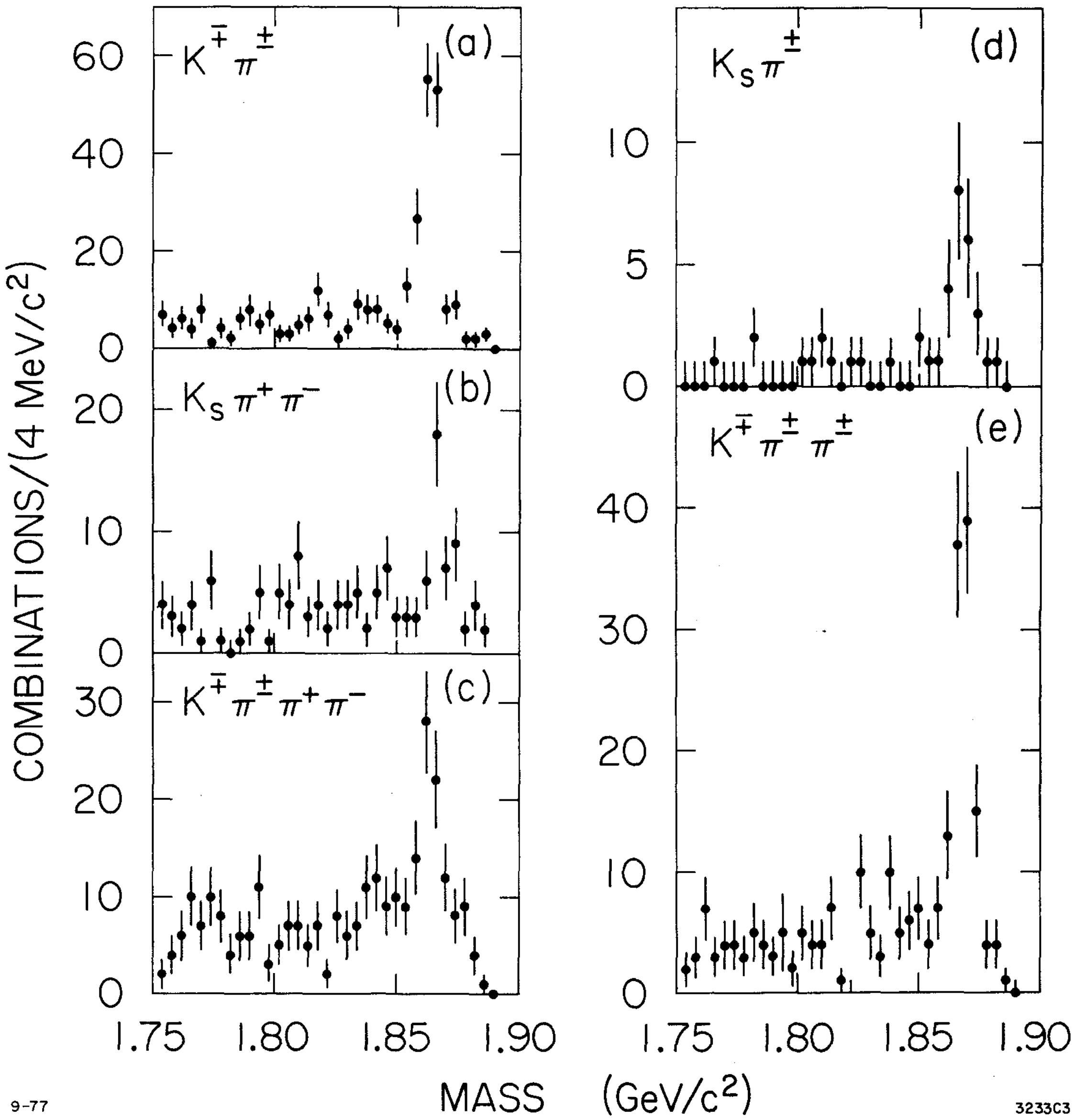

Fig. 3. Invariant mass spectra for five D decay modes at the $\psi(3772)$

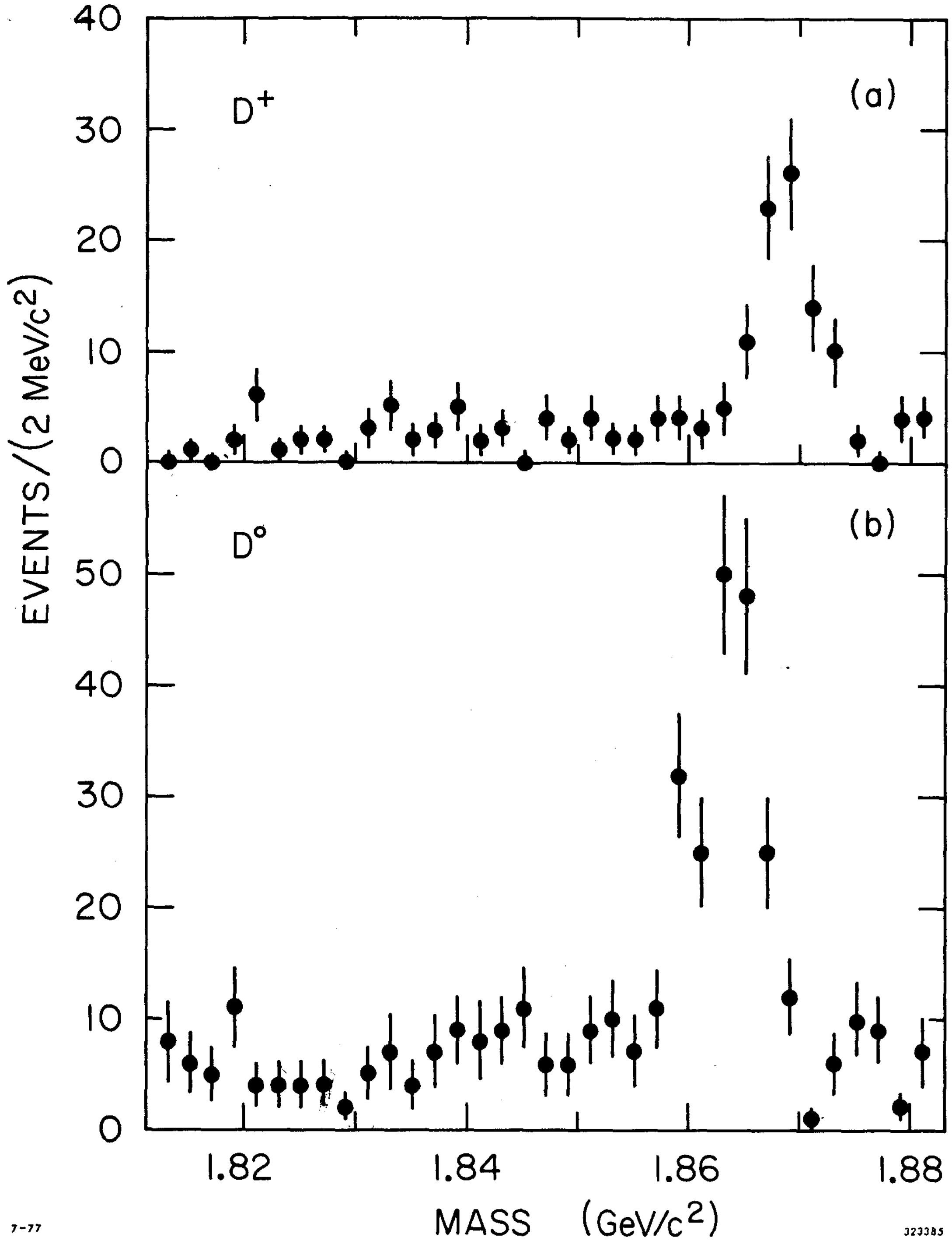

Fig. 4. Invariant mass spectra for (a) $D^+ \to \bar{K}^o\pi^+$, $K^-\pi^+\pi^+$ and (b) $D^o \to K^-\pi^+$, $\bar{K}^o\pi^+\pi^-$, $K^-\pi^+\pi^+\pi^-$ at the $\psi(3772)$. Charge conjugated modes are included.

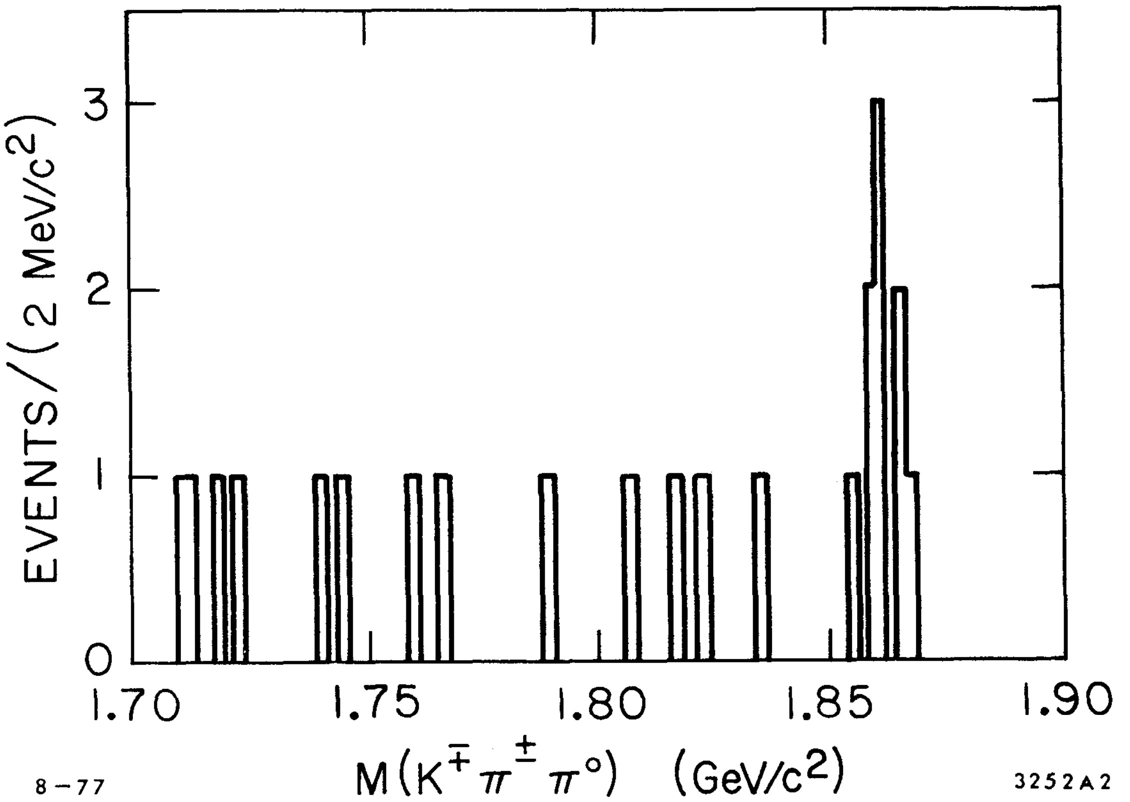

Fig. 5. Invariant mass spectrum for $D^o \rightarrow K^-\pi^+\pi^o$ and its charge conjugated mode at the $\psi(3772)$.

TABLE I Inclusive cross section times branching ratio, $\sigma \cdot B$, and absolute branching ratio B for various hadronic D decay modes at 3.772 GeV c.m. energy. Charge conjugated modes are included.

decay mode	$\sigma \cdot B$ (nb)	B (%)
$D^o \to K^-\pi^+$	0.25 ± 0.05	2.2 ± 0.6
$\bar{K}^o\pi^+\pi^-$	0.46 ± 0.12	4.0 ± 1.3
$K^-\pi^+\pi^+\pi^-$	0.36 ± 0.10	3.2 ± 1.1
$K^-\pi^+\pi^o$	1.4 ± 0.6	12 ± 6
$D^+ \to \bar{K}^o\pi^+$	0.14 ± 0.05	1.5 ± 0.6
$K^-\pi^+\pi^+$	0.36 ± 0.05	3.9 ± 1.0

B. ABSOLUTE BRANCHING RATIOS FOR D DECAYS

Analysis of production and decay of D mesons at the $\psi(3772)$ allows a determination of absolute branching ratios for D decays. We use the measured values of $\sigma \cdot B$ at the $\psi(3772)$ given in Table I for each observed decay mode, and the total cross section[10] at the $\psi(3772)$. In addition we make two reasonable assumptions to derive the inclusive cross sections $\sigma(D^o,\bar{D}^o)$ and $\sigma(D^+,D^-)$ from the total cross section of the $\psi(3772)$:

a) The $\psi(3772)$ decays completely into $D\bar{D}$ pairs. This assumption can explain the observation that the total width of the $\psi(3772)$ is about 100 times larger than the total width of the ψ' (28 ± 5 MeV compared to 228 ± 56 keV) because the $\psi(3772)$ is energetically above the $D\bar{D}$ threshold while the ψ' is lying below it.

b) The $\psi(3772)$ is a state of definite isospin, either 0 or 1, which are the only possible values for the decay into a $D\bar{D}$ pair.

After phase space corrections for the different masses of D^o and D^+ we find $B(\psi(3772) \to D^o\bar{D}^o) = 0.56 \pm 0.03$, $B(\psi(3772) \to D^+D^-) = 0.44 \pm 0.03$, and the inclusive D, $\bar{D}$ cross sections $\sigma(D^o, \bar{D}^o) = 11.5 \pm 2.5$ nb, $\sigma(D^+, D^-) = 9.1 \pm 2.0$ nb at $E_{c.m.} \approx 3.772$ GeV.[11]

Using these cross sections the absolute branching ratios for D decays given in Table I are obtained. It should be noted that only about 20% of the D^o decays and about 5% of the D^+ decays have been accounted for in Table I. Except for semileptonic decays[12] the unidentified decays have not been detected so far.

III. SEARCH FOR F MESONS

While production of D mesons in e^+e^- annihilation has been observed for more than a year in several experiments, production of the strange charmed meson F has not been conclusively established so far. The F^+, a $c\bar{s}$ isosinglet, may decay into η + pions or η'+ pions or $K\bar{K}$ + pions.

Some evidence for the production of F and F^* has been reported recently[13] by the DASP group who found 5 events at a c.m. energy of 4.4 GeV. These events show the subsequent decays $F^* \rightarrow F\gamma$ and $F \rightarrow \eta\pi$, and they fit both hypotheses $e^+e^- \rightarrow F\overline{F}^*$ and $F^*\overline{F}^*$. The F mass was determined to be 2039 ± 60 MeV, the F^* mass 2140 ± 60 MeV.

In this section we discuss some preliminary results on the search for F production in the MARK I data. At a c.m. energy of 4.161 GeV we studied about 16,000 hadronic events with 3 or more prongs, collected with an integrated luminosity of 830 nb^{-1}. The MARK I detector identifies charged kaons in a relatively large solid angle (about 60% of 4π) with good π/K separation (better than 3 standard deviations for momenta up to 800 MeV). The technique to identify neutral kaons has been described in Section II for the case of the D mesons. The energy of the F meson was constrained to the beam energy by the same technique which was used for D mesons. This results in a mass resolution of about 3 MeV. We selected particle combinations for which the measured energy equals the beam energy within 60 MeV.

The following particle combinations $K\overline{K}$ + pions were observed (with an estimated value for the acceptance given in parentheses): $K^+K^-\pi^\pm$ (about 15% acceptance), $K^+K^-\pi^+\pi^-\pi^\pm$ (about 5% acceptance) and $K^\pm K^o$ (about 5% acceptance). All other combinations involving $K\overline{K}$ + pions have an acceptance of less than 2% and will not be considered here. Each of the above three decay modes shows some events above background at an invariant mass of about 2040 MeV.

Fig. 6(a) gives the combined distribution for the modes $K^+K^-\pi^\pm$, $K^+K^-\pi^+\pi^-\pi^\pm$ and $K^\pm K^o$. In the mass range 2036-2044 MeV an accumulation of 23 events is seen with a background of 7.3 events estimated from the mass distribution outside the range 2036-2044 MeV. A conservative estimate for the significance of the observed enhancement is obtained by applying binomial statistics to the whole mass distribution in Fig. 6(a). The probability that an accumulation of 23 (or more) events at this mass is a statistical fluctuation is about $2 \cdot 10^{-5}$, which corresponds to 5.0 standard deviations in binomial statistics (or 4.1 standard deviations in gaussian statistics).

Since in the conventional quark model the F^+ meson is not allowed to decay into $K^+K^+\pi^-$, one would expect no signal in the $K^+K^+\pi^-$ mass distribution. Indeed, this distribution, shown in Fig. 6(b) has no structure.

Next we want to show that though $D^\pm$ and $D^{*\pm}$ mesons are produced at a c.m. energy of 4.161 GeV, the observed signal at 2040 MeV cannot be due to decay of $D^\pm$ where one of the $\pi^\pm$ in the decay products of the $D^\pm$ is misidentified as $K^\pm$ by the time-of-flight system. A simple calculation of the constrained mass $M = \sqrt{E_b^2 - p^2}$ gives the following results:

a) $D^\pm$ mesons produced in $e^+e^- \rightarrow D^+D^-$ show up as a sharp peak at a mass M = 1868.3 MeV.

b) $D^\pm$ mesons produced in $e^+e^- \rightarrow D^+D^{*-}$ or D^-D^{*+} show up at M = 1939 MeV (if they are not decay products of the D^*) or as a broad bump in a mass range between 1923 and 1954 MeV (if they are decay products of the D^*).

c) $D^\pm$ mesons produced in $e^+e^- \rightarrow D^*\overline{D}^*$ (with $D^* \rightarrow D\pi$) show up as a broad bump in a mass range between 2008 and 2027 MeV.

Thus production of D and D^* cannot fake a signal at 2040 MeV.

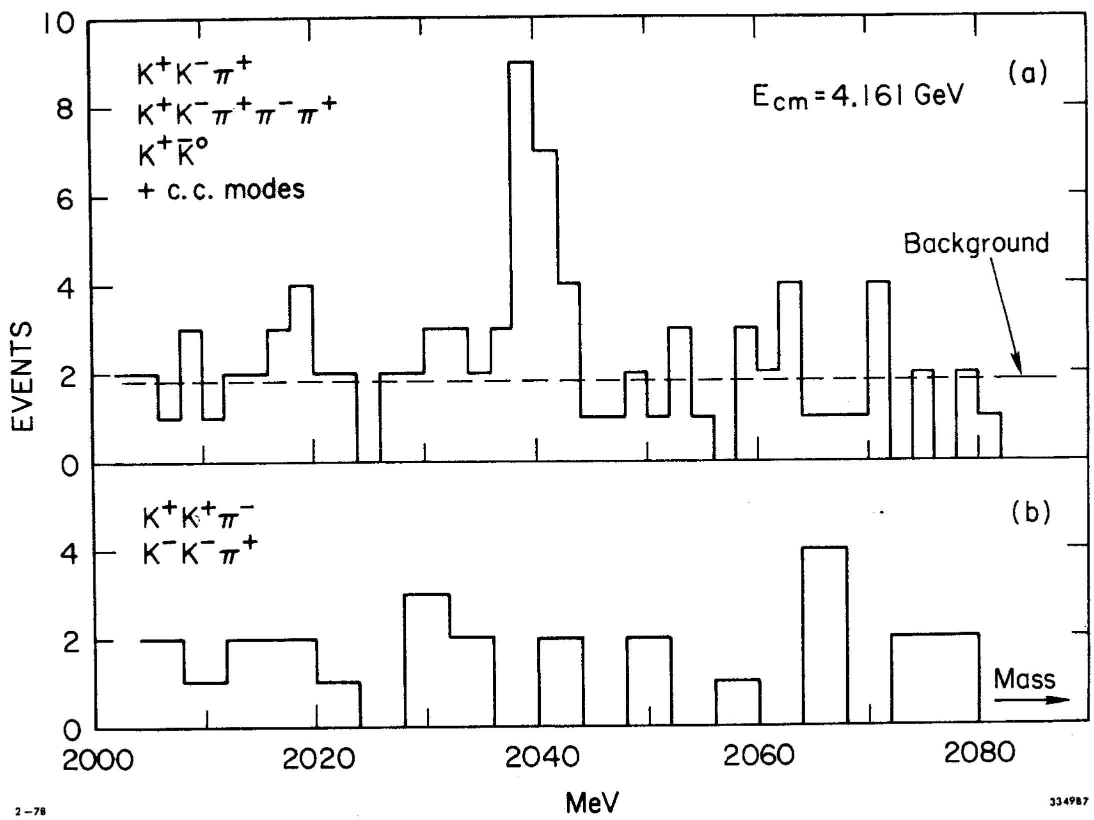

Fig. 6. Preliminary invariant mass spectra at 4.161 GeV center of mass energy for the combinations (a) $K^+K^-\pi^+$, $K^+K^-\pi^+\pi^-\pi^+$, $K^+\bar{K}^0$; and (b) $K^+K^+\pi^-$. Charge conjugated modes are included. Particle combinations have a time-of-flight probability larger than 0.1.

A fit of Gaussian shape for the F meson, plus a constant background to the mass distribution in Fig. 6(a) results in a mass of 2039.5 ± 1.0 MeV for the F. The error includes statistical and systematic effects as mentioned in the case of the D mesons. The rms width of about 3 MeV is consistent with the expected mass resolution.

The following arguments show that the reaction $e^+e^- \to F^+F^-$ is the only mechanism of F production which fits our data:

a) The F is produced in a two-body final state where the other particle has a small width ($\lesssim$ 3 MeV), otherwise the plot of the constrained mass would not show a narrow peak.

b) The requirement $|E - E_b| \leq 60$ MeV for the energy E of the F excludes the reaction $e^+e^- \to F\,\overline{F}^*$.

We conclude that our preliminary results indicate F production in $e^+e^- \to F^+F^-$ at a c.m. energy of 4.161 GeV where the F^+ decays into $K^+K^-\pi^-$, $K^+K^-\pi^+\pi^-\pi^+$, $K^+\overline{K}^o$. The signal has a probability of about $2 \cdot 10^{-5}$ to be a statistical fluctuation. The analysis of these data will be continued, but it is certain that new data are required before detailed questions concerning branching ratios or spin or parity can be studied.

IV. SEARCH FOR CHARMED BARYONS

Experimentally little is known about charmed baryons. The lowest mass charmed baryon state is believed to be the Λ_c, a udc isosinglet. Among its possible decays are the modes: Λ + pions, Σ + pions, pK + pions. Quark model calculations predict a mass of about 2.25 GeV for the Λ_c.

Two experiments show evidence for the decay $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$ or its antistate $\overline{\Lambda}_c \to \overline{\Lambda}\pi^-\pi^-\pi^+$. The first experiment reports one bubble chamber event interpreted as $\nu p \to \mu^-\Lambda\pi^+\pi^+\pi^+\pi^-$.[14] In this event the $\Delta S = \Delta Q$ rule is violated as expected for a charmed baryon decay. One of the $\Lambda\pi^+\pi^+\pi^-$ combinations has a mass of 2.26 GeV. The other evidence comes from a photoproduction experiment[15] at high energies where a clear mass peak at 2260 ± 10 MeV with a width less that 75 MeV was found in the $\overline{\Lambda}\pi^-\pi^-\pi^+$ combination. It has been interpreted as coming from $\overline{\Lambda}_c$ decay.

In e^+e^- annihilation no peak in invariant mass spectra corresponding to charmed baryons has been observed so far. In this section we report an indication of charmed baryon production in e^+e^- annihilation seen in the data of MARK I.[16] This indication comes from a sharp rise in the inclusive production of ordinary baryons at c.m. energies between 4.4 and 5.0 GeV.

We studied the inclusive cross section for production of $\overline{p}$ and of Λ and $\overline{\Lambda}$ at c.m. energies between 4.0 and 7.8 GeV. The data sample consists of about 280,000 hadronic events with 3 or more prongs at c.m. energies between 4.0 and 7.8 GeV (integrated luminosity 36 pb^{-1}).

For the inclusive $\overline{p}$ cross section, the antiprotons were identified by the time-of-flight system which allows a separation between protons and kaons of better than three standard deviations for momenta less than 1.0 GeV. For larger momenta, corrections for particle misidentifications were applied. The inclusive nucleon cross section was determined for antiprotons only because beam-gas interactions in the storage ring result in a large background for protons.

In Fig. 7(a) the quantity $R(p+\overline{p}) = 2\sigma(\overline{p})/\sigma_{\mu\mu}$ is plotted where the factor 2 is to account for protons. $R(p+\overline{p})$ increases about a factor of two from a value of about 0.3 to 0.6 at c.m. energies between 4.4 and 5.0 GeV. Such a rise in the $p+\overline{p}$ yield can be explained by production of charmed baryons since they decay into ordinary baryons like nucleons and lambdas. In fact, the thresholds for the production of the lowest mass charmed baryons $\Lambda_c\overline{\Lambda}_c$, $\Sigma_c\overline{\Sigma}_c$, $\Sigma_c\overline{\Sigma}^*_c$, $\Sigma^*_c\overline{\Sigma}^*_c$) are expected to lie between 4.5 and 5 GeV.

To identify Λ and $\overline{\Lambda}$, $p\pi^-$ and $\overline{p}\pi^+$ combinations were selected using the time-of-flight. The Λ vertex was reconstructed and appropriate cuts on its position were applied. The amount of Λ and $\overline{\Lambda}$ was then determined from the invariant mass distribution. About 1050 Λ and $\overline{\Lambda}$ were found at c.m. energies above 4 GeV. The quantity $R(\Lambda+\overline{\Lambda}) = \sigma(\Lambda, \overline{\Lambda})/\sigma_{\mu\mu}$ is shown in Fig. 7(b) as a function of the c.m. energy. The larger errors in the $\Lambda + \overline{\Lambda}$ yield make it impossible to establish its detailed energy dependence, but Figs. 7(a,b) show that $R(\Lambda+\overline{\Lambda})$ is about 10% to 15% of $R(p+\overline{p})$ at all energies.

Thus, if the rise in the $\overline{p}$ yield is explained by the onset of charmed baryon production between 4.4 and 5.0 GeV c.m. energy, the small ratio of $\Lambda+\overline{\Lambda}/p+\overline{p}$ indicates that charmed baryons are less likely to decay into final states containing lambdas than final states containing nucleons and kaons.

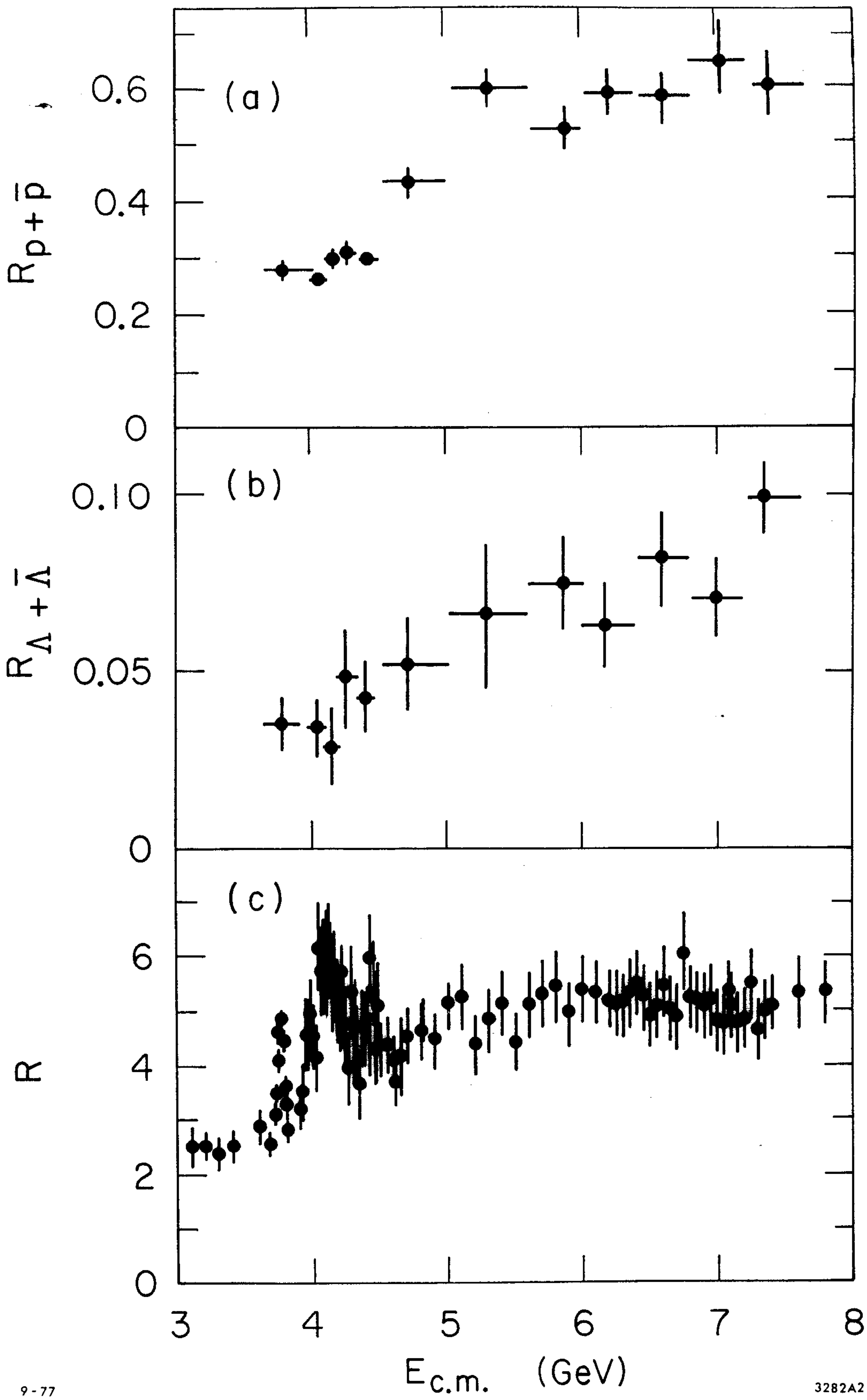

Fig. 7. Inclusive production of (a) p plus $\bar{p}$, (b) Λ plus $\bar{\Lambda}$, and (c) hadronic events.

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2. The members of the SLAC-LBL-Hawaii-Northwestern-Stanford collaboration are: J.M. Dorfan, G.J. Feldman, G. Hanson, J.A. Jaros, B.P. Kwan, D. Lüke, J.F. Martin, M.L. Perl, I.Peruzzi, M. Piccolo, T.P. Pun, P.A. Rapidis, D.L. Scharre(Stanford Linear Accelerator Center); A. Barbaro-Galtieri, R. Ely, J.M. Feller, A. Fong, P. Lecomte, R.J. Madaras, M.T. Ronan, R.R. Ross, T.G. Trippe, V. Vuillemin (Lawrence Berkeley Laboratory and Department of Physics, University of California at Berkeley); S.I. Parker, D.E. Yount (Department of Physics and Astronomy, University of Hawaii); B. Gobbi, D.H. Miller (Department of Physics and Astronomy, Northwestern University); A.M. Litke (Department of Physics, Stanford University).
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