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ASYMMETRY PARAMETER AND BRANCHING RATIO OF $\Sigma^+ \to p\gamma$*

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Abstract

We have measured the proton asymmetry parameter α for 61 $\Sigma^+ \to p\gamma$ events. We found $\alpha = -1.03^{+0.52}_{-0.42}$. Using a more restricted sample of 31 events, we found the branching ratio $(\Sigma^+ \to p\gamma)/(\Sigma^+ \to p\pi^0) = (2.76 \pm 0.51) \times 10^{-3}$.

I. Experimental Procedure

An exposure of 1.3×10^6 pictures in the Berkeley 25-in. hydrogen bubble chamber yielded about 57 000 events of the type $K^-p \to \Sigma^+\pi^-$, $\Sigma^+ \to p$ + neutral, with K^- momenta ranging from 270 to 470 MeV/c. The vast majority of the events were near 390 MeV/c, where the $Y_0^*(1520)$ resonance is formed. Of the 48 000 measured events, we were able to identify 61 events of the decay $\Sigma^+ \to p\gamma$.

The problem in the experiment was to separate the rare $\Sigma^+ \to p\gamma$ decays from the more copious $\Sigma^+ \to p\pi^0$ decays.[1] The proton momentum in the rest frame of the Σ is 189.0 MeV/c for $\Sigma^+ \to p\pi^0$ and 224.6 MeV/c for $\Sigma^+ \to p\gamma$. Bazin et al.[2] found a branching ratio of $(3.7 \pm 0.8) \times 10^{-3}$, using only events with stopped protons. For such events the proton momentum is determined from range rather than curvature, and is thus very accurately known, so that the two decay modes are almost always distinguishable.

Some events with protons which left the chamber were also used in this experiment. Generally such events present considerable resolution difficulty because the proton momentum is determined from the curvature measurement, and the associated error in the momentum is determined by the large multiple Coulomb scattering. The $\Sigma^+ \rightarrow p\gamma$ decay, however, releases more momentum to the proton than does the $\Sigma^+ \rightarrow p\pi^0$ decay, so that it is sometimes possible for the laboratory-system angle between the proton and the Σ in a $\Sigma^+ \rightarrow p\gamma$ decay to exceed the maximum possible angle for a $\Sigma^+ \rightarrow p\pi^0$ decay, for a given Σ momentum. Since the angles were well measured, many $\Sigma^+ \rightarrow p\gamma$ decays could be identified because of an excessive lab decay angle. A smaller contribution to the $\Sigma^+ \rightarrow p\gamma$ sample came from events with a leaving or scattering proton in which the proton track length was too great for the proton to be from a $\Sigma^+ \rightarrow p\pi^0$ decay.

II. Asymmetry Parameter

The scanners were required to distinguish between $\Sigma^+ \rightarrow p$ decays and $\Sigma^+ \rightarrow \pi^+$ decays by ionization. Those events identified as $\Sigma^+ \rightarrow p$ decays were fitted to the hypotheses

(i) $K^- p \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow p\pi^0$,

(ii) $K^- p \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow p\gamma$, and

(iii) $K^- p \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow p$ + missing mass.

Reaction (iii) is essentially a fit to the Σ^+ production hypothesis, with a calculation of the missing mass of the neutral decay particle.

We considered as candidates for $\Sigma^+ \rightarrow p\gamma$ those events fitting reaction (ii), but not fitting reaction (i) with a confidence level $> 10^{-5}$. There were 253 such events after the regular measuring of the events was completed. The candidates were carefully examined on the scanning table in order to

eliminate those events which had been mismeasured and those which were not, in fact, $\Sigma^+ \rightarrow p$ decays. Some $\Sigma^+ \rightarrow \pi^+$ decays which had been misidentified as $\Sigma^+ \rightarrow p$ decays gave successful fits to $\Sigma^+ \rightarrow p\gamma$. Those events which appeared to be proper candidates were remeasured at least once, with particular attention given to small-angle scatterings of the proton. An event which unambiguously fitted $\Sigma^+ \rightarrow p\gamma$ after remeasurement was retained if all the following conditions were met:

(a) It was resolvable from $\Sigma^+ \rightarrow p\pi^0$ by either the range or decay angle of the proton. Of the 61 events ultimately identified as $\Sigma^+ \rightarrow p\gamma$, 31 had stopped protons, 24 had decay angles too great for π^0 decay, and 6 had leaving or scattering protons whose length was too great for π^0 decay.

(b) The measured quantities were reproducible upon remeasurement. The Σ had to be clearly visible, and the production and decay vertices had to be clearly distinguishable. The confidence level for the $\Sigma^+ \rightarrow p\gamma$ fit was required to be > 0.01.

(c) The event fitted $\Sigma^+ \rightarrow p\gamma$ unambiguously when a fit without beam averaging was performed. Five events near the front of the chamber fitted $\Sigma^+ \rightarrow p\pi^0$ without beam averaging, with a lower K^- momentum. We considered these events to be possible $\Sigma^+ \rightarrow p\pi^0$ decays in which the K^- had scattered and lost momentum before entering the chamber.

(d) The proton was distinguishable from a π^+ either by its stopping in the chamber or by its greater ionization. If the track left the chamber, it was considered unidentifiable if the dip angle exceeded 60 deg.

(e) The event was inconsistent with a stopped Σ decaying via $\Sigma^+ \rightarrow p\pi^0$. Events with Σ momenta below 80 MeV/c at decay were not considered as $\Sigma^+ \rightarrow p\gamma$ if the proton momentum was near 189 MeV/c.

There were 61 events satisfying these requirements. Because of the criteria that were used in obtaining the $\Sigma^+ \rightarrow p\gamma$ events, we estimate less than one event of $\Sigma^+ \rightarrow p\pi^0$ as contamination.[3] The distribution in missing mass squared, MMSQ, is shown in Fig. 1 for 59 of these.[4] The four events with high or low MMSQ had protons which scattered, but which satisfied the decay angle or range requirements. The typical error in MMSQ is 0.1 $m^2_{\pi^0}$ for the events with stopped protons and 0.15 to 0.20 for those with leaving protons which did not scatter.

The angular distribution of the proton from a polarized Σ is

$$I(\hat{q}) = 1 + \alpha \langle \vec{\sigma}_\Sigma \rangle \cdot \hat{q} . \tag{1}$$

Here $\hat{q}$ is the proton momentum unit vector and $\langle \vec{\sigma}_\Sigma \rangle$ is the Σ polarization. The Σ^+ polarizations in this experiment were determined by observing the decay asymmetry in $\Sigma^+ \rightarrow p\pi^0$, where the asymmetry parameter is nearly -1.[5] Preliminary polarization curves were shown in Ref. 5. The Σ polarization arises principally from the interference between the resonant D-wave amplitude and the strong S-wave background. The Σ polarization for each event was calculated from a multichannel partial-wave analysis. The average polarization was 0.4.

A maximum-likelihood analysis was performed, by use of the likelihood function

$$\mathcal{L}(\alpha) = \prod_i (1 + \alpha \langle \vec{\sigma}_\Sigma \rangle_i \cdot \hat{q}_i). \tag{2}$$

Evaluating $\mathcal{L}(\alpha)$, we find $\alpha = -1.03^{+0.52}_{-0.42}$. Since physically $|\alpha| \leq 1$, the most likely physical value is $\alpha = -1$.

III. Branching Ratio

A straightforward determination of the branching ratio was made by applying cuts to all $\Sigma^+ \rightarrow p$ decays independent of the identity of the decay neutral, except in two cases which were easily corrected for. The criteria used were more restrictive than those for the asymmetry parameter determination, where additional events could be used because they had configurations which precluded their being $\Sigma^+ \rightarrow p\pi^0$ decays.

The following series of cuts was imposed on the events with two-body Σ^+ production fits:

(a) a fiducial volume stricter than the measuring volume, imposed to eliminate all events in the last quarter of the bubble chamber, and events near the front and sides;

(b) Σ length > 1 mm, to assure reasonably high scanning efficiency;

(c) confidence level for the missing mass fit > 0.01 to eliminate mismeasured events;

(d) lab-dip angle of the proton < 45 deg. The scanning efficiency for distinguishing protons from π^+ as the decay product of the Σ became worse as the dip angle increased. The efficiency was greater than 95% for dip angles below 45 deg. A correction was calculated for this cut, since it affected γ and π^0 events differently.

After these cuts were imposed, 30 806 events remained. A simple way to impose the criteria of identifying $\Sigma^+ \rightarrow p\gamma$ by range or decay angle of the proton was to choose a particular region in the space of $(\hat{\Sigma} \cdot \hat{q})_{RF}$, the rest frame decay cosine, vs. p_Σ, the Σ momentum. Because the Σ polarization is normal to its line of flight, the decay distribution is uncorrelated with the Σ direction. Consequently, apart from experimental biases, events should be uniformly distributed in $(\hat{\Sigma} \cdot \hat{q})_{RF}$.

Scatter plots of $(\hat{\Sigma}\cdot\hat{q})_{RF}$ vs. p_Σ are shown in Figs. 2a and 2b for the $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow p\gamma$ events respectively, after the particular region of the space had been chosen. The cuts on the variables were applied to the fitted values of the appropriate decay. The unpopulated regions 1 through 4 are described below:

Region 1: Events in region 1 were excluded because $p_\Sigma < 125$ MeV/c at decay. This was done to eliminate low-momentum Σ's, which either stopped or had a large uncertainty in momentum at decay because they were losing momentum rapidly.

Region 2: Events in region 2 were excluded because the range of the proton from either a γ decay or a π^0 decay with the given p_Σ and $(\hat{\Sigma}\cdot\hat{q})_{RF}$ would have been less than 1.2 cm. The scanning efficiency was lower for these short protons.

Region 3: The scanning efficiency was lower for a small lab angle between Σ and p. The events in region 3 were excluded because either the γ decay or the π^0 decay with the given p_Σ and $(\hat{\Sigma}\cdot\hat{q})_{RF}$ would have resulted in a lab cosine > 0.966.

Region 4: It was found that events were completely resolvable for $-0.8 < (\hat{\Sigma}\cdot\hat{q})_{RF} < -0.1$. In addition, the proton always stopped for both decay modes in the two small areas at the upper left and lower right of Fig. 2a, since the imposed fiducial volume required a proton to have a track at least 10 cm long before leaving the chamber. The events in region 4 were not in any of these areas and were excluded. For events with higher p_Σ in the region $-0.8 < (\hat{\Sigma}\cdot\hat{q})_{RF} < -0.1$, the lab decay angles for $\Sigma^+ \rightarrow p\gamma$ exceed the maximum possible angle for $\Sigma^+ \rightarrow p\pi^0$. For lower p_Σ, the protons from $\Sigma^+ \rightarrow p\pi^0$ always stop, because of the imposed fiducial volume, while the protons from $\Sigma^+ \rightarrow p\gamma$ either always stop, or have a track length too great to be from the π^0 decay.

A histogram of MMSQ is shown in Fig. 3a, before examination and remeasurement, for the 11 775 events lying within the region defined in Fig. 2a. Examination showed that a number of events in the tail regions (MMSQ < 0.45 $m^2_{\pi^0}$ and MMSQ > 1.55 $m^2_{\pi^0}$) had protons which scattered instead of stopping, so that they were not resolvable. Events with scattering protons were removed from the tail regions, and a weight averaging 1.04 was calculated for the $\Sigma^+ \rightarrow p\gamma$ events based upon the p-p low energy cross sections. It was not necessary to weight the π^0 events for scattering, since almost all the events that scattered were already included in the π^0 peak. Other non- $\Sigma^+ \rightarrow p\gamma$ events in the low MMSQ region were $\Sigma^+ \rightarrow \pi^+$ decays, and a few were non-beam events.

After elimination of events in the tail regions by careful examination and remeasurement, we found the distribution shown in Fig. 3b. The 31 events below 0.25 $m^2_{\pi^0}$ are $\Sigma^+ \rightarrow p\gamma$, the event at 2.83 $m^2_{\pi^0}$ is probably $\Sigma^+ \rightarrow p\pi^0\gamma$, and 11 670 events are $\Sigma^+ \rightarrow p\pi^0$. A weight averaging 1.14 for both $\Sigma^+ \rightarrow p\gamma$ and $\Sigma^+ \rightarrow p\pi^0$ was applied for the events cut out by the proton dip-angle requirement. The weighted number of γ events was 36.85, with a statistical error of 6.76; the weighted number of π^0 events was 13 348. The branching ratio was $(\Sigma^+ \rightarrow p\gamma)/(\Sigma^+ \rightarrow p\pi^0) = (2.76 \pm 0.51) \times 10^{-3}$.

Because of the complete separation of the γ and π^0 peaks in Fig. 3b, it was not necessary to subtract any background events from the γ peak. All 31 events were included among the 61 events used for the asymmetry parameter. Only regions of high scanning and detection efficiencies were chosen, so that the relative efficiencies at any point of the scatter plot differ by a negligible amount.

This result is in agreement with the previous result of Ref. 2, which is about one standard deviation higher.

IV. Theoretical Description

Behrends showed[6] that the most general effective Lagrangian is

$$\mathcal{L}_{eff} = \bar{p}\,(a + b\,\gamma_5)\,\sigma_{\mu\nu}\,q^{\nu}\,A^{\mu}\,\Sigma^{+} + \bar{\Sigma}\,(a^{*} - b^{*}\gamma_5)\,\sigma_{\mu\nu}\,q^{\nu}\,A^{\mu}\,p, \tag{3}$$

where the second term is the Hermitian conjugate of the first, q^{ν} is the proton four momentum, A^{μ} is the electromagnetic field, and a and b are parity-conserving and parity-nonconserving amplitudes, respectively. Other forms of coupling which one might consider on the basis of Lorentz invariance reduce to Eq. (3) when gauge invariance and momentum conservation are applied.

The decay asymmetry parameter α of Eq. (1) is

$$\alpha = 2\,\mathrm{Re}(a^{*}b)/(\,|a|^{2} + |b|^{2}). \tag{4}$$

Assuming U-spin invariance alone, $\alpha = 0$ if $U = 0$ for the photon.[7] This latter requirement is suggested by the Gell-Mann–Nishijima formula. The conclusion $\alpha = 0$ can be seen by performing a U-spin rotation of $\mathcal{L}_{eff}$ by 180 deg and requiring U-spin invariance. These imply that a and b are relatively imaginary, so that $\alpha = 0$. Adding CP invariance would impose the stronger requirement that $b = 0$ also. Several authors have shown[8,9] that CP invariance and SU(3) invariance of $\mathcal{L}_{eff}$ imply that $b = 0$ for $\Sigma^{+} \rightarrow p\gamma$, so that $\alpha = 0$.

Our experimental result for α is two standard deviations from the SU(3) result.

Some authors[9,10] have made dynamical calculations of the asymmetry parameter and branching ratio, using pole-model and current-algebra techniques.

Only Ahmed obtains results in good agreement with this experiment for both the asymmetry parameter and branching ratio; the others obtain small asymmetry parameters.

References and Footnotes

*Work done under the auspices of the U. S. Atomic Energy Commission.

†Address after Oct. 1: Nevis Laboratories, Columbia University, Irvington, N. Y.

1. A more detailed discussion of the experiment can be found in L. K. Gershwin's Ph. D. Thesis, UCRL-19246, June 1969 (unpublished).

2. M. Bazin, H. Blumenfeld, U. Nauenberg, L. Seidlitz, and C. Y. Chang, Phys. Rev. Letters 14, 154 (1965).

3. We investigated the possibility that some of these events were $\Sigma^+ \rightarrow p\pi^0$ decays arising from K^- interactions with deuterium. About 300 $\Sigma^+ \rightarrow p$ decays were analyzed from deuterium film taken during the experiment. The deuterium contamination in the hydrogen film was estimated by counting the $K^- n \rightarrow \Lambda \pi^-$ interactions. We estimate that from 1 to 5% of the identified $\Sigma^+ \rightarrow p\gamma$ decays are actually deuterium events.

4. Two events had good Σ^+ production fits, but the missing mass of the neutral decay particle was not calculated because of intricacies in the fitting program. The events were nevertheless identified as $\Sigma^+ \rightarrow p\gamma$.

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8. Y. Hara, Phys. Rev. Letters 12, 378 (1964); M. Hirooka and M. Hosoda, Progr. Theoret. Phys. (Kyoto) 35, 648 (1966).

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10. H. S. Mani, Y. Tomozawa, and Y. P. Yao, Phys. Rev. 158, 1577 (1967); M. A. Ahmed, Nuovo Cimento 58A, 728 (1968); G. M. Papaioannou, Phys. Rev. 178, 2169 (1969).

Figure Captions

Fig. 1. The MMSQ distribution for 59 of the 61 $\Sigma^+ \to p\gamma$ events used in determining α.

Fig. 2. p_Σ vs. $(\hat{\Sigma}\cdot\hat{q})_{RF}$ for (a) the 11 775 events satisfying all the branching ratio criteria (the regions 1-4 that have been removed are explained in the text), (b) the 31 events determined to be $\Sigma^+ \to p\gamma$ decays.

Fig. 3. The MMSQ distribution for the 11 775 events satisfying the branching ratio criteria, (a) before examination and remeasurement (the scale is logarithmic); (b) after examination and remeasurement of events with MMSQ < 0.45 and MMSQ > 1.55. Thirty-one events below 0.25 are $\Sigma^+ \to p\gamma$ decays; the event at 2.83 is probably $\Sigma^+ \to p\pi^0\gamma$.

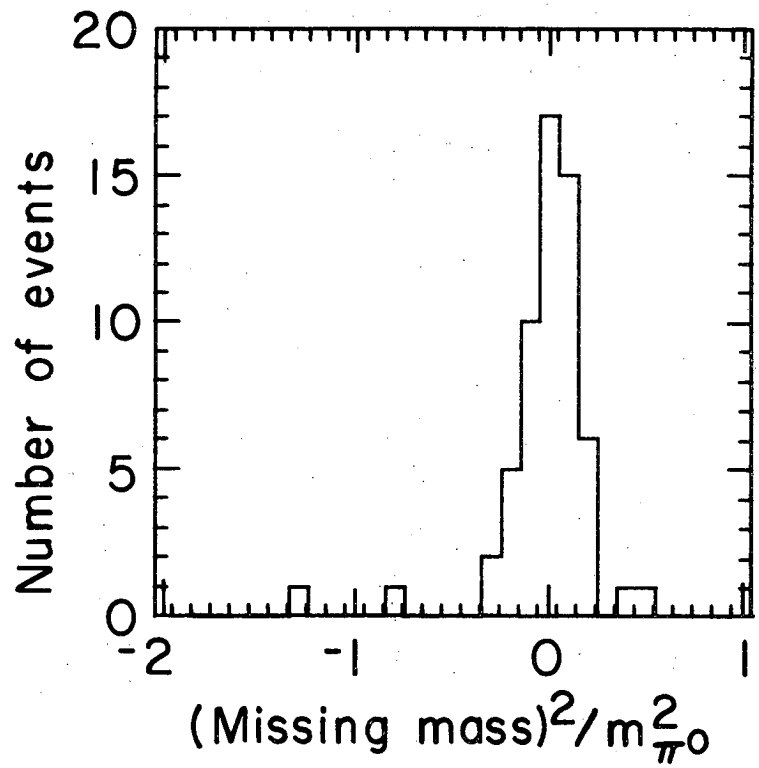

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Fig. 1

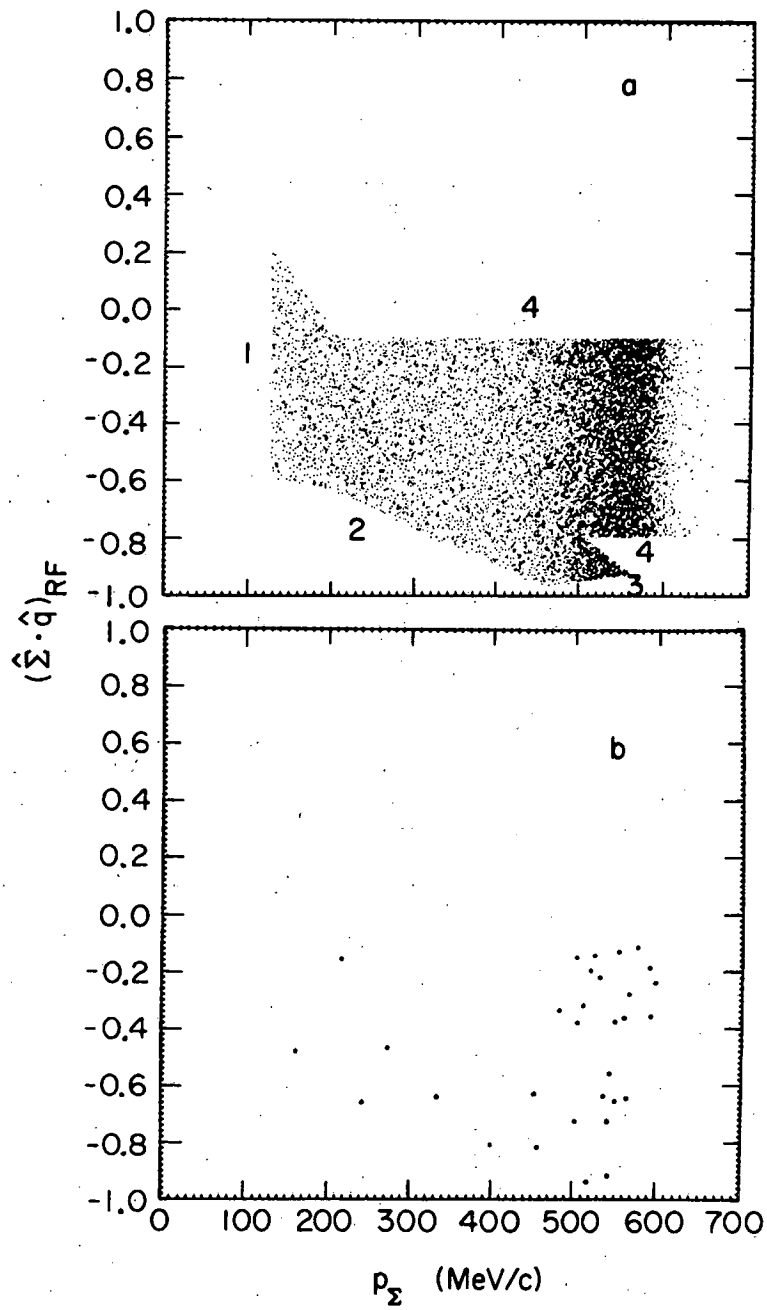

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Fig. 2

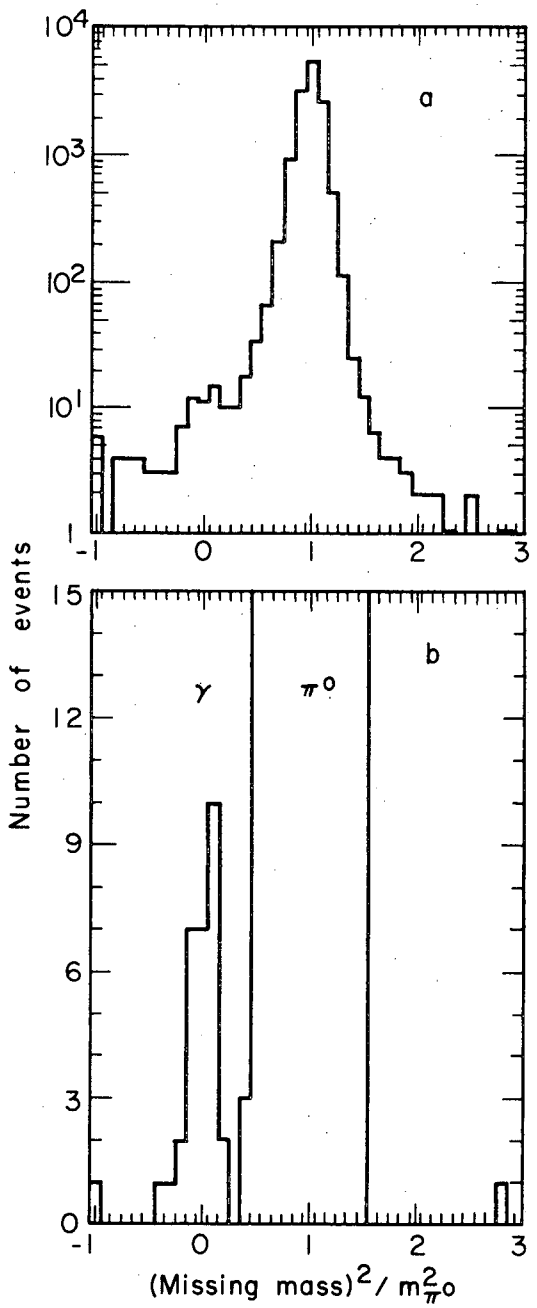

Fig. 3

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