Search for the associated production of charmed baryon and meson states by a 9.3-GeV photon beam*

D. J. Quinn† and R. H. Milburn
Tufts University, Medford, Massachusetts 02155
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We report a search for narrow ($\lesssim 15$ MeV) resonances decaying into one strange particle and other hadrons, and produced in 9.3-GeV γp interactions in the SLAC-LBL 82-in. bubble chamber. A search for the exclusive reactions $\gamma p \to B^{++}M^-$ ($\gamma p \to B^+M^0$), where B and M refer to narrow baryon and meson resonances decaying into any of a large number of specific channels, yielded upper limits at the 95% confidence level of 110 nb (120 nb). An independent search for the inclusive production of narrow states decaying into a Λ or K^0 with charged pions was made, also with negative results.

One possible explanation for the new narrow high-mass particles[1] is that they are "charmonium," a bound system of quark and antiquark carrying a new quantum number, charm.[2] If this is so, then states with nonzero total charm should also exist.[3]

Such states have been the object of searches in e^+e^-,[4] πp,[5,6] pp,[7] and γp[8] interactions. We wish to report the results of a search for the photoproduction of charmed particles.

If they exist, charmed particles must have a *mass* greater than about 1.8 GeV, to allow for the relative stability of the $\psi'(3684)$. There exist predictions for the meson masses that are in this range, while predictions for the lightest baryon mass are somewhat higher.[9] Charm is conserved in strong interactions, leading to a associated production of charmed particles by hadron beams or photons. The nonleptonic decays of these particles would be predominantly (by the cosine-squared of the Cabbibo angle, about 95%) into a final state containing a strange particle, according to certain predictions.[3] These modes may lead to complicated final states for which a bubble chamber is a useful detector.

The speculative status of these particles makes it important to search for their production in as wide a variety of circumstances as possible.[10] We have examined for this purpose the highest-energy high-statistics exposure of a bubble chamber to a photon beam to date, the SLAC-LBL 9.3-GeV exposure of the hydrogen-filled 82-in. chamber. Experimental details have been given elsewhere.[11] The photon beam was produced by the backscattering of laser light from the SLAC electron beam. The spectrum peaked at 9.3 GeV, with a full width at half maximum (FWHM) of 0.6 GeV. (The center-of-mass energy of the γp system was thus centered at 4.28 GeV, with a FWHM of 0.13 GeV.[12]) A total of 1.26×10^6 pictures was taken, yielding 289 ± 6 events/μb. Our search was based on data summary tapes of those events containing at least one visible strange-particle decay (kink or vee), as found on the scan table and successfully fitted to a known strange-particle decay: a total of 2787 events. Bingham *et al.*[11] assign a topological cross section of 9.8 ± 0.4 μb to these events.

Both an exclusive and an inclusive search were made. The *exclusive* search was for either of the two reactions:

$$\gamma p \to B^{++}M^- , \tag{1}$$

$$\gamma p \to B^{+}\bar{M}^0 , \tag{2}$$

where B, M stand for charmed baryon and meson, respectively. The charmed particles were allowed all those nonleptonic decay modes that are proportional to the cosine-squared of the Cabbibo angle.[3] These modes are determined by specifying the charge and strangeness of the particles in the final state: The baryons (mesons) decay into states of strangeness -1 $(+1)$. Fits requiring two or more π^0's in the final state were excluded. The invariant mass of the baryon combination was plotted against the missing mass of the meson combination and we looked for significant accumulations of events. None was seen larger than four standard deviations. To establish an upper limit the largest number of counts in any 60-MeV $\times$ 60-MeV region was used. This size (60 MeV) would encompass more than two standard deviations in our mass resolution on either side of a hypothetical narrow peak, for the majority of our events. Each final state was examined individually; the upper limits at the 95%-confidence level are displayed in Table I. We note that these results are quite insensitive to the size of the sampling region used; increasing this to 80 MeV $\times$ 80 MeV makes no change to the majority of the limits presented in Table I, and only a small change to the rest.

The plots used in Table I were added together to

TABLE I. Exclusive-channel candidates (individual channels). Mass range: 1.7 GeV ≤ baryon mass ≤ 2.6 GeV; 1.7 GeV ≤ meson mass ≤ 2.1 GeV. These limits hold when both baryon and meson widths are ≲ 15 MeV.

$\gamma p \to B^{++} M^-$

Baryon $B^{++}\to$	Meson $M^-\to$	Max. events found in 60-MeV × 60-MeV bin	95% upper limit to observed (cross section) × (branching ratio) × (vee-detection efficiency) (nb)	Detection efficiency of strange vee [a]	95% upper limit to (cross section) × (branching ratio) (nb)
$\Lambda\pi^+\pi^+$	$K^0\pi^-$	0	10	0.22	50
$\Lambda\pi^+\pi^+\pi^+\pi^-$ $\Lambda\pi^+\pi^+$	$K^0\pi^-$ $K^0\pi^+\pi^-\pi^-$	1	20	0.22	70
"with π^0" [b]		3	30	0.22	130
$\Lambda\pi^+\pi^+$	$K^+\pi^-\pi^-$	2	20	0.64	40
$\Lambda 3\pi^+\pi^-$ $\Lambda 2\pi^+$	$K^+2\pi^-$ $K^+\pi^+3\pi^-$	0	10	0.64	20
$\Lambda\pi^+\pi^+\pi^0$	$K^+\pi^-\pi^-$	3	30	0.64	40
$\Lambda\pi^+\pi^+$	$K^+\pi^-\pi^-\pi^0$	5	40	0.64	60
$\Sigma^0\pi^+\pi^+$	$K^0\pi^-$	0	10	0.22	50
$\Sigma^0 3\pi^+\pi^-$ $\Sigma^0 2\pi^+$	$K^0\pi^-$ $K^0\pi^+2\pi^-$	5	40	0.5 [a]	80
$\Sigma^0\pi^+\pi^+$	$K^+\pi^-\pi^-$	1	20	0.64	30
$\Sigma^0 3\pi^+\pi^-$ $\Sigma^0 2\pi^+$	$K^+2\pi^-$ $K^+\pi^+3\pi^-$	0	10	0.64	20
$\Sigma^+\pi^+$	$K^0\pi^-$	0	10	0.34	30
$\Sigma^+\pi^+\pi^+\pi^-$ $\Sigma^+\pi^+$	$K^0\pi^-$ $K^0\pi^+\pi^-\pi^-$	1	20	0.34	50
"with π^0" [b]		2	20	0.34	70
$\Sigma^+\pi^+$	$K^+\pi^-\pi^-$	1	20	1	20
"with π^0" [b]		4	30	1	30
$pK^0\pi^+$	$K^0\pi^-$	1	20	0.12	140
$pK^0\pi^+\pi^0$	$K^0\pi^-$	1	20	0.12	140
$pK^0\pi^+$	$K^+\pi^-\pi^-$	2	20	0.34	70
$pK^0\pi^+\pi^+\pi^-$ $pK^0\pi^+$	$K^+\pi^-\pi^-$ $K^+\pi^+3\pi^-$	0	10	0.34	30
"with π^0" [b]		5	40	0.34	110
$pK^-\pi^+\pi^+$	$K^0\pi^-$	1	20	0.34	50
"with π^0" [b]		1	20	0.34	50

$\gamma p \to B^+ M^0$

Baryon $B^+\to$	Meson $M^0\to$	Max. events found in 60-MeV × 60-MeV bin	95% upper limit to observed (cross section) × (branching ratio) × (vee-detection efficiency) (nb)	Detection efficiency of strange vee [a]	95% upper limit to (cross section) × (branching ratio) (nb)
$\Lambda\pi^+$	$K^0\pi^+\pi^-$	1	20	0.22	80
$\Lambda 2\pi^+\pi^-$ $\Lambda\pi^+$	$K^0\pi^+\pi^-$ $K^0 2\pi^+2\pi^-$	0	10	0.22	50
"with π^0" [b]		3	30	0.22	130
$\Lambda\pi^+$	$K^+\pi^-$	1	20	0.64	30
$\Lambda\pi^+\pi^+\pi^-$	$K^+\pi^-$	1	20	0.64	30
$\Lambda\pi^+$	$K^+\pi^+\pi^-\pi^-$	2	20	0.64	40
$\Lambda\pi^+\pi^0$	$K^+\pi^-$	2	20	0.64	40
$\Lambda\pi^+$	$K^+\pi^-\pi^0$	3	30	0.64	40

TABLE I. *(Continued)*

Baryon $B^+ \to$	Meson $M^0 \to$	Max. events found in 60-MeV × 60-MeV bin	95% upper limit to observed (cross section) × (branching ratio) × (vee-detection efficiency) (nb)	Detection efficiency of strange vee [a]	95% upper limit to (cross section) × (branching ratio) (nb)
$\Lambda\pi^+$	$K^0\pi^0$	1	20	0.22	80
$\Lambda\pi^+\pi^+\pi^-$	$K^0\pi^0$	3	30	0.22	130
$\Sigma^0\pi^+$	$K^0\pi^+\pi^-$	1	20	0.22	80
$\Sigma^0\pi^+\pi^+\pi^-$	$K^0\pi^+\pi^-$	0	10	0.22	50
$\Sigma^0\pi^+$	$K^02\pi^+2\pi^-$				
$\Sigma^0\pi^+$	$K^+\pi^-$	1	20	0.64	30
$\Sigma^0\pi^+\pi^+\pi^-$	$K^+\pi^-$	3	30	0.64	40
$\Sigma^0\pi^+$	$K^+\pi^+\pi^-\pi^-$				
$\Sigma^-\pi^+\pi^+$	$K^0\pi^0$	2	20	0.34	70
pK^0	$K^0\pi^+\pi^-$	1	20	0.12	140
$pK^0\pi^+\pi^-$	$K^0\pi^+\pi^-$	1	20	0.12	140
pK^0	$K^02\pi^+2\pi^-$				
"with π^0" [b]		7	50	0.12	390
pK^0	$K^0\pi^0$	2	20	0.12	200
$pK^0\pi^+\pi^-$	$K^0\pi^0$	3	30	0.12	230
pK^0	$K^+\pi^-$	1	20	0.34	50
$pK^0\pi^+\pi^-$	$K^+\pi^-$	2	20	0.34	70
pK^0	$K^+\pi^+2\pi^-$				
"with π^0" [b]		8	50	0.34	150
$pK^-\pi^+$	$K^0\pi^+\pi^-$	2	20	0.34	70
$pK^-2\pi^+\pi^-$	$K^0\pi^+\pi^-$	0	10	0.34	30
$pK^-\pi^+$	$K^02\pi^+2\pi^-$				
"with π^0" [b]		6	40	0.34	120
$pK^-\pi^+$	$K^0\pi^0$	2	20	0.34	70
$pK^-2\pi^+\pi^-$	$K^0\pi^0$	8	50	0.34	150
$nK^0\pi^+$	$K^0\pi^+\pi^-$	3	30	0.12	240
$nK^02\pi^+\pi^-$	$K^0\pi^+\pi^-$	0	10	0.12	90
$nK^0\pi^+$	$K^02\pi^+2\pi^-$				
$nK^0\pi^+$	$K^+\pi^-$	2	20	0.34	70
$nK^02\pi^+\pi^-$	$K^+\pi^-$	6	40	0.34	120
$nK^0\pi^+$	$K^+\pi^+2\pi^-$				
$nK^-2\pi^+$	$K^0\pi^+\pi^-$	4	30	0.34	90
$nK^-3\pi^+\pi^-$	$K^0\pi^+\pi^-$	0	10	0.34	30
$nK^-2\pi^+$	$K^02\pi^+2\pi^-$				
$\Sigma^+\pi^+\pi^-$	$K^0\pi^+\pi^-$	1	20	0.34	50
$\Sigma^+2\pi^+2\pi^-$	$K^0\pi^+\pi^-$	0	10	0.34	30
$\Sigma^+\pi^+\pi^-$	$K^02\pi^+2\pi^-$				
$\Sigma^+\pi^+\pi^-\pi^0$	$K^0\pi^+\pi^-$	4	30	0.34	90
$\Sigma^+\pi^+\pi^-$	$K^0\pi^+\pi^-\pi^0$	5	40	0.34	110
$\Sigma^+\pi^+\pi^-$	$K^0\pi^0$	3	30	0.34	80
$\Sigma^+2\pi^+2\pi^-$	$K^0\pi^0$	4	30	0.34	90
$\Sigma^+\pi^0$	$K^0\pi^+\pi^-$	2	20	0.34	70
$\Sigma^+\pi^0$	$K^02\pi^+2\pi^-$	2	20	0.34	70
$\Sigma^+\pi^0$	$K^+\pi^-$	1	20	1	20
$\Sigma^-2\pi^+$	$K^0\pi^+\pi^-$	1	20	0.34	50
$\Sigma^-3\pi^+\pi^-$	$K^0\pi^+\pi^-$	0	10	0.34	30
$\Sigma^-2\pi^+$	$K^02\pi^+2\pi^-$				
"with π^0" [b]		3	30	0.34	80

TABLE I. *(Continued)*

Baryon $B^+ \to$	Meson $M^0 \to$	Max. events found in 60-MeV × 60-MeV bin	95% upper limit to observed (cross section) × (branching ratio) × (vee-detection) efficiency) (nb)	Detection efficiency of strange vee [a]	95% upper limit to (cross section) × (branching ratio) (nb)
$\Sigma^-2\pi^+$	$K^+\pi^-$	1	20	1	20
$\Sigma^-3\pi^+\pi^-$ $\Sigma^-2\pi^+$	$K^+\pi^-$ $K^+\pi^+2\pi^-$ }	2	20	1	20
"with π^0" [b]		3	30	1	30

[a] We sometimes sum over events in which the vee decay was not detected.
[b] "with π^0" are events where one of the baryon or the meson decays included one π^0. This category includes events with additional $\pi^+\pi^-$ pairs on either baryon or meson. For instance, for the case $B^{++}\to\Lambda\pi^+\pi^+$, $M^-\to K^0\pi^-$, the "with π^0" category includes the decay schemes: $[B^{++}\to\Lambda\pi^+\pi^+\pi^0,\ M^-\to K^0\pi^-]$, $[B^{++}\to\Lambda\pi^+\pi^+,\ M^-\to K^0\pi^-\pi^0]$, $[B^{++}\to 3\pi^+\pi^-\pi^0,\ M^-\to K^0\pi^-]$, etc.

derive the upper limits given in Table II. These upper limits are derived from the largest number of counts above a smooth background in any 60-MeV × 60-MeV region in a plot of the baryon mass vs the meson mass. Increasing the area used to 80 MeV × 80 MeV raises the upper limits in Table II by between 0 and 50%. Since these plots combine events with different numbers of K^0 and Λ, it was not possible to correct the upper limits in Table II for the detection efficiency of the strange vee.

For those events admitting fits with no missing neutral particle we find an overall upper limit, at the 95% confidence level, for the processes $\gamma p \to B^{++}M^-$ ($\gamma p\to B^+M^-$), where the baryon and meson each have width $\lesssim 15$ MeV and both decay into charged particles or strange neutral particles detected in the chamber, to be

$$\sum_i \sigma_i R_i e_i \lesssim 30 \text{ nb } (50 \text{ nb}) ,$$

where σ_i is the cross section for production of charmed pairs having decay modes i, R_i is the product of branching ratios to these modes, and e_i represents the strange-vee detection efficiency. For events which require an undetected π^0 or neutral strange particle to achieve a fit, these limits rise to 110 nb (120 nb). The largest of these limits corresponds to less than 0.1% of the total γp cross section, or about 1% of the topological γp cross section, to produce strange particles at this energy.

The exclusive search described above provided high sensitivity, and made use of the requirement of associated production. Its disadvantage was that it required both the baryon and the meson to decay into one of the modes sought and did not allow for extra pions or other particles in the final state. If either particle decayed leptonically or into a nonstrange channel, the event would be excluded. The inclusive search thus complemented the exclusive, and looked for the following processes:

$$\gamma p \to B + \text{anything}$$

$$\text{and} \qquad\qquad (3)$$

$$\gamma p \to M + \text{anything}$$

in which the baryon (meson) decayed into Λ (K^0)

TABLE II. Exclusive-channel candidates—summary of results. Upper limits to topological cross sections for the reactions $\gamma p\to B^{++}M^-$, $\gamma p \to B^+\bar{M}^0$, where both baryon and meson decay into a final state containing one strange particle plus other hadrons, summed over all such final states detected. (See text.) Mass range: 1.7 GeV ≤ baryon mass ≤ 2.6 GeV; 1.7 GeV ≤ meson mass ≤ 2.1 GeV.

$\gamma p \to B^{++}M^-$	
No undetected neutral particles	30 nb
One undetected neutral strange particle (K^0, Λ, Σ^0)	90 nb
Sum of above two cases	90 nb
One undetected π^0 among either the B^{++} or M^- decay products	50 nb
Sum of all above cases—overall upper limit	110 nb
$\gamma p \to B^+\bar{M}^0$	
No undetected neutral particles	50 nb
One undetected neutral strange particle (K^0, Λ, Σ^0)	50 nb
Sum of above two cases	50 nb
One undetected π^0 among the decay products of either the B^+ or $\bar{M}^0$	80 nb
Sum of all above cases—overall upper limit	120 nb

TABLE III. Inclusive-channel candidates. Upper limits to the cross section for *inclusive* photoproduction of narrow states in the mass range 1.7 to 2.6 GeV. Column A is the 95% upper limit on the number of excess events in any one, two, or three adjacent 25-MeV bins. Column B is column A divided by the detection efficiency. Mass range: 1.7 GeV ≤ baryon mass ≤ 2.6 GeV; 1.7 GeV ≤ meson mass ≤ 2.6 GeV.

Reaction	A. Observed upper limit (nb)	B. Final upper limit to production cross section times branching ratio (nb)
Baryons (Λ detection efficiency = 0.64)		
$\gamma p \to B^{++}$ + anything		
$B^{++} \to \Lambda 2\pi^+$	80	120
$B^{++} \to \Lambda 3\pi^+\pi^-$	60	90
$B^{++} \to \Lambda 4\pi^+\pi^-$	10	20
Sum over decay modes	110	160
$\gamma p \to B^{+}$ + anything		
$B^{+} \to \Lambda \pi^+$	140	220
$B^{+} \to \Lambda 2\pi^+\pi^-$	140	210
$B^{+} \to \Lambda 3\pi^+2\pi^-$	30	50
$B^{+} \to \Lambda 4\pi^+3\pi^-$	10	20
Sum over decay modes	180	270
$\gamma p \to B^{0}$ + anything		
$B^{0} \to \Lambda \pi^+\pi^-$	120	190
$B^{0} \to \Lambda 2\pi^+2\pi^-$	60	100
$B^{0} \to \Lambda 3\pi^+3\pi^-$	10	20
Sum over decay modes	140	210
$\gamma p \to B^{-}$ + anything		
$B^{-} \to \Lambda \pi^-$	90	140
$B^{-} \to \Lambda \pi^+2\pi^-$	90	140
$B^{-} \to \Lambda 2\pi^+3\pi^-$	10	20
$B^{-} \to \Lambda 3\pi^+4\pi^-$	10	20
Sum over decay modes	100	160
$\gamma p \to B^{--}$ + anything		
$B^{--} \to \Lambda 2\pi^-$	70	100
$B^{--} \to \Lambda \pi^+3\pi^-$	30	40
$B^{--} \to \Lambda 2\pi^+4\pi^-$	10	20
Sum over decay modes	70	100
Mesons (K^0 detection efficiency = 0.34)		
$\gamma p \to M^{++}$ + anything		
$M^{++} \to K^0 2\pi^+$	80	220
$M^{++} \to K^0 3\pi^+\pi^-$	60	180
$M^{++} \to K^0 4\pi^+2\pi^-$	20	50
Sum over decay modes	100	300
$\gamma p \to M^{+}$ + anything		
$M^{+} \to K^0 \pi^+$	70	200
$M^{+} \to K^0 2\pi^+\pi^-$	120	340
$M^{+} \to K^0 3\pi^+2\pi^-$	70	200
$M^{+} \to K^0 4\pi^+3\pi^-$	10	30
Sum over decay modes	190	550
$\gamma p \to M^{0}$ + anything		
$M^{0} \to K^0 \pi^+\pi^-$	160	450
$M^{0} \to K^0 2\pi^+2\pi^-$	110	320
$M^{0} \to K^0 3\pi^+3\pi^-$	20	50
Sum over decay modes	130	370

TABLE III. *(Continued)*

Reaction	A. Observed upper limit (nb)	B. Final upper limit to production cross section times branching ratio (nb)
$\gamma p \to M^- +$ anything		
$M^- \to K^0\pi^-$	40	110
$M^- \to K^0\pi^+2\pi^-$	80	240
$M^- \to K^0 2\pi^+3\pi^-$	30	70
$M^- \to K^0 3\pi^+4\pi^-$	10	30
Sum over decay modes	120	340
$\gamma p \to M^{--} +$ anything		
$M^{--} \to K^0 2\pi^-$	30	80
$M^{--} \to K^0\pi^+3\pi^-$	30	80
$M^{--} \to K^0 2\pi^+4\pi^-$	10	30
Sum over decay modes	40	110

plus charged pions only. Baryons and mesons of charge between +2 and −2 were considered, even though not all of these happen to be predicted by the standard charm hypothesis. Neutral vees fitting $K^0 \to \pi^+\pi^-$ or $\Lambda \to p\pi^-$ were used. (The 35 events fitting both hypotheses were binned in each category.) Any decay mode of the possible associated charmed particle and any number of missing neutrals and/or uncharmed particles were allowed to be part of the missing mass [designated by "anything" in Eq. (3)].[13] All charged tracks were assumed to be pions.

The effective mass distribution for any particular decay mode was made by combining events of all relevant multiplicities and was plotted between 1.6 and 2.6 GeV. [Charmed particles more massive than 2.6 GeV could not be produced in association with a heavy ($\geq$1.7 GeV) partner at our available c.m. energy.] The mass resolutions in in these plots were of the order of our 25-MeV bin size or better. An excess of events in any one, two, or three adjacent bins was sought. No enhancement of more than four standard deviations was observed.

We thus find no evidence for charmed-particle photoproduction. Analogously to the exclusive search, the upper limit of events for each decay mode was taken to be the largest number above a smoothly interpolated background in any one, two, or three adjacent bins, plus two times the standard deviation of the total number of events in those bins. (When only a few counts were found in a bin, we estimated an equivalent 95% confidence level on the basis of Poisson statistics.) These limiting event counts were converted to cross-section limits by correcting for a fiducial cut, a photon energy cut, and scanning inefficiencies as described in Ref. 11. A correction for missed vee decays was also included. The results are presented in Table III and are the upper limits on the product of the production cross section and the unknown decay branching ratio of the charmed candidate.

Also contained in Table III are the overall upper limits grouped by charmed particle. These were obtained by combining mass distributions and then obtaining the upper limits as described above, and the resulting cross sections are less than or equal to the simple sum of the upper limits for the constituent decay modes. Upper limits for the product of the inclusive production cross section and branching ratio of charmed baryons in the reactions $\gamma p \to B^{++} +$ anything ($\gamma p \to B^+ +$ anything) when the baryon decays into a Λ and charged pions are 160 (270) nb, or 3% (6%) of the inclusive γp cross section for producing Λ at this photon energy. The corresponding upper limits for $\gamma p \to M^0 +$ anything ($\gamma p \to M^- +$ anything), when the meson decays into a K^0 and pions, are 370 (340) nb, or about 3% of the K^0 inclusive production cross section at this photon energy.

This experiment was similar, in concept and execution, to that described by Baltay *et al.*[5] The main differences, in addition to the incident beam beam (photons yielding a singly charged initial state as opposed to a doubly charged initial state from π^+p) and center-of-mass energy (4.3 as opposed to 5.4 GeV) are

(1) We have considered events with visible charged as well as uncharged strange-particle decays in our exclusive search.

(2) Reference 5 considered additional exclusive production processes (with extra π^+, p, or Δ^{++} in the final state).

(3) We considered a larger variety of final states for the potential charmed-particle decay.

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†Present address: Decision Analysis Group, S.R.I., Menlo Park, California.

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[10]We note very recent reports from SLAC concerning observations of possible charmed particles from e^+-e^- interactions near 4 GeV [I. Peruzzi *et al.*, Phys. Rev. Lett. 37, 569 (1976)].

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[12]We wish to point that it is possibly better to run not too far above potential thresholds in searches of this kind rather than at energies of several hundreds of GeV, since exclusive cross sections may be expected to decrease rapidly at high energies. We speculate that the upper reaches of the SLAC energy range may prove to be the ideal place for such a search, should it become feasible to do bubble-chamber experiments there.

[13]Eliminating events where the missing mass was more than two standard deviations below 1.7 GeV did not significantly change the results