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Monte Carlo Study of CP Asymmetry Measurement at a Tau-Charm Factory*

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ABSTRACT

It is shown that, for $D^0\bar{D}^0$ mixing of order $\sim 1\%$, it **may** be possible to observe in a Tau-Charm Factory a CP violation effect in the $D^0\bar{D}^0$ system via a CP asymmetry. The method used is to tag one D by its semi-leptonic decay and to look for decays of the other D into CP eigensfates. It is estimated that within 1 year of running at the designed luminosity of $L = 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, $\sim$ 6600 such events can be collected.

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THEORETICAL MOTIVATION

It has been argued[1] that certain D^0 decays can exhibit CP asymmetries on the percent level, if the strength of the $D^0 - \bar{D}^0$ mixing, characterized by

$$Prob.(D^0 \to \bar{D}^0) \equiv \frac{BR(D^0 \to l^- + X)}{BR(D^0 \to l^+ + X)} = \frac{1}{2}(x^2 + y^2) \tag{1}$$

is of the order of $\sim 1\%$. Here $x = \Delta m/\Gamma$, $\Delta m = | m_2 - m_1 |$, $y = \Delta\Gamma/2\Gamma$, $\Delta\Gamma = | \Gamma_2 - \Gamma_1 |$ and $l^\pm$ is an outgoing lepton. The proposed method is the following: a) Tag the charm quantum number (i.e.D^0 or $\bar{D}^0$) via the sign of the lepton $l^\pm$ in a semileptonic decay; b) For the other D^0 (or $\bar{D}^0$), look for a final state **f** that is common to **both** D^0 and $\bar{D}^0$ decays, i.e. a CP eigenstate; c) Calculate the CP asymmetry, A , defined by

$$A = \frac{\sigma(e^+e^- \to l^+/K^- + Xf) - \sigma(e^+e^- \to l^-/K^+ + Xf)}{\sigma(e^+e^- \to l^+/K^- + Xf) + \sigma(e^+e^- \to l^-/K^+ + Xf)}. \tag{2}$$

According to ref.[1]: A=0 if the relative angular momentum between the D^0 and $\bar{D}^0$, $l(D^0\bar{D}^0)$, is odd, and $A = 2x\sin 2\varphi$, if $l(D^0\bar{D}^0)$ is even, where φ is the CP violation complex phase.

A clear advantage in this method is that **A** is **linear** in x, and thus less suppressed, whereas the usual mixing observables, such as the number of like-sign dileptons, $N(l^\pm l^\pm)$ from semileptonic D^0 and $\bar{D}^0$ decays, or the non-leptonic decays with D^0 decaying into K^+ mesons, depend on x^2 and y^2. Another advantage is that, unlike B-decays from the $\Upsilon(4S)$, where $l(B^0\bar{B}^0)$ is odd, the $l(D^0\bar{D}^0)$=even states yield a non-zero CP asymmetry with no time information needed. In this configuration, D^0 decays to certain final states can yield CP asymmetries of order 0.1φ.

For two identical spin zero bosons, the relation $C = (-1)^l$ holds. Thus, it is easy to see that $D^0\bar{D}^0$ occur in a P-wave (l=1) in the reactions:

$$e^+e^- \to \gamma^* \to D^0\bar{D}^0 \tag{3}$$

$$e^+e^- \to \gamma^* \to D^0\bar{D}^{*0}, D^{*0}\bar{D}^0 \to D^0\bar{D}^0\pi^0 \tag{4}$$

$$e^+e^- \to \gamma^* \to D^{*0}\bar{D}^{*0} \to D^0\bar{D}^0\gamma\gamma \tag{5}$$

$$e^+e^- \to \gamma^* \to D^{*0}\bar{D}^{*0} \to D^0\bar{D}^0\pi^0\pi^0 \tag{6}$$

and in an S-wave (l=0) in the reactions:

$$e^+e^- \to \gamma^* \to D^0\bar{D}^{*0},\ D^{*0}\bar{D}^0 \to D^0\bar{D}^0\gamma \tag{7}$$

$$e^+e^- \to \gamma^* \to D^{*0}\bar{D}^{*0} \to D^0\bar{D}^0\gamma\pi^0. \tag{8}$$

EXPERIMENT

In order to measure an asymmetry effect of $\sim 1\%$, one needs about 10^4 events with $l(D^0\bar{D}^0)$=even. Therefore, it is desirable: a) to run at a CM energy where the inclusive D^* cross-section is maximal (see fig.1), e.g. at $\sqrt{(s)}$ =4.14 GeV, b) to accumulate as many channels as possible of reactions (7) and (8), c) to achieve a very good separation between γ's and π^0's in order to minimize the dilution of the asymmetry by contamination of reactions which have zero asymmetry. With such a separation, the $l(D^0\bar{D}^0)$=odd channels (e.g. reaction 4) can provide an automatic self-calibration' for any non CP-violation instrumental effects that may exist in the corresponding $l(D^0\bar{D}^0)$=even channel (e.g. reaction 7).

EVENT GENERATION

The following particular process has been taken as an example of the type of channels discussed above:

$$e^+e^- \to \gamma^* \to D^{*0}\bar{D}^0 \tag{9}$$

$$D^{*0} \to D^0\gamma \textbf{\textit{ or }} D^0\pi^0 \tag{10}$$

$$D^0 \to K^+K^- \textbf{\textit{ (branching ratio = 0.51\%)}} \tag{11}$$

$$\bar{D}^0 \to K_e^+ e^-\bar{\nu}_e \textbf{\textit{ (branching ratio = 3.4\%)}} \tag{12}$$

In all cases, the corresponding processes where each particle is replaced by its anti-particle are included.

We have generated 10,000 Monte Carlo events at $\sqrt(s)$ =4.14 GeV for each of the following cases: a) $D^{*0} \to D^0\gamma$ for a detector with a moderate energy resolution σ_E/E=8%/$\sqrt(E)$ for the electromagnetic (EM) calorimeter; b) $D^{*0} \to D^0\gamma$ for an "ultimate" detector with a resolution of σ_E/E=2%/$\sqrt(E)$; c) Same as a) for $D^{*0} \to D^0\pi^0$; d) Same as b) for $D^{*0} \to D^0\pi^0$; *e)* $D^{*0} \to D^0\gamma$ for background studies, where the D^0 decay in (12) is replaced by all the known D^0 decays other than the $Ke\nu$ one. The angular resolution assumed for both types of detector was 10 *mrad.*

ANALYSIS

The above Monte Carlo events have been run through an analysis program, requiring the following cuts: a) The final state consists of two positively and two negatively good charged tracks. b) There is exactly one photon in the final state with energy E_γ > 25 MeV and with polar angle with respect to the beam line $|\cos\vartheta_\gamma| < 0.95$. The photon detection efficiency was assumed to rise approximately linearly from $\sim$ 25% at E_γ = 25 MeV to $\sim$ 100% at E_γ = 100 MeV. 4503 events of reaction (7) and 2237 (2134) events of reaction *(4)* survived these cuts, where the unbracketed (bracketed) number refers to the "moderate" ("ultimate") detector.

The time-of-flight (TOF) counters in the simulated detector are used in order to identify the charged kaons in reactions (11) and (12). Two independent sets of 96 TOF counters covering the full 2π azimuthal range with time resolution of 180 ***psec*** each were used for this simulation. Using gaussian weights, W_i, proportional to the probability that a given particle is of type i, we define an identified $K^\pm$ as a particle for which $W_K > 0.01$ and $W_K > W_\pi$.

Electrons are identified as follows: For slow particles (p<0.3 GeV/c) the TOF counters are used to identify electrons with the requirement $W_e/(W_e + W_\pi) > 0.9$. For fast particles (p>0.3 GeV/c), the momentum measured in the drift chamber is required to be approximately equal to the energy measured for the same particle in the EM calorimeter.

For the π^0 case (reaction 4), a kinematical 1C fit, constraining the $\gamma\gamma$ effective mass to the π^0 mass, has been applied.

In fig.2, the effective mass distribution of any pair of oppositely charged $K^{\pm}$ mesons, $M(K^+K^-)$, is plotted for the $D^0\gamma$ channel. A clean and narrow D^0 signal is seen with a width of $\sigma \sim 4$ MeV. For further analysis we apply the cut $1.855 < M(K^+K^-) < 1.880$ GeV, yielding 3585 D^0 candidates for reaction (7) and 1784(1702) candidates for reaction (4), using a "moderate" ("ultimate") detector.

In fig.3a, the missing mass distribution recoiling against the above D^0 candidates is plotted for the $D^0\gamma$ channel. This distribution represents the combination of the second D^0 and the γ. The same distribution for the $D^0\pi^0$ channel, representing the second D^0 and the π^0, is shown in fig.3b. The later distribution is narrower than that of fig.3a, probably due to the very low Q-value of the decay $D^{*0} \rightarrow D^0\pi^0$, yielding some separation between the $D^0\gamma$ and $D^0\pi^0$ channels.

In fig.4(a,b) we plot, respectively for the $D^0\gamma$ channel (2759 entries) and for the $D^0\pi^0$ channel (1405 entries), the effective mass distribution $M(K^+K^-\gamma)$ for the "moderate" detector configuration. This distribution should represent the measured D^* for the $D^0\gamma$ channel, and the D^* minus one γ for the $D^0\pi^0$ channel. Again, due to the low Q-value for the-later, the distribution is quite narrow, and a good separation between the 2 channels is achieved. The equivalent plots for the "ultimate" detector configuration are shown in fig.5(a,b), yieldn gespectively 2759 and 1337 entries. Here, due to the better photon measurement, an excellent separation is obtained between the $D^0\gamma$ and $D^0\pi^0$ channels.

Finally, in figs.6 and 7 we plot, for the "moderate" and "ultimate" detectors respectively, the missing-mass squared $(MM)^2$ distribution recoiling against the effective-mass combination $M(K^+K^-K_e^+e^-\gamma)$ (see eqs.10-12). This distribution should yield, for the $D^0\gamma$ channel, the missing neutrino of the $\bar{D}^0$ semi- leptonic decay (eq.12). Indeed the distributions in figs.6a and 7a peak near zero with some tail for positive $(MM)^2$ values. The same distributions for the $D^0\pi^0$ channel (figs.6b,7b) should include a missing γ in addition to the neutrino, and thus they are broader and peak at positive $(MM)^2$ values. Figs.6(a-b) show that for a "moderate" detector one gets a substantial overlap between the $D^0\gamma$ and $D^0\pi^0$ channels, where figs.7(a-b) reveal a much better separation in the $(MM)^2$ variable between these channels for an "ultimate" detector.

In order to estimate the possible background contributions in this study, we show in fig.8 the $(MM)^2$ distribution recoiling against $M(K^+K^-K_e^+e^-\gamma)$ for the Monte Carlo event sample (e), as described in the event generation section. Only 5 events survive after applying all the above selection criteria. The 3 entries close to $(MM)^2 \sim 0$ are due to the decay mode $\bar{D}^0 \rightarrow K^+\mu^-\bar{\nu}_\mu$, and are thus signal events as well. We conclude that the amount of background from other D^0 decays, contributing to our signal is negligible. The background from the e^+e^- continuum is also expected to be negligible.

The most efficient separation seems to come from the $M(K^+K^-\gamma)$ distributions (figs.4-5). Applying a cut of $M(K^+K^-\gamma) > 1.98$ GeV for the $D^0\gamma$ channel, we estimate, after all cuts, an efficiency of 23% (27%) for a "moderate" ("ultimate") detector for measuring the chain of processes (9-12). The contamination with these cuts from the $D^0\pi^0$ channel in these samples is 7.5% for the "moderate" and 0.6% for the "ultimate" detector.

ESTIMATED NUMBER OF RECONSTRUCTED EVENTS

In table 1 we present an estimate of the number of all semileptonic tagged events of the type $K(\pi)e\nu$ and $K(\pi)\mu\nu$, where the neutrino is the only missing particle, with CP-eigenstates that can be collected in a 5000 hours (about 1 year) of running at $\sqrt{(s)}=4.14$ GeV with a luminosity of $L = 10^{33}$ cm^{-2}sec^{-1} -. The chain of reactions considered is as in eqs. (9-12) with the $D^0\bar{D}^0$ being in an l=even state, i.e. using the $D^0\gamma$ channel of eq. (10). The production cross-section used for reaction (9) was[2] $\sigma(D^0\bar{D}^{*0}) = 0.9f0.2$ nb, and the branching ratio assumed for the decay $D^{*0} \rightarrow D^0\gamma$ was[3] 0.37. The CP-eigenstate branching ratios (BR) are taken from refs. 4,5,6,7,8. The efficiencies are estimates based on solid angle and particle identification criteria. All the numbers are normalized via the BR's and efficiencies-to the estimate for the chain (9-12) (1040 events) extracted from the current analysis. One sees that the desired number of 10,000 events can be achieved in $\sim$ 1.5 years. Moreover, one can even increase the statistics by: a) improving the efficiency for the γ/π^0 separation by using D^0 and/or D^{*0} kinematical fits in addition to the π^0 fit; b) doing a similar analysis on events of reaction (8). Note, however, that for the later case, the separation between the required l=even channel and the l=odd background channels (reactions 5-6) may be harder than in the present analysis.

CONCLUSION

We have demonstrated that, if there exists a small $D^0\bar{D}^0$ mixing of order $\sim 1\%$, and if the CP violation phase, ϕ, is not too small, it **may** be possible to observe in a Tau-Charm-Factory detector a CP violation effect by measuring the CP asymmetry in a $D^0\bar{D}^0$ system, where one D^0 is tagged by its semileptonic decay and the other one decays into a CP eigenstate.

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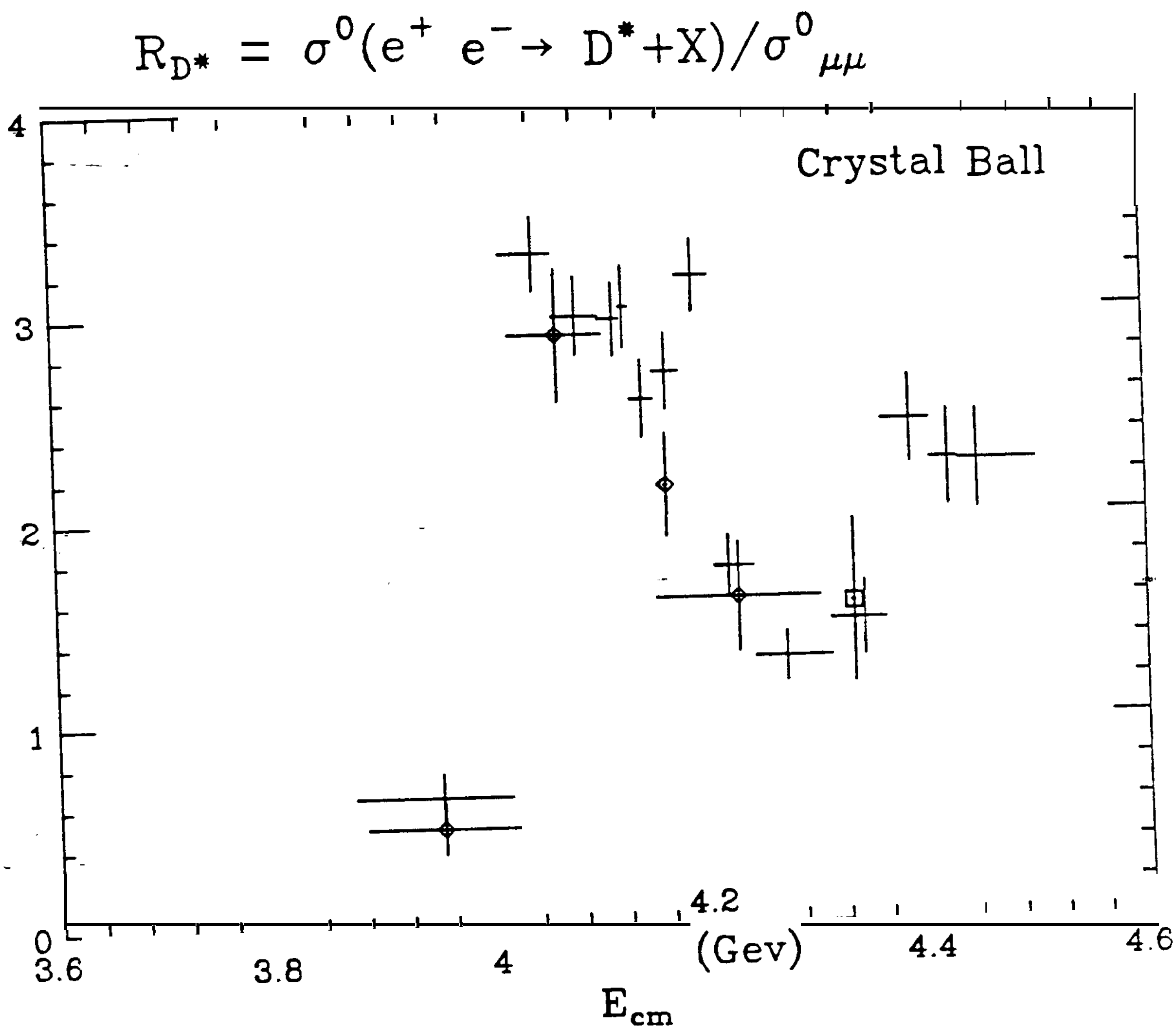
Table I. Estimate of the number of fully reconstructed semileptonic tagged events with CP-eigenstates in a one year running time.

Eigenstate	CP	BR(%)	Efficiency	$\gamma D^o \overline{D}^o$ Events
$K_s^o \rho^o$	-1	*0.27* ± *0.17*	*0.42*	*460*
$K_s^o \eta$	-1	*0.60* ± *0.32*	*0.12*	*290*
$K_s^o \Phi$	*-1*	*0.29* ± *0.18*	*0.05*	*60*
$K_s^o \pi^o$	*-1*	*0.73* ± *0.24*	*0.26*	*770*
$K_s^o \omega$	-1	*1.3* ± *0.7*	*0.06*	*320*
$\rho^o \pi^o$	+1	*1.1* ± *0.4*	*0.70*	*3140*
$\pi^+ \pi^-$	+1	0.14 ± 0.05	*0.80*	*460*
$K^+ K^-$	+1	*0.51* ± *0.11*	*0.50*	*1040*
$K_s^o K_s^o$	+1	0.03 ± 0.01	0.26	30

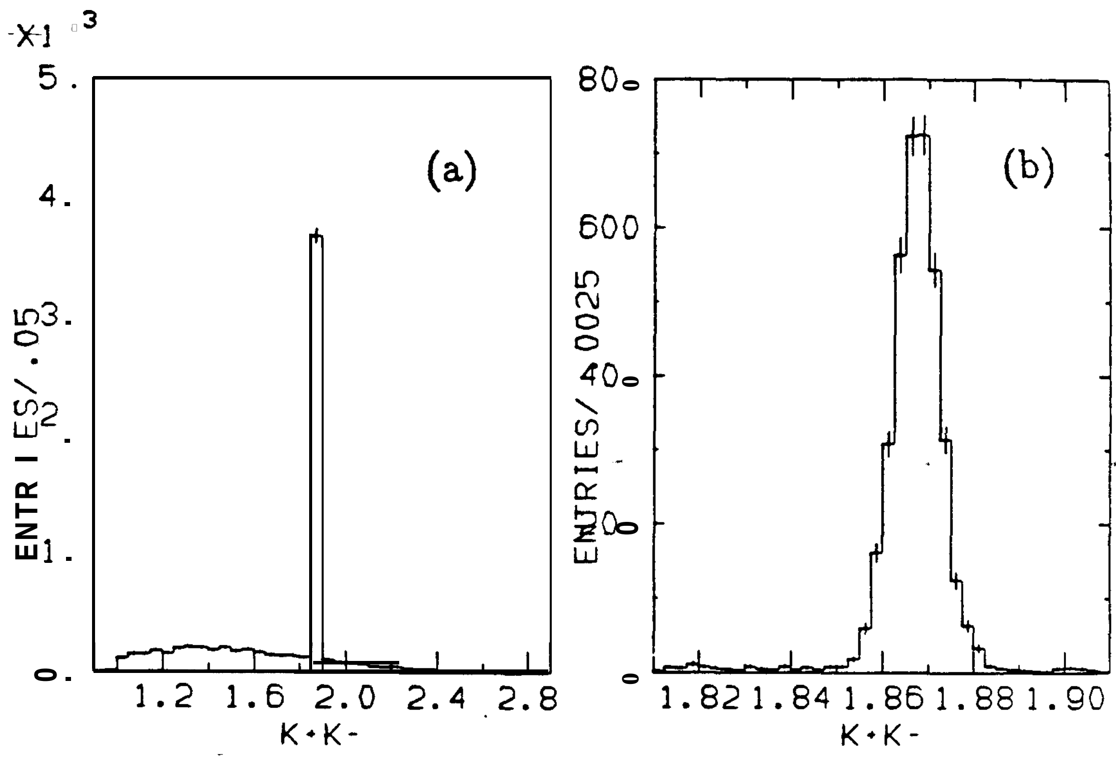
FIGURE CAPTIONS

1. Compilation of the inclusive D^* cross-section $\sigma(e^+e^- \rightarrow D^* + X)$ normalized to the point-like cross-section $\sigma_{\mu\mu}$ as a function of the total CM energy, E_{CM}.
2. Effective mass distribution $M(K^+K^-)$ of any pair of oppositely charged $K^{\pm}$ mesons for the $D^0\gamma$ channel in the chain (9-12). a)Bin size 50 MeV; b)Bin size 2.5 MeV.
3. The missing mass distribution recoiling against the D^0 candidates, as defined in text, for the (a) $D^0\gamma$ channel, (b) $D^0\pi^0$ channel.
4. Effective mass distribution $M(K^+K^-\gamma)$ for the "moderate" detector for the (a) $D^0\gamma$ channel, (b) $D^0\pi^0$ channel.
5. Effective mass distribution $M(K^+K^-\gamma)$ for the "ultimate" detector for the (a) $D^0\gamma$ channel, (b) $D^0\pi^0$ channel.
6. The missing mass squared distribution recoiling against $M(K^+K^-K_e^+e^-\gamma)$ for the "moderate" detector for the (a) $D^0\gamma$ channel, (b) $D^0\pi^0$ channel.
7. The missing mass squared distribution recoiling against $M(K^+K^-K_e^+e^-\gamma)$ for the "ultimate" detector for the (a) $D^0\gamma$ channel, (b) $D^0\pi^0$ channel.
8. The missing mass squared distribution recoiling against $M(K^+K^-K_e^+e^-\gamma)$ for the $D^0\gamma$ channel, when the semileptonic D^0 decay in (12) is replaced by all the known D^0 decays other. than the $Ke\nu$ one.



$R_{D*} = \sigma^0(e^+ e^- \rightarrow D^* + X)/\sigma^0{}_{\mu\mu}$
Crystal Ball
4
3
2
1
0
3.6
3.8
4
4.2
(Gev)
4.4
4.6
E_{cm}

Fig. 1



X10^3
(a)
ENTRIES/.05
K+K-
1.2 1.6 2.0 2.4 2.8
(b)
ENTRIES/.0025
K+K-
1.82 1.84 1.86 1.88 1.90

Fig 2

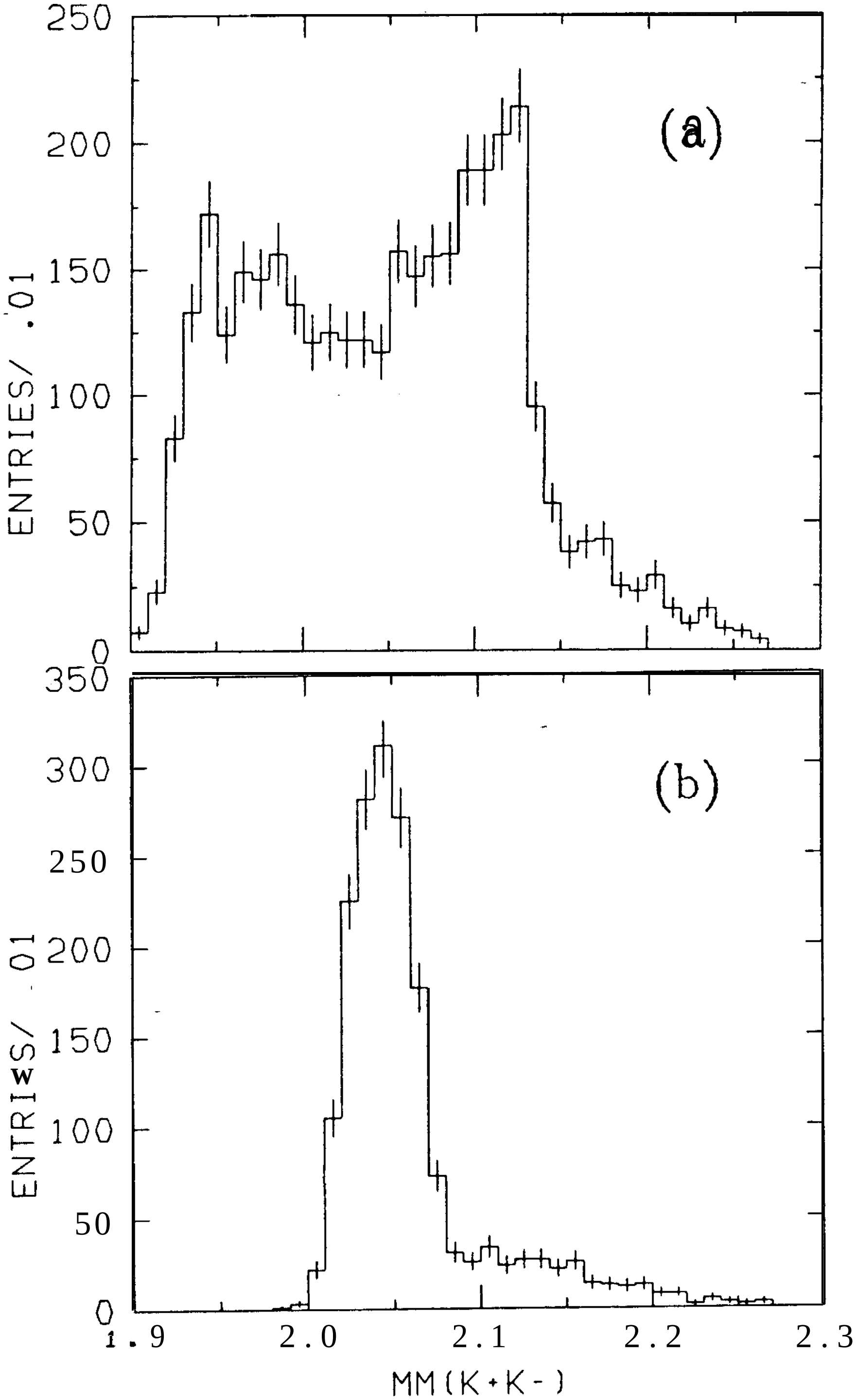
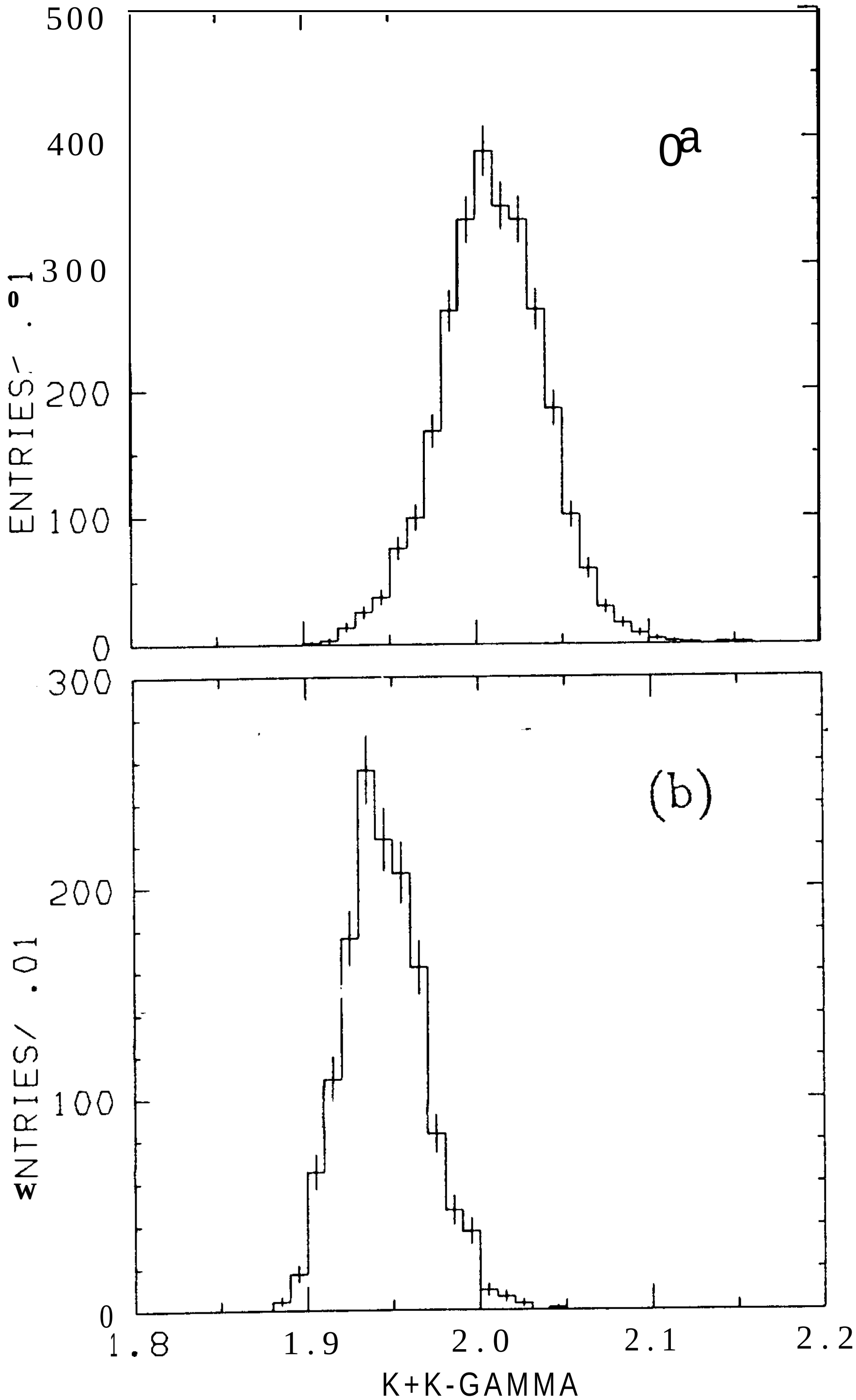

(a)
(b)
ENTRIES/ .01
ENTRIwS/ . 01
MM(K+K-)
250
200
150
100
50
0
350
300
1.9
2.0
2.1
2.2
2.3

Fig. 3



500
400
300
200
100
0
ENTRIES/ .01
(a)
300
200
100
0
ENTRIES/ .01
(b)
1.8
1.9
2.0
2.1
2.2
K+K-GAMMA

Fig. 4

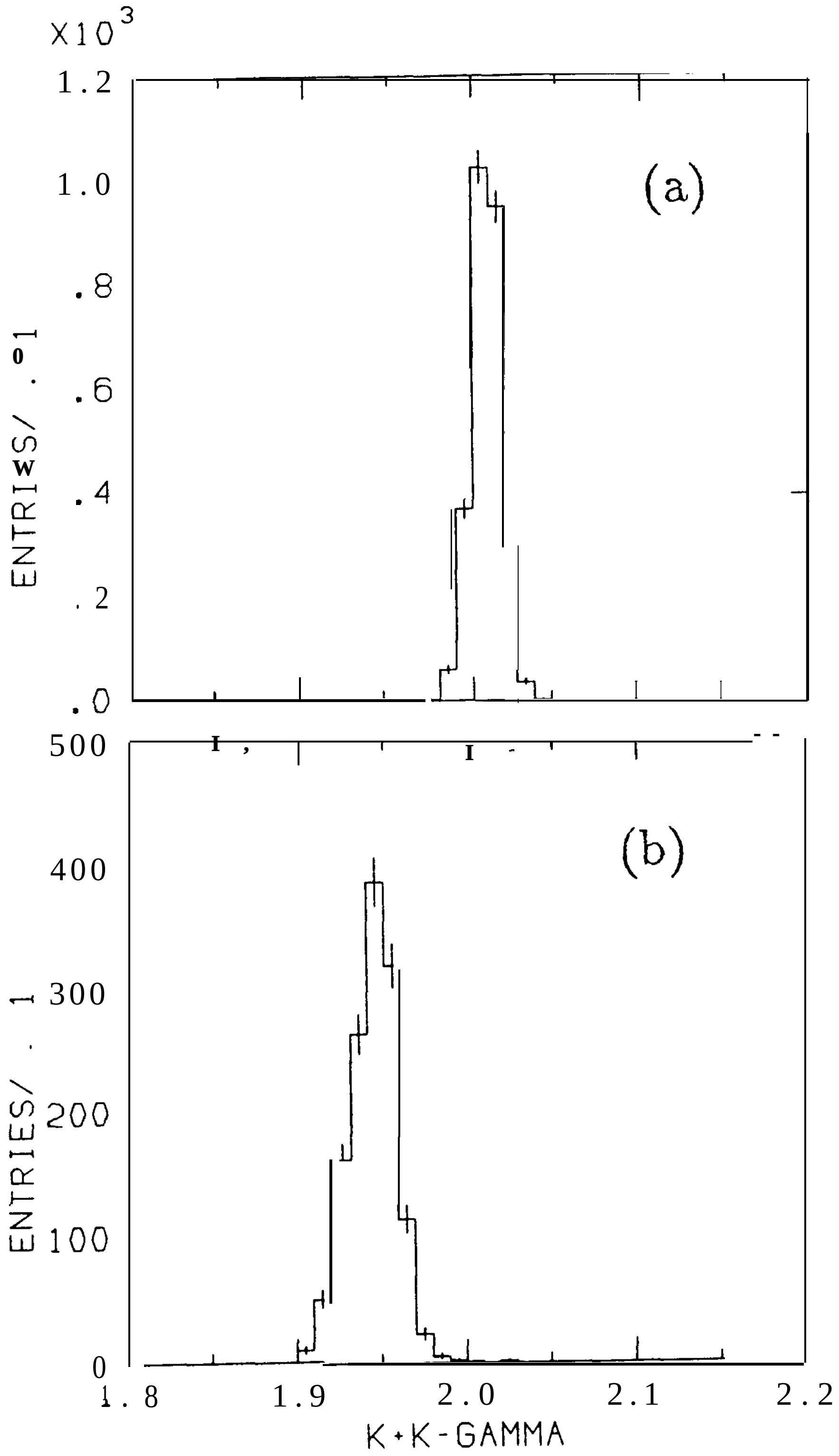

X10³
1.2
1.0
.8
.6
.4
.2
.0
ENTRIES/ .01
(a)
500
400
300
200
100
0
ENTRIES/ .01
(b)
1.8
1.9
2.0
2.1
2.2
K+K-GAMMA

Fig. 5

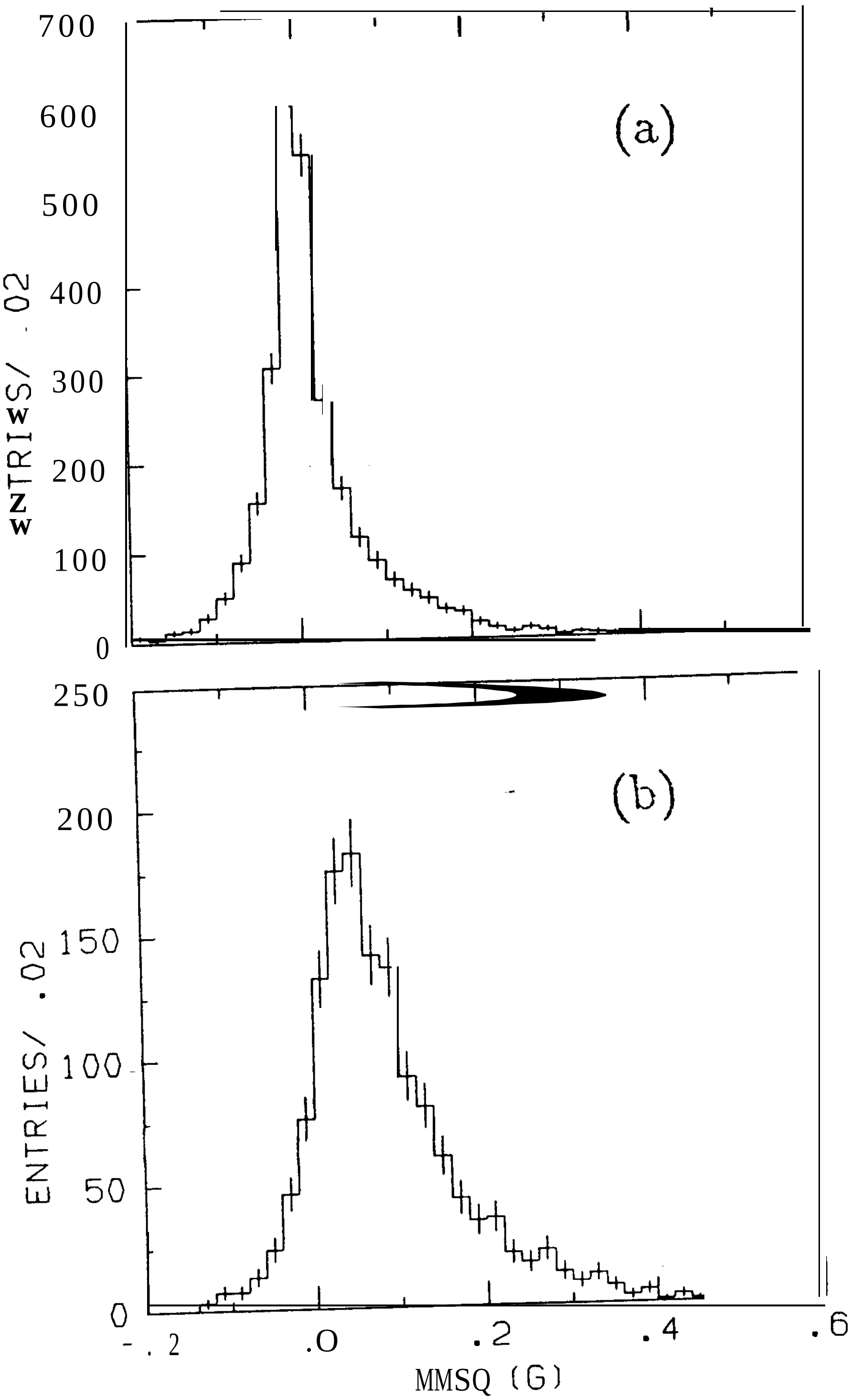

(a)
(b)
700
600
500
400
300
200
100
0
ENTRIES/ .02
250
200
150
100
50
0
-.2
.O
.2
.4
.6
MMSQ (G)

Fig. 6

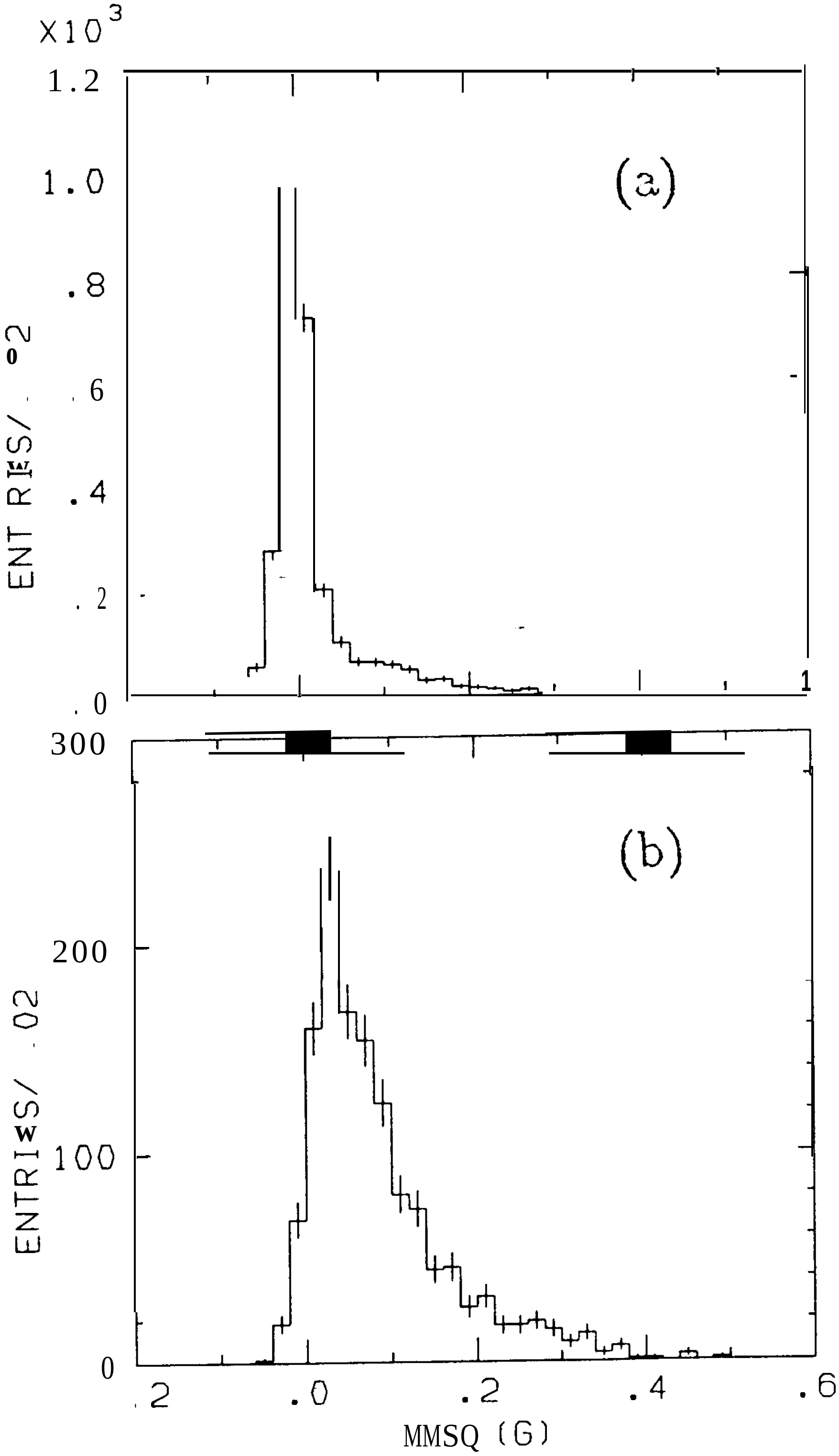


Fig. 7

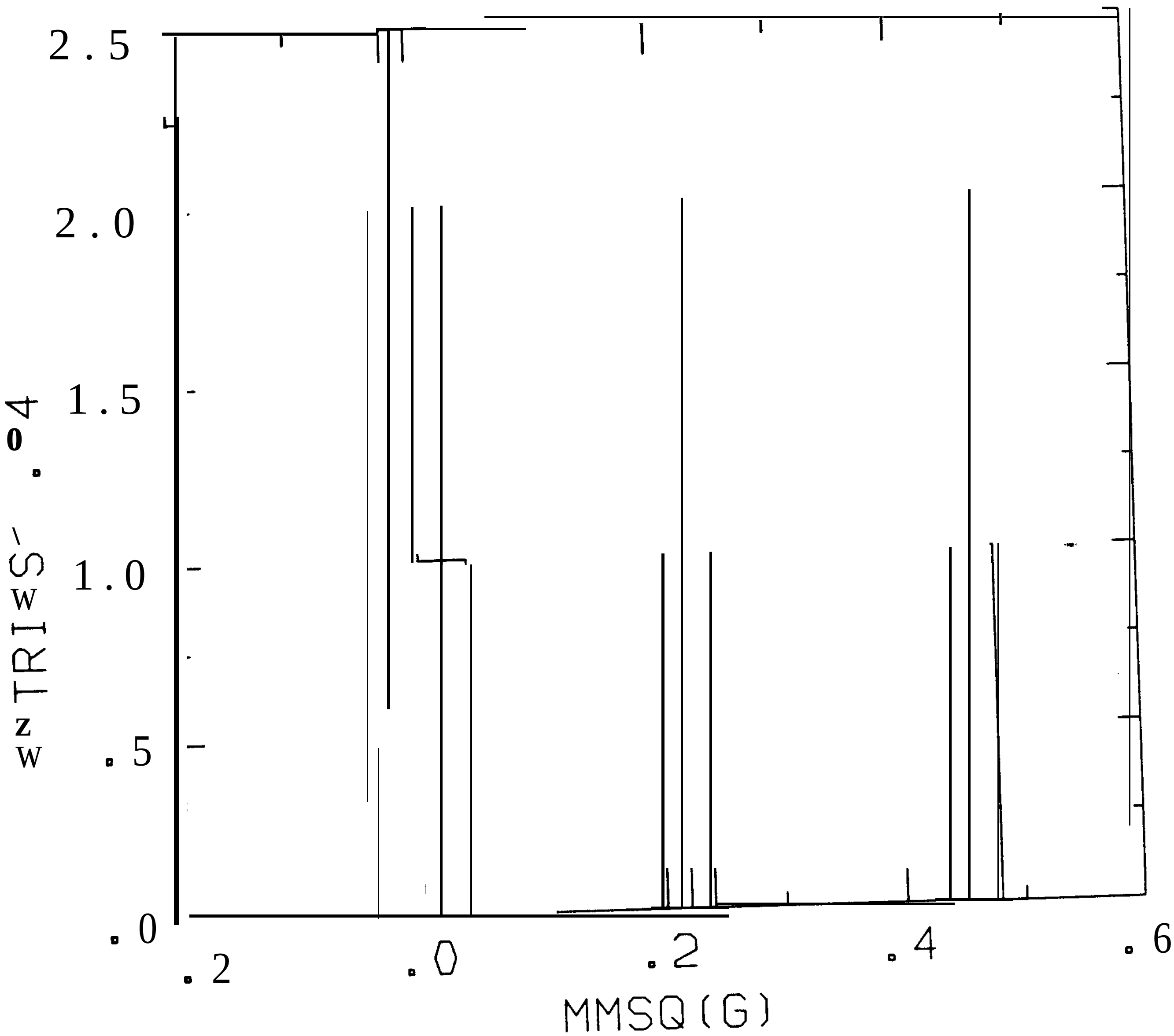


Fig. 8