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Quasi-Free Strangeness Production in Nuclei

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Quasi-Free Strangeness Production in Nuclei

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ABSTRACT

We propose to use the tagged photon beam in the CLAS to measure the (γ, K) yield in ^{3}He, ^{4}He, and ^{12}C, in the kinematics of the quasi free $N(\gamma, K)Y$ reaction ($Y = \Lambda, \Sigma$). We discuss how particular aspects of these measurements will: 1) Test the extrapolation of the elementary (γ, K) amplitudes to the nuclear medium; 2) Test the one-body hypothesis for the (γ, K) response in nuclei; and 3) Probe the kaon-nucleus interaction. We request 150 hours on each target, with an incident electron energy between 1.6 and 2.0 GeV.

1. Introduction

The quasi elastic (e, e') and $(e, e'p)$ reactions have provided a wealth of information about the one-body and two-body structure of nuclei. The early (e, e') data (*e.g.* Ref. 1) were well described by the fermi-gas model. The $(e, e'p)$ experiments provided an almost direct observation of the shell model orbits in the nucleus.[2] More detailed investigations, however, revealed a number of important complications. The spectral shape of the inclusive data, particularly in the "dip" region between the quasi-elastic and quasi-free Δ peaks could not be accounted for in a purely one-body model.[3] The ratio of the cross sections for absorption of longitudinal and transverse polarized virtual photons is anomalously low, relative to the free nucleon.[4] The coulomb sum-rule of the integrated longitudinal cross section at fixed momentum transfer is 10% to 30% less than the nuclear charge Z, even for momentum transfers greater than twice the nuclear Fermi momentum p_F.[5,6] These phenomena may be explainable by a combination of two-nucleon correlations and two-body currents in the reaction itself. From both the experimental and theoretical side, this is a fascinating story that is not yet complete. The quasi free $N(\gamma, K)Y$ reaction (the hyperon Y is either a Λ or a $\Sigma^{+,-,0}$, the kaon is either K^+ or K^0) offers an important opportunity to continue these studies with a new probe.

The quasi elastic (e, e') and (γ, K) reactions are illustrated in Fig. 1. We note that even for real photons, the energy transfer $k - E_K$ and the invariant momentum transfer

$$t = (k_\mu - K_\mu)^2 \tag{1.1}$$

are independent kinematic vaiables. Thus kinematically the (e, e') and (γ, K)

reactions are qualitatively equivalent.

Just as the (e, e') and $(e, e'p)$ reactions probe the elastic γN vertex in the nuclear medium, the $(\gamma, K)Y$ reactions (with real or virtual tagged photons) probe the exclusive $N(\gamma, K)\Lambda, \Sigma$ vertex functions in the nuclear medium. All of the final state particles under discussion ($K^+, K^0, \Lambda^0, \Sigma^{+,0,-}$) are stable particles that cannot decay or be absorbed in the nucleus. The particles can charge exchange $K^+ \leftrightarrow K^0$ and $\Lambda^0 \leftrightarrow \Sigma^+ \leftrightarrow \Sigma^0 \leftrightarrow \Sigma^-$, but for every KY pair produced on a nucleon, a KY pair must emerge from the nucleus. The only exceptions are the small amplitudes for hypernuclear formation (a $\Lambda - A$ bound state) or KY recombination *after* rescattering. Thus the total strangeness production cross section in these kinematics must directly reflect the in-medium amplitude.

2. Elementary Amplitudes

The inclusive (γ, K) yield in nuclei will include the incoherent contribution of the following six reactions:

$$\begin{aligned}
\gamma + p &\to K^+\Lambda \\
\gamma + p &\to K^+\Sigma^0 \\
\gamma + n &\to K^+\Sigma^- \\
\gamma + n &\to K^0\Lambda \\
\gamma + n &\to K^0\Sigma^0 \\
\gamma + p &\to K^0\Sigma^+
\end{aligned} \tag{2.1}$$

Only the first two have been measured. The proton amplitudes will be remeasured with much greater precision with the CLAS. The neutron amplitudes will be extracted from $D(\gamma, K)$ data also from the CLAS.

The existing data have been parameterized in an extensive set of effective Lagrangian theories, using an assortment of K, K^*, N, Y, N^*, and Δ exchange graphs. Ref. 7 - 10 are a representative sample. Applying isospin symmetry to the hadronic vertices and (in some cases) known electromagnetic couplings, these models make specific predictions for the heretofore unmeasured amplitudes. For example, the model of Ref. 10 has only two free parameters – the $n + \gamma \rightarrow N^*$ (1650) and (1710) couplings – with which to fit the future $n(\gamma, K)$ data. The model of Ref. 8 is even more restrictive, with only a single sign ambiguity in the neutron case, as we discuss below.

We apply isospin symmetry to the hadronic vertices of the five graphs of Ref. 8 (N, Λ, Σ, K, and K^*[892] exchange). The relevant electromagnetic couplings are known for all five graphs in the $n(\gamma, K^0)\Lambda$ case, except that only the magnitude of the $K^0 + \gamma \rightarrow K^{0*}$ transition moment is known from the K^* decay.[11] From a naïve quark model calculation, we determine that the K^{*0} coupling has the opposite sign as the K^{*+} coupling. This results from a spin triplet to spin singlet transition with quark magnetic moments taken from Ref. 11. We display $n(\gamma, K^0)\Lambda$ cross section obtained from this model in Fig. 2.

For this proposal, we note that the predicted total cross section on the neutron is approximately 2.5 times greater than the proton cross section, and that the neutron cross section is backward peaked in the center of mass. Similar features are found in the model of Ref. 12 for the $n(\gamma, K^+)\Sigma^-$ channel.

3. The Quasi-Free Response

It is important to stress that *ab initio* calculations of the quasi free (γ, K) response in nuclei will be possible. The primary ingredients to these calculations are the 4-momentum distribution of nucleons in the nucleus, the elementary $N(\gamma, K)Y$ vertex and the final state interactions (FSI) of the kaon and hyperon. Although the kaon final state interaction with the nucleus will distort the kaon momentum distribution and will alter the K^+/K^0 ratio by charge exchange, the total kaon yield is unaffected by the FSI. This is a consequence of strangeness conservation. Similarly, although the hyperon FSI can alter the inclusive (γ, K) spectral shape, the absence of the Pauli principle acting on the final state hyperon implies that the total kaon yield will be insensitive to hyperon FSI. Thus the experiment proposed here will provide a comprehensive test of our understanding of quasi-free reactions.

For the quasi-free strangeness production on a nucleon of momentum $\mathbf{p}_N$ and energy E_N in a nucleus, the (γ, K) energy and invariant momentum transfer are related by:

$$
\begin{aligned}
k - E_K &= \frac{-t}{2E_N} + \frac{M_Y^2 - (E_N^2 - \mathbf{p}_N^2)}{2E_N} + \frac{[\mathbf{k} - \mathbf{K}] \cdot \mathbf{p}_N}{E_N} \\
&\approx \frac{-t}{2M_N} + \frac{M_Y^2 - M_N^2}{2M_N} + \frac{[\mathbf{k} - \mathbf{K}] \cdot \mathbf{p}_N}{M_N}.
\end{aligned} \tag{3.1}
$$

This quasi free response is illustrated in Fig. 3. In this figure, the proton momentum $\mathbf{p}$ was picked at random from a plane-wave fermi gas with fermi-momentum $p_F = 200$ MeV/c and binding energy $B = -30$ MeV such that the proton energy is

$$E_p = \sqrt{M_N^2 + \mathbf{p}^2} + B. \tag{3.2}$$

For simplicity, the kaon scattering angle is chosen uniformly in the (photon plus proton) center-of-mass frame. As expected from Eq. (3.1), Fig. 3 clearly illustrates that the position and width of the quasi-free peak (in an energy loss spectrum) are proportional to the invariant momentum transfer squared and the three momentum transfer, respectively.

Eqn. (3.1) and Fig. 3 suggest a y-scaling analysis. We define

$$y_\Lambda = \left[(k - E_K) + \frac{t}{2M_N} - \frac{M_\Lambda^2 - M_N^2}{2M_N} \right] / |\mathbf{k} - \mathbf{K}| \, . \tag{3.3}$$

y_Λ is defined in terms of measured quantities, however, for the fermi gas:

$$y_\Lambda \approx \mathbf{p}_{\|}/M_N, \tag{3.4}$$

where $\mathbf{p}_{\|}$ is the component of the nucleon's initial momentum along the 3-momentum transfer direction. The calculated fermi-gas response is displayed in the $(y_\Lambda, -t)$ plane in Fig. 3, illustrating that as a function of y_Λ the response is nearly independent of invariant momentum transfer.

Simply comparing a large data set with a sophisticated calculation (even a parameter free calculation) is not completely satisfactory. In the next sections, we discuss measurements to isolate specific aspects of the quasi free (γ, K) reaction.

3.1 The Integrated Response

The (γ, K) response at fixed photon energy, integrated over kaon solid angle, energy and charge state should be independent of the K or Y final state interaction. This integrated response should depend only on the sum of the elementary $N(\gamma, K)\Lambda$ and $N(\gamma, K)\Sigma$ amplitudes integrated over the nucleon momentum distribution in the nucleus. The Λ and Σ amplitudes will not be resolved in an inclusive (γ, K) measurement, because the splitting (75 MeV) is comparable with the Fermi broadening (± 80 MeV for momentum transfer to baryon of 400 MeV/c). The comparison of this yield in isoscalar nuclei to the yield on the deuteron provides a very clean test of the one-body ansatz. This comparison is largely insensitive to details of the extraction of the $n(\gamma, K)$ amplitude from the $D(\gamma, K)$ data. Instead, the $C : He : D$ ratios are sensitive to effects such as enhanced two body currents $NN(\gamma, K)YN$. These effects need not be small. The coulomb sum rule is suppressed by 10% in ^{12}C, and 30% in Ca and Fe. Therefore, it is not unreasonable to expect effects of similar magnitude in the integrated (γ, K) response.

3.2 The K^+ to K^0 Yield Ratio

The double ratio $\left[{}^A Z(\gamma, K)^+/(\gamma, K)^0\right]/\left[D(\gamma, K)^+/(\gamma, K)^0\right]$ for an isoscalar nucleus ${}^A Z$ provides a direct measure of the charge exchange part of the kaon final state interaction. This charge exchange should be dominated by one pion exchange. Similarly, the double ratio for the $(\gamma, K)\Lambda/(\gamma, K)\Sigma$ coincidence reactions will measure the charge exchange part of the hyperon final state interaction.

The absolute sensitivity of this double ratio experiment to kaon charge exchange is governed primarily by the elementary K^+/K^0 ratio. If this ratio is significantly different from unity, then, for example, a 10% measure of the double ratio yields an approximately 10% measure of the charge exchange probability. The relative uncertainty in the charge exchange probability depends in addition on the charge exchange magnitude. The simple $1/\sigma\rho$ formula (neglecting nucleon pauli blocking) estimates the kaon mean free path in nuclei to be ≈ 10 fm for $|\mathbf{K}| < 800$ MeV/c, and purely elastic. For $|\mathbf{K}| > 1$ GeV/c, the kaon mean free path is ≈ 5 fm. and dominated by Δ excitation of the nucleon. For the kaon momenta of interest here the rescattering probability in ^{12}C. with or without charge exchange. is between 10% and 50%.

Aside from the general interest in the kaon nucleus potential. this measurement has significance for the formation of hypernuclei. The large $n(\gamma, K^0)\Lambda$ amplitude discussed in the previous chapter suggests the possibility that the (γ, K) reaction can populate hypernuclei by a two body current. For example. the $n(\gamma, K^0)\Lambda$ amplitude can be followed by a coherent $p(K^0, K^+)n$ charge exchange. This process would share the large ($>$ 400 MeV/c) momentum transfer with two nucleons.

3.3 ^{3}He. ^{4}He. ^{12}C

The ^{3}He nucleus provides an important test for the elementary amplitudes to be extracted from the proton and deuterium data. After the deuteron. ^{3}He is the simplest nucleus for which exact bound state wave-functions exist. We also anticipate significant progress in the theory of the continuum three and four body problems. Thus it is possible to envision a completely microscopic description of the ^{3}He(γ, K) reaction.

Using the deuteron as a benchmark. ^{4}He and ^{12}C provide a progression of isoscalar targets for the studies outlined above. We choose isoscalar targets (aside from the special case of ^{3}He) so that the neutron and proton amplitudes are weighted equally. We choose these light systems because they are relatively simple, and the inclusive (e, e') response discussed in the introduction shows significant variation from D to C.

3.4 Higher Resonances

The ideas outlined above are complicated in part by the excitation of higher hyperon and kaon resonances, notably the $\Sigma^*(1385)$. The missing energy separation of the Λ and $\Sigma(1385)$ peaks on the free proton is 360 MeV. At high momentum transfer the quasi-free Σ^* excitation will overlap the Σ excitation. This difficulty will be addressed in several ways. The threshold for free Σ^* excitation is 1.4 GeV. The threshold for Σ^* excitation in the fermi-gas is 1.2 GeV. Thus the low energy spectra (0.9 GeV$< k <$ 1.3 GeV) will be free of the higher resonances. At higher photon energies the low t spectra will still separate the resonances from the ground state hyperons. For $k \geq 1.4 GeV$ and large three momentum transfer the resonance production can be included in the analysis, since these amplitudes will also be present in the deuterium and proton data.

4. Experimental Requirements

The inclusive (γ, K) response offers a rich physics program, which can be pursued essentially "all-at-once" with the CLAS in conjunction with the photon tagger. The tagger is required to establish the kinematics of the initial state. The fully-instrumented CLAS will be needed to detect and record the multi-particle final states. Typical events we must reconstruct are: (γ, K^+), $(\gamma, \pi^+\pi^-)$ for K^0 reconstruction, $(\gamma, K^+p\pi^-)$ for Λ reconstruction, $(\gamma, K^+n\pi^-)$ for Σ reconstruction, *etc.*

4.1 TRIGGERING

Because of the difficulty of triggering on K^0 events directly, we will seek to record all events in which at least 1 charged particle is tracked through all 3 layers of drift chambers to the scintillation counters. We assume a photon tagging rate of 10^7/ sec with a tagging range of $50\% < k/E_e < 95\%$, where E_e is the incident electron beam energy. We assume the CLAS data acquisition system will be able to handle a 1.5 kHz rate. In order to estimate trigger rates, we assume a constant $200\mu b$ per nucleon cross section above π threshold. Assuming a 1 g/cm^2 target, we have a tagged luminosity of 6 / μ b /sec, or a real (γ,hadron) rate of 1.2 kHz. To this we must add the accidental tagged-gamma hadron coincidences. The accidental rate is the photon tagging rate times the hadron singles rate times the coincidence resolving time. With a $1/k$ photon spectrum, and E_e between 1.6 GeV and 2.0 GeV, we obtain a total (untagged) rate of less than 5 kHz events in the target above π threshold. Assuming an on-line resolution of 5 ns in the trigger (off line it will be much better) the accidental rate is 250 Hz. Thus the total trigger rate is approximately 1.5 kHz, as required.

4.2 TARGETS

We propose to run on 1 gm/cm^2 targets of ^{3}He, ^{4}He, and ^{12}C. For ^{12}C, this is a simple solid target. In order to make high precision comparisons of the C yield with the yield on He and D, we may choose to use a multi-segment C target. For He, we require a cryogenic liquid target cell approximately 8 cm long. We will investigate the possibility of bringing an existing target to the CLAS.

4.3 BEAM

The exact beam energy is not critical for this experiment. A minimum incident electron energy of 1.6 GeV is required in order to tag photons from Λ threshold up to the Σ^* and Λ^* threshold. Above 2 GeV, the singles rates are considerably larger, and the (γ, K) response will have large contributions from the higher hyperon resonances.

4.4 ACCEPTANCE AND RATES

We consider the $p(\gamma, K^+)\Lambda$ reaction as proto-typical of the six amplitudes. The cross section rises sharply at threshold (911 MeV). At 1.2 GeV, the total cross section is $\approx 2.5\mu b$. At higher energy the cross section rises slowly. For average rate and acceptance estimates, we assume a constant $2.5\mu b/(4\pi)$ differential cross section in the center-of-mass, independent of energy above threshold. We studied the CLAS acceptance for events generated from a fermi-gas distribution using the FAST monte carlo code.[13]

We generate events by first picking the proton momentum at random in the fermi gas, with energy specified by Eq (3.2). If the photon plus proton invariant mass is above threshold, then the event is kept and the kaon is generated at random in the local center-of-mass (CM) frame.

The kaon distributions for incident photons of 1.1 GeV and 1.5 GeV are shown in Fig. 4. The CLAS acceptance for these events is displayed in Fig. 5. The kaon acceptance as a function of incident energy is shown in Fig. 6. These figures do not include the probability for the kaon to decay before reaching the scintillator, which we take to be 50%. Except very close to threshold, the acceptance is everywhere greater than 10%.

Very conservatively, we expect

$$
\begin{aligned}
p(\gamma, K^+)\Lambda \text{ Rate} &= \text{Luminosity } \cdot \text{Cross section} \\
&\quad \cdot \text{Acceptance} \cdot \text{Survival Probability} \\
&= (6/\mu b/\text{sec}) \cdot 2.5\mu b \cdot 10\% \cdot 0.5 \\
&= 0.75 \text{ Hz.}
\end{aligned}
\tag{4.1}
$$

Similar rates will be obtained for the other two K^+ channels in Eq. (2.1), for a total rate of 2.2 Hz. We propose to divide the entire kinematic domain into 100 spectra, with 10 bins each in photon energy and in momentum transfer. The remaining kinematic variable is the energy transfer, or equivalently the scaling variable y_Λ. Each spectrum will count at an average rate of 0.022 Hz. The increase in efficiency and cross section with increasing energy is partially balanced by the $1/k$ photon spectrum. In 150 hours, we will obtain greater than 10,000 (γ, K) counts per spectrum.

We also studied the acceptance for K^0 events, and found an acceptance of $\approx 10\%$. This includes the $K^0 \to K_S^0$ and $K_S^0 \to \pi^+\pi^-$ decay probabilities, but does not include the pion survival probability. Thus the K^0 counting rates will be comparable with the K^+ rates.

5. Near Term Developments

We are proposing to measure the (γ, K) response with 1% statistical precision. Our systematic uncertainties will depend primarily on the change in acceptance from deuterium to nuclei. The additional smearing of the quasi-free response in nuclei relative to deuterium may smear some of the (γ, K) yield into the region of zero CLAS acceptance. We will model the kaon rescattering in the nucleus to estimate the precision obtainable for the total strangeness production measurement. We note from Fig. 4–5 that although the average acceptance is greater than 10%, the acceptance is near zero for $p < 200$ MeV/c, $\theta > 90°$, or $\theta < 10°$. This represents less than 10% of the kaon yield that is missed. From deuterium to carbon we expect that the change in the missing yield will be less than 10% of the total yield. Thus we should be able to measure the change in the total yield per nucleon to within a few percent.

We will also study the CLAS acceptance to reconstruct Λ and Σ decays. The (γ, KY) coincidence reaction is analogous to the $(e, e'p)$ reaction. We can expect a missing mass resolution of approximately 5 MeV.

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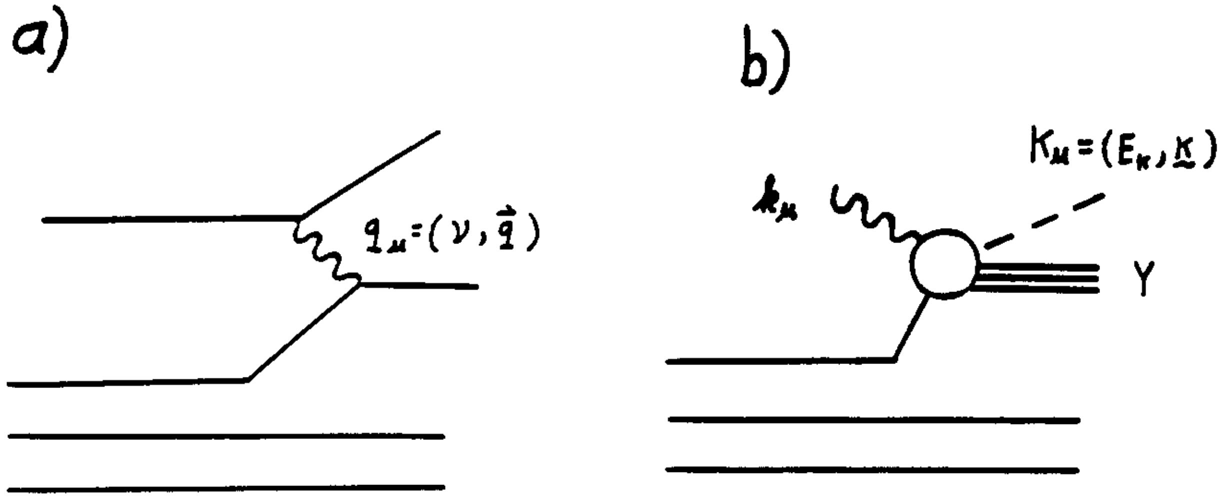

Fig. 1. a) The quasi elastic (e,e') reaction. b)The quasi free (γ,K) reaction.

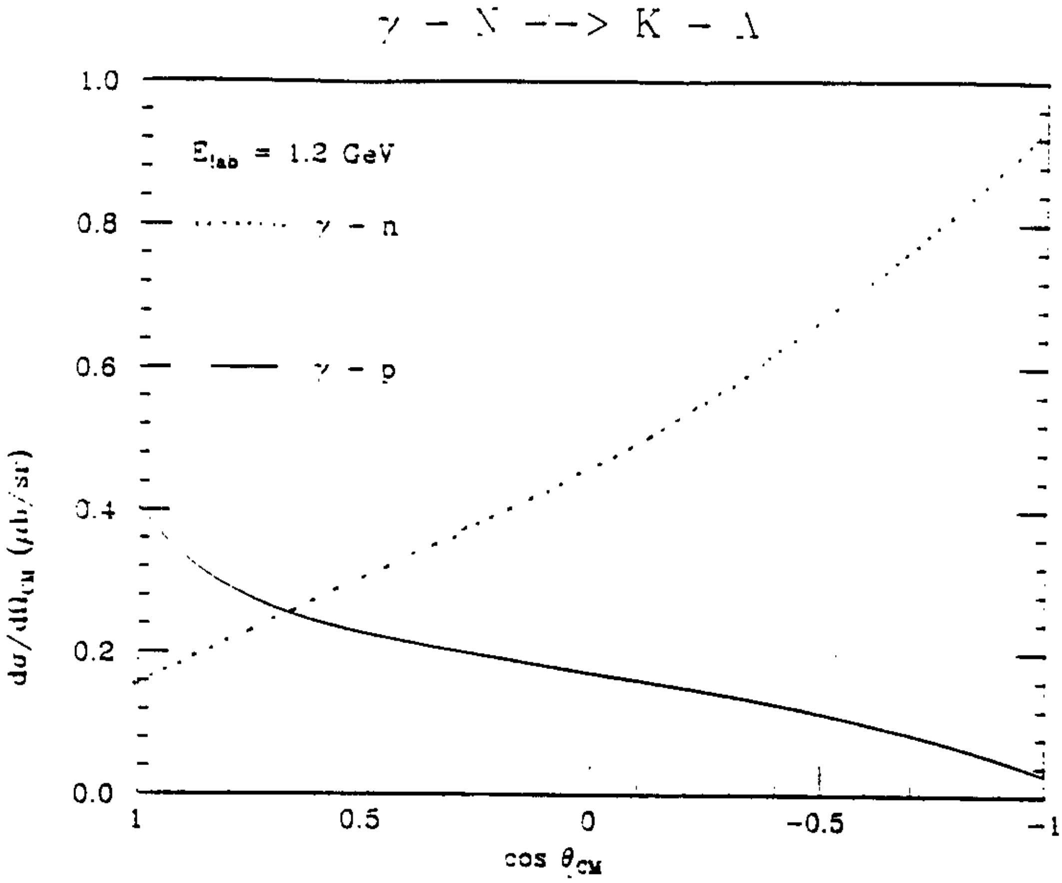

Fig. 2. The $N(\gamma, K)\Lambda$ cross section for $k = 1.2$ GeV, obtained from the model of Ref. 8, as described in the text.

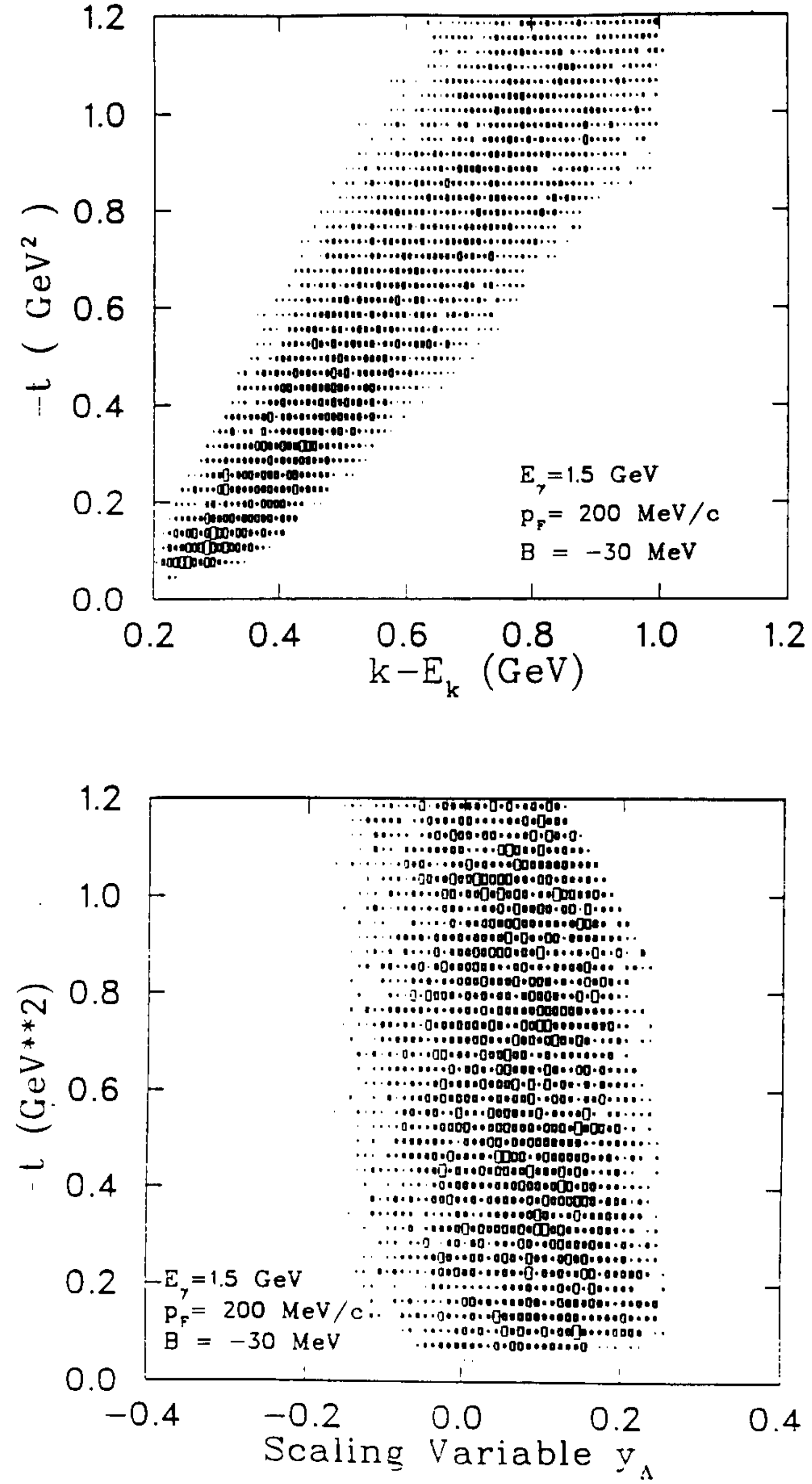

Fig. 3. The quasi free $p(\gamma, K)\Lambda$ response surface. Top: Invariant momentum transfer vs. Energy transfer. Bottom: Invariant momentum transfer vs y-scaling variable defined in text. The event generator is described in the text.

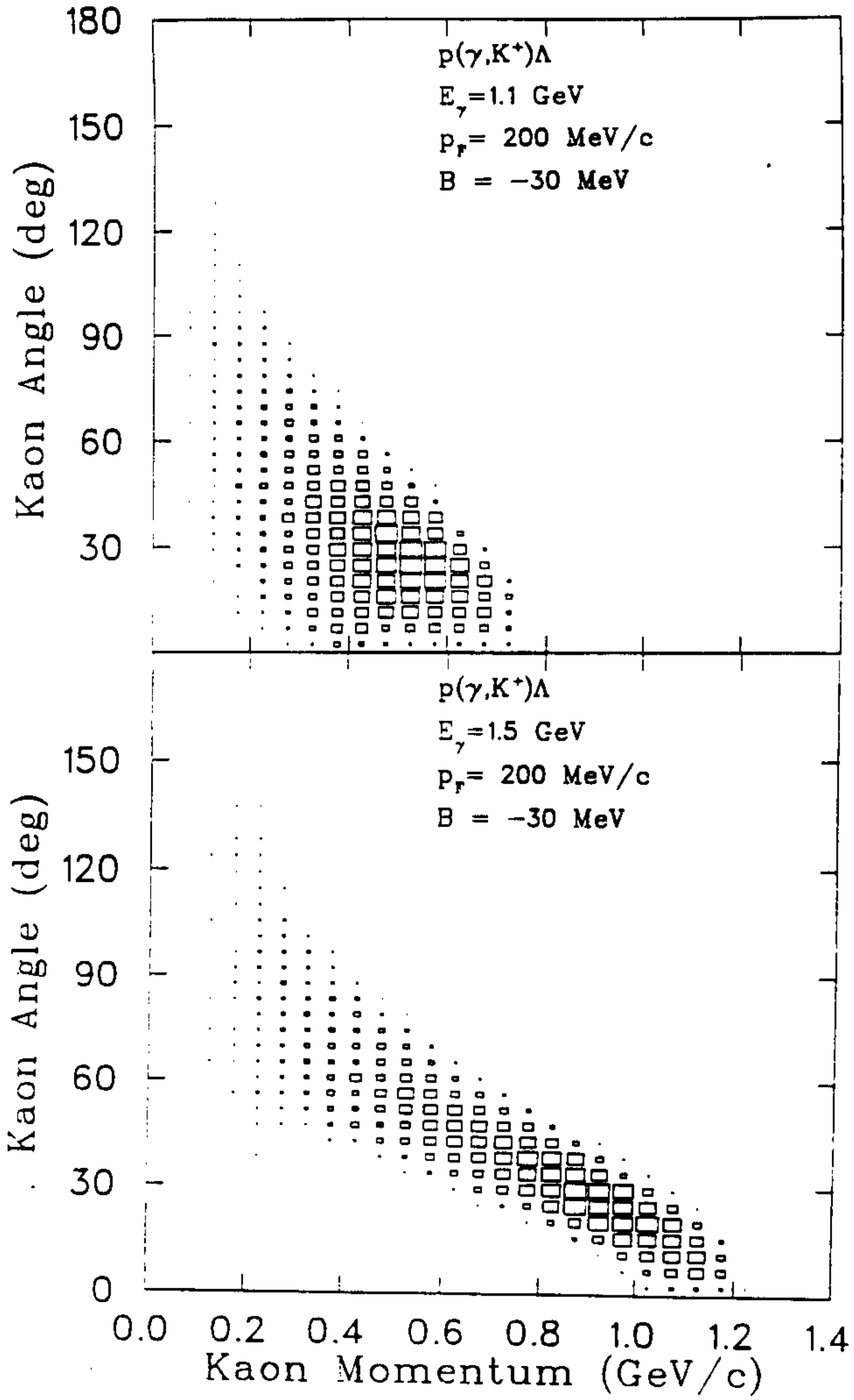

Fig. 4. 10000 event sample of generated kaons, at two different photon energies.

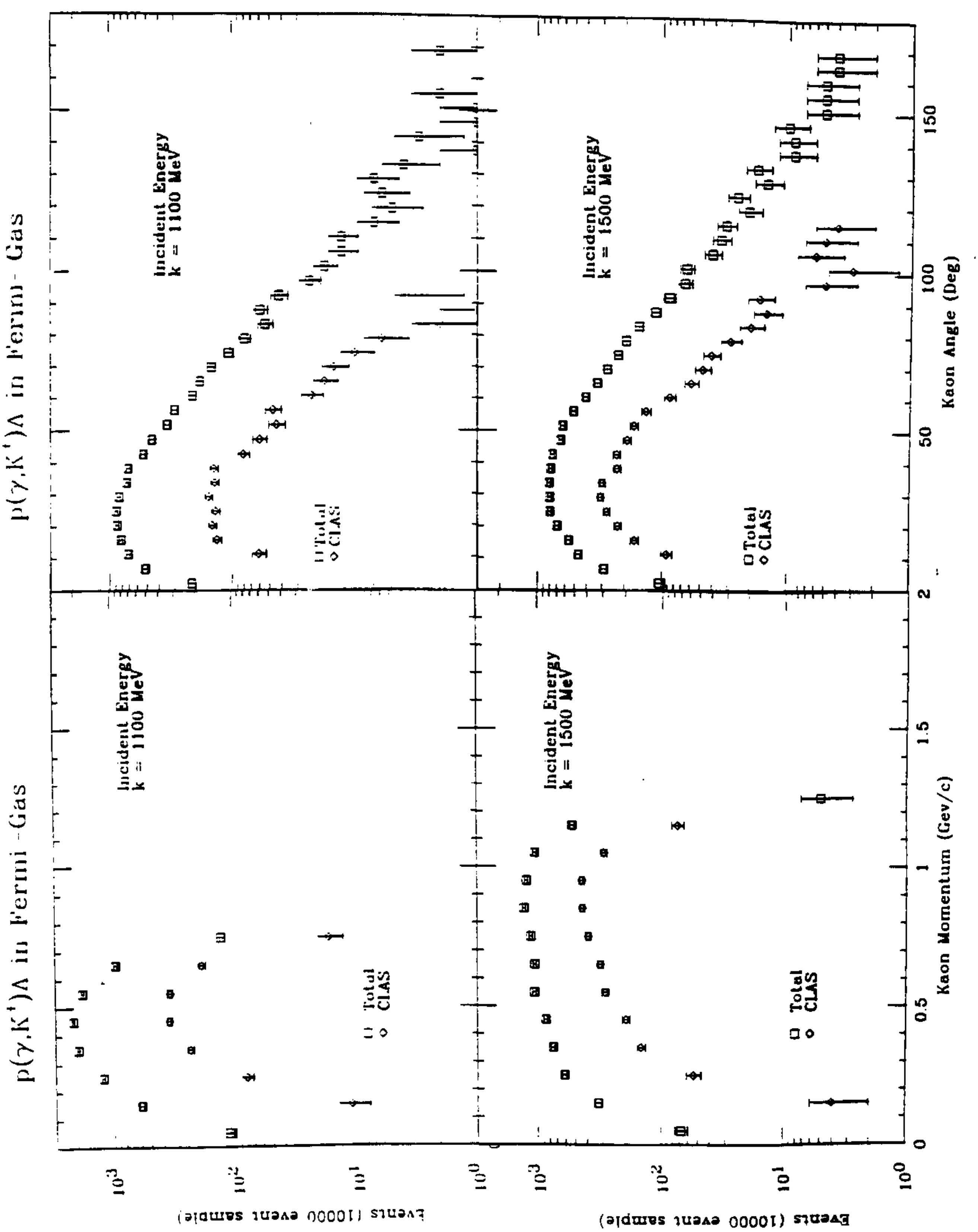

Fig. 5. Kaon momentum and angle distributions for the event samples of Fig. 4. Squares: total events. Diamonds: Kaons tracked through all three drift chambers and the scintillator.

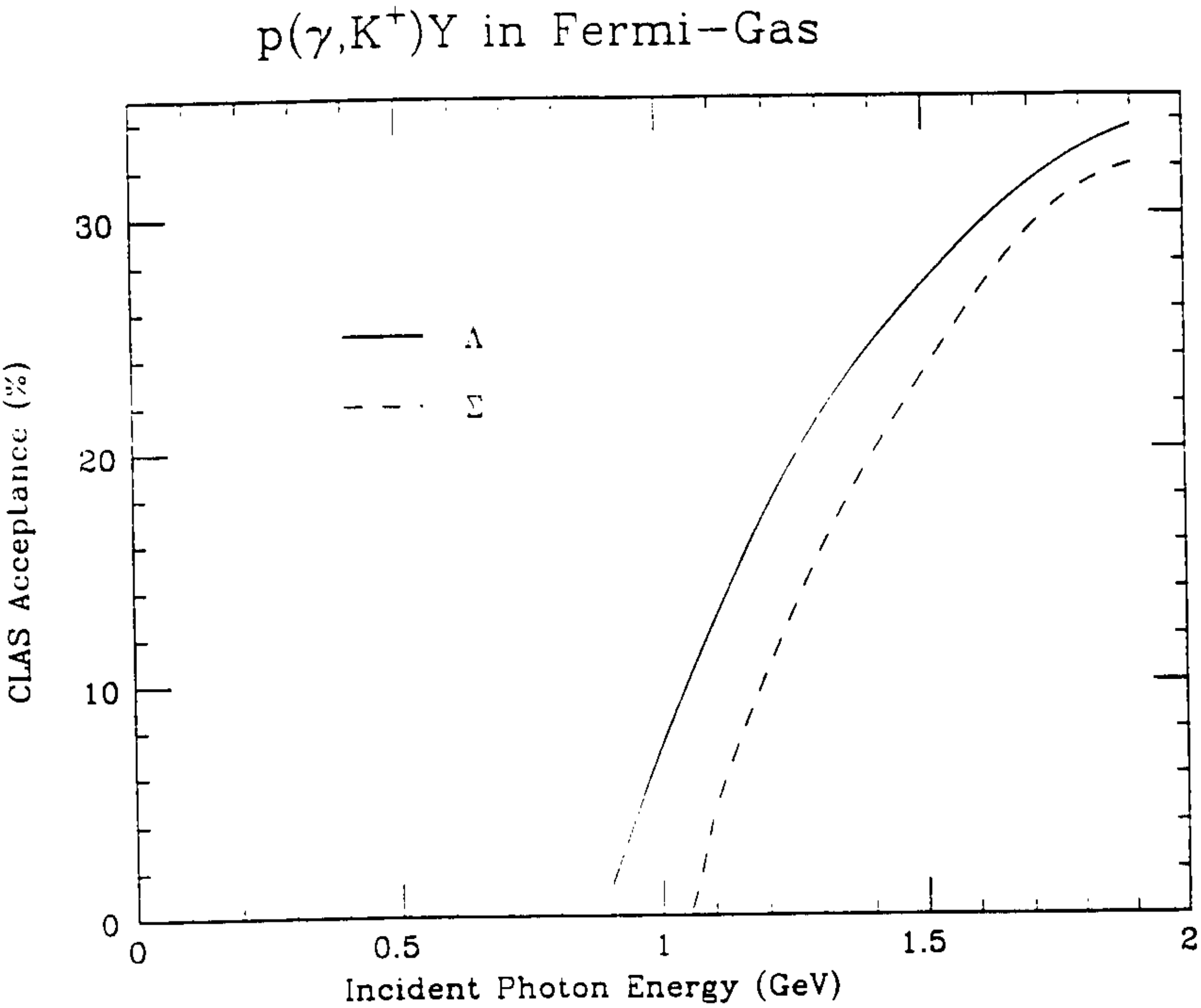

Fig. 6. CLAS acceptance for the $p(\gamma, K)\Lambda$ and $N(\gamma, K)\Sigma$ reactions in the fermi gas.