tures formed in solids by electrons or holes of very small effective mass in more moderate magnetic fields. Analytic solutions for one-dimensional hydrogen atoms in the limit $B\to\infty$ give for its binding energy[9]

$$E \to -(\hbar^2/2ma_0^2)[2\ln(a_0/\hat{\rho})]^2, \qquad (7)$$

where a_0 is the usual Bohr radius. For $B \sim 4\times10^{13}$ G the ionization energy is near 1 keV.

Almost all scenarios for the formation of a neutron star indicate that they have cooled from enormously high ($T > 10^9$ K) initial temperatures. Then the outer layers of the star where the densities are low should be largely iron-peak elements. If the surface temperatures are less than 10^6 K, or if the magnetic fields greatly exceed 2×10^{12} G, then Eq. (6) suggests that the dominant ions may be protons and alpha particles since the more abundant heavier elements would be un-ionized. Electric fields which pull ionized matter from the stellar surface may accelerate only the relatively few protons among the iron-peak atoms. In those models which attribute cosmic rays to the acceleration of such matter near pulsars the observed abundances would not be indicative of the nuclear abundances in the stellar surface.[10]

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SEARCH FOR $T=1$ BOSONS NEAR 1 GeV IN THE REACTION $pp\to d+\mathrm{MM}$*

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Using a wire-spark-chamber deuteron spectrometer, we have measured the missing-mass (MM) spectrum up to ~1.5 GeV in the reaction $pp\to d+\mathrm{MM}$ for deutrons produced at 0° in the laboratory and incident momenta of 3.8, 4.5, and 6.3 GeV/c. Production cross sections for π and ρ are reported. Evidence of $\pi_N(980)$ production with mass 975 ± 6 MeV and width 60^{+16}_{-10} MeV is presented. No other statistically significant enhancements were found.

Experimental evidence for the existence of a nonstrange isovector meson with mass near 1 GeV has appeared in recent years. An isovector meson of $J^{PC}=0^{++}$ is required to complete the P-wave bound states of the $\bar{q}q$ system in the nonrelativistic quark model of Dalitz.[1] If we associate the $A2(1300)$, $B(1200)$, and $A1(1080)$ mesons with the $^3P_2$, $^1P_1$, and $^3P_1$ states, respectively, then a spin-orbit mass-splitting term predicts the mass of the $^3P_0$ state to be $\simeq 950$ MeV. This state could be associated with the $\delta(962)$, a narrow enhancement, which is not presently considered to be well established.

The $\delta(962)$ was first observed[2] in π^-p interactions with a width of 5 MeV or less. The production cross section was less than 2% of that for the ρ meson. Apparent support came with the observation of an enhancement at 966 MeV of width less than 10 MeV in the missing-mass (MM) spectrum of the reaction

$$pp\to d+\mathrm{MM} \qquad (1)$$

at 3.85 GeV/c incident momentum.[3] Subsequent searches in π^-p and pp interactions have failed to confirm the presence of this state.[4,5] Recently, however, several experiments have shown evidence for a broad $\eta\pi$ resonance, called $\pi_N(980)$, in this mass region.[6-11] For example, Ammar et al.[8] observe the effect at a mass of 980 ± 10 MeV with a width of 80 ± 30 MeV in the reaction $K^-p \to \Lambda\pi^+\pi_N^-(980) \to \Lambda\pi^+\pi^-$MM. Evidence that the enhancement might be a spurious effect caused by the $\Lambda\pi^+\rho^-\pi^0$ final state is presented by Crennell et al.,[12] but a rebuttal is provided by Barnes et al.[11] who observed the reaction $K^-p \to \Sigma^+(1385) + \pi_N^-(980)$. Other groups have observed the process $D^0 \to \pi^\pm\pi_N^\mp(980)$. The strong decay of $\pi_N(980)$ into $\eta\pi$ indicates that $I^G = 1^-$ with J^P in the normal-parity series $0^+, 1^-, 2^+, \cdots$.

We have performed a high-statistics experiment to measure the differential cross section of Reaction (1) for deuterons produced at 180° in the c.m. system with laboratory momenta in the range 1.1 to 1.9 GeV/c. A magnetic spectrometer using six wire spark chambers measured the momentum of the deuterons from which the MM was calculated. Our full width at half-maximum mass resolution at MM = 1 GeV was 8, 12, and 23 MeV at the incident momenta 3.8, 4.5, and 6.3 GeV/c, respectively. This was deduced from a study of the deviations of the fitted orbits from the measured spark coordinates, and is in agreement with the width of the peak arising from the reaction $pp \to d\pi^+$.

A diagram of the experimental apparatus is shown in Fig. 1. Deuterons were produced at a laboratory angle of 0° in a 3-in. long liquid-hydrogen target placed in the Bevatron external proton beam. Charged secondaries separated from the primary beam by the bending magnet $M1$ passed through a 24-in. brass collimator; the quadrupole doublet $Q12$ and the bending magnet $M2$ directed the secondary beam into the spectrometer. This consisted of the bending magnet $M3$ and six 10×10-in.[2] double-plane magnetostrictive spark chambers, $S1$-$S6$, distributed over a 44-ft path. To reduce multiple Coulomb scattering, the region from the target to the spectrometer entrance was in vacuum and helium bags were placed between the spark chambers.

The chambers were triggered by a suitably delayed coincidence between the set of scintillation counters $C1, 2$ at the front of the spectrometer and set $C3, 4, 5$ at the rear. This allowed selection of deuterons by time of flight. Further discrimination against pions and protons was provided by introducing a veto signal from a water-filled threshold Čerenkov counter, $\check{C}$, located between $C4$ and $C5$. The nondeuteron contamination, evaluated by comparing the time of flight with the fitted momentum for each event, was negligible in the raw data even though the deuterons represented less than 1% of the secondary beam. Up to fifty events per burst were recorded; spark coordinates, particle times of flight, magnet currents, and scaler readings for each event were collected by a PDP-5 computer during the Bevatron spill and loaded onto magnetic tape between bursts.[13] The primary beam intensity was typically 2×10^{10} protons over a spill time which varied from 0.2 to 1.2 sec. The intensity was monitored by the scintillation counters $C6, 7$ which detected secondaries emit-

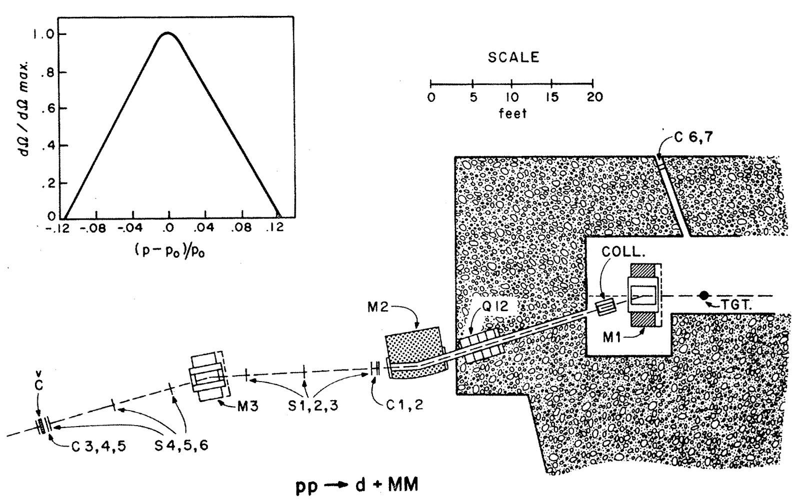

FIG. 1. Bevatron beam arrangement for this experiment. The momentum acceptance of the beam is shown in the inset.

ted at an angle of 72° from the beam line.

The raw data were obtained in individual runs of 30 000 events. The considerable overlap of runs at adjacent momentum settings provided a valuable consistency test for the data. Part of each run was spent in measuring the background spectrum with the target empty. The ratio of counting rates, target full to target empty, varied from 2 to 6, depending on the incident and secondary beam momenta. Typically 99 % of the events were kinematically analyzable. Of these, 7 % were rejected for having unsatisfactory orbit fits in the horizontal plane. The remaining events were subjected to strict limitations on the allowable coordinates and slopes which defined the accepted solid angle and the detection efficiency as functions of the fractional deviation $(p-p_0)/p_0$ from the central momentum of the spectrometer, p_0. Finally, 630 000 events were accepted from the central 12% momentum bands of the runs.[14]

The differential cross section in the laboratory for Reaction (1) as determined from a single run is

$$\frac{d^2\sigma}{d\Omega dp}=\frac{dN}{dp}\frac{F_1F_2F_3(\Delta p/p_0)F_4(p)}{\Omega(\Delta p/p_0)F_5}, \tag{2}$$

where dN/dp is the subtracted deuteron momentum distribution, $\Omega(\Delta p/p_0)$ is the effective solid angle accepted [the dependence of Ω on $(p-p_0)/p_0$ is shown in the inset in Fig. 1; $\Omega(0)\simeq 0.08$ msr], F_1 is the dead-time correction factor (typically 1 %), F_2 corrects for nuclear absorption in the target and first two counters $(2\pm1)\%$ and beam attenuation in the hydrogen (0.6%), F_3 varies smoothly from 1.0 to 1.2 over the accepted momentum band to correct for the detection inefficiency of the spectrometer due to multiple scattering in $C1,2$, $F_4(p)$ corrects for rejection of deuterons by the Čerenkov counter due to production of fast electrons (4-30)%, and F_5 is the product of target nuclei per cm^2 and the number of incident protons. These corrections are smooth functions of momentum and cannot generate structure with characteristic mass widths of 100 MeV or less.

The results of this experiment at the three incident momenta are shown in Fig. 2. The errors indicated are statistical and do not reflect the overall normalization uncertainty (11%). The prominent features of these data are a sharp peak due to the reaction

$$pp\to d\pi^+ \tag{3}$$

and a broad enhancement due to

$$pp\to d\rho^+ \tag{4}$$

on a slowly varying background. Noting that the laboratory cross sections $d^2\sigma/d\Omega dp$ are approximately linear beyond the ρ region ($\gtrsim$1550 MeV/c), we have fitted straight lines to them in the interval corresponding to $0.75<\mathrm{MM}^2<1.25\ \mathrm{GeV}^2$.

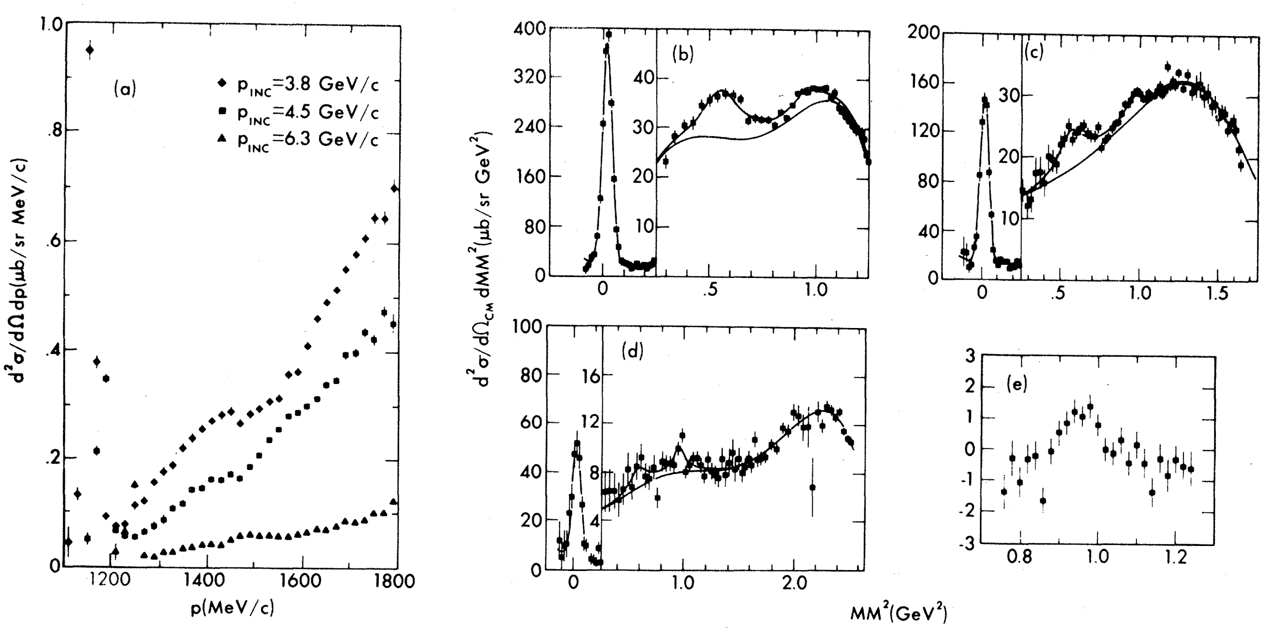

FIG. 2. (a) Deuteron laboratory momentum spectra; (b)-(d) MM^2 distributions at 3.8, 4.5, and 6.3 GeV/c, respectively; (e) MM^2 spectrum near 1 GeV^2 for all incident momenta with background subtracted. See text for details.

The deviations from these fits, transformed to the MM^2 distribution and averaged over the three incident momenta, are shown in Fig. 2(e). A broad enhancement is evident at $MM^2 \simeq 0.95$ GeV^2.

The cross sections for Reactions (3) and (4) as well as the mass and width of the ρ were obtained by fitting the c.m. differential cross sections versus MM^2 to an expression containing a smooth background plus π, ρ, and $\pi_N(980)$ enhancements. The π was represented by a Gaussian of width equal to the experimental resolution, while Breit-Wigner forms were used for the ρ and $\pi_N(980)$. The resulting parameters are listed in Table I, and corresponding curves are shown in Figs. 2(b)-2(d). The smooth background alone is given by the lower of the two curves.

To obtain the $\pi_N(980)$ cross sections and width Γ, we determined the mass from the 4.5 GeV/c data, then in the mass region 0.88 to 1.18 GeV, the cross sections were fitted to a background polynomial plus a Breit-Wigner term, and the likelihood was determined as a function of $d\sigma(\pi_N(980))/d\Omega$ and $\Gamma(\pi_N(980))$. The 4.5- and 6.3-GeV/c data agree in fixing the width at 60 MeV (the 3.8-GeV/c likelihood falls monotonically with increasing width). The maximum-likelihood cross sections of Table I improve the χ^2 probabilities of the fits significantly, as compared with the hypothesis $d\sigma(\pi_N(980))/d\Omega = 0$.

In order to set a limit on the production of the narrow $\delta(962)$, we have fitted the data with an expression containing a Gaussian at MM = 963 MeV of width equal to the experimental resolution over a smooth background. The result is shown in Table I. We estimate that the peak at 966 MeV in the MM spectrum for Reaction (1) given by Oostens et al.[3] corresponds to a c.m. $\delta(962)$ production cross section of $\simeq 0.2$ μb/sr at an incident momentum of 3.8 GeV/c and a deuteron c.m. angle of 180°. The present experiment sets a 95% confidence level upper limit of 0.08 μb/sr for this cross section, in definite disagreement with the Oostens et al. result.

Our experiment agrees with Banner et al.[4] at 3.8 GeV/c in that we see no evidence for the narrow $\delta(962)$. Moreover, it is clear from Fig. 2(b) that at 3.8 GeV/c, the $\pi_N(980)$ resonance contribution is as wide as the rapidly varying phase-space background and cannot be effectively separated from the latter, given the smallness of the $\pi_N(980)$ production cross section. Kinematically, at 3.8 GeV/c the 3π phase-space contribution peaks at 1 GeV in the mass and falls rapidly away from this maximum. At the higher energies, where the 3π phase space extends well beyond the $\pi_N(980)$ mass region, structure is evident at 0.95 GeV^2. Our conclusions regarding the $\pi_N(980)$ mass and width are consistent with the results of other groups.[6-11] Identification with the $\delta(962)$ of the CERN missing-mass spectrometer experiment[2] is ruled out if the width of the latter object is 5 MeV as reported.

Table I. Parameters determined from the fitted data.

p_{inc} (GeV/c)	3.8	4.5	6.3
$pp \to d\pi$			
$d\sigma/d\Omega$, μb/sr(c.m.)	21.0±0.5	9.4±0.3	4.6±0.5
$pp \to d\rho$			
$d\sigma/d\Omega$, μb/sr(c.m.)	3.2±0.5	2.0±0.4	0.5±0.5
Γ (GeV)	0.10±0.01	0.10±0.02	0.09[a]
MM^2 (GeV^2)	0.572±0.008	0.574±0.012	0.59[a]
$pp \to d\pi_N(980)$ [b]			
$d\sigma/d\Omega$, μb/sr(c.m.)	$0.5^{+0.7}_{-0.15}$	$0.48^{+0.28}_{-0.15}$	$0.35^{+0.10}_{-0.15}$
MM^2 (GeV^2)	0.952[a]	0.952±.012	0.952[a]
Γ (GeV)	0.06[a]	$0.060^{+0.016}_{-0.010}$	$0.055^{+0.016}_{-0.015}$
χ^2 probability (%)[c]	16 (21)	5.3 (4.6)	3.4 (3.1)
χ^2 probability (%) with $d\sigma/d\Omega = 0$[c]	6 (14)	0.22 (0.78)	0.15 (0.11)
no. bins fitted	127	78	38
$pp \to d\delta(962)$			
$d\sigma/d\Omega$, μb/sr(c.m.)	0.043±.023	0.019±.032	0.069±.074

[a]Fixed.

[b]Background polynominal has 4 terms at 3.8 GeV/c, 3 terms at 4.5 GeV/c, and 1 term at 6.3 GeV/c.

[c]Values in parentheses refer to fits with one more background term.

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LIMIT ON THE $K^+ \to \pi^+ + \gamma + \gamma$ DECAY RATE*

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The branching ratio for the process $K^+ \to \pi^+ + \gamma + \gamma$ is shown by a counter—spark-chamber experiment to be less than 4×10^{-5} of all decay modes, assuming a phase-space pion energy spectrum. A limit of 4×10^{-6} is established for the process $K^+ \to \pi^+ + \gamma$. The apparatus was sensitive to pions in the kinetic energy range 117-127 MeV.

M. Chen et al.[1] have reported a search for the process

$$K^+ \to \pi^+ + \gamma + \gamma \qquad (1)$$

using apparatus which was sensitive to pions of kinetic energy 60 to 90 MeV (kinematic limit = 127 MeV). They set an upper limit of 1.1×10^{-4} for the branching ratio into this decay mode. We report here a search for the same process with an apparatus which was sensitive for π^+ above 117 MeV. Assuming a phase-space model for the decay, i.e.,

$$d\Gamma(K\pi\gamma\gamma)/dE_\pi = \lambda P_\pi, \qquad (2)$$

where λ is a constant, we obtain a limit of 4×10^{-5} on the branching ratio.

The significance of this search has been discussed by Chen et al.[1] Briefly, they point out that a limit on (1) may be interpreted as a limit on the off-the-mass-shell behavior of the $K^+ \to \pi^+ + \pi^0$ amplitude. It has been suggested that the $|\Delta T| = \frac{1}{2}$ law may be exact, and that $K^+ \to \pi^+\pi^0$ may occur because the π^+-π^0 mass difference prevents the $\pi^+\pi^0$ from being in a pure $T = 2$ state. If we imagine that the two gamma rays from the process $K^+ \to \pi^+\gamma\gamma$ come from a virtual π^0 intermediate state, then for our energy range the π^+-$(\gamma\gamma)$ mass difference is much greater than the π^+-π^0 mass difference. According to this picture the rate for $K^+ \to \pi^+\gamma\gamma$ may be greatly enhanced.[2-5]

Our experiment has been performed in conjunction with a search[6] for the process $K^+ \to \pi^+ + \nu + \bar{\nu}$. The experiment depends on the fact that no observed K^+ decay at rest produces a π^+ with an energy greater than that from $K^+ \to \pi^+\pi^0$ [T_π = 109 MeV; branching ratio (b.r.) = 0.21]. In order to produce a π^+ of higher energy the K^+ must decay into a π^+ and a neutral system with rest mass less than that of the π^0. If we neglect decays into four or more particles, the only possibilities are $K^+ \to \pi^+e^+e^-$ (b.r. $< 2.5\times 10^{-6}$),[7] $K^+ \to \pi^+\nu\nu$ (b.r. $< 1.2\times 10^{-6}$),[6] and Reaction (1) [or (3)]. The last two reactions may give pions with energies up to 127 MeV. Hence the fact that we observe no π^+ emitted with energy between 117 and 127 MeV accompanied by high-energy γ's in the opposite hemisphere is sufficient to exclude the process $\pi^+\gamma\gamma$.

The techniques for identifying stopping K^+ and π^+ and for measuring the energy of the π^+ were identical to those used in the $K^+ \to \pi^+\nu\bar{\nu}$ experi-