Measurement of the total cross section of the reaction $K^-p\rightarrow\Sigma^0\gamma$ between 514 and 750 MeV/c

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We report the first measurements of the total cross section of the reaction $K^- p \rightarrow \Sigma^0 \gamma$ at eight beam momenta from 514 to 750 MeV/c. The data were obtained at the Alternating Gradient Synchronotron (AGS) at Brookhaven National Laboratory using the Crystal Ball detector consisting of 672 NaI crystals. All charged particles were vetoed by a barrel of plastic scintillators, resulting in a study of only the neutral decays of the $\Sigma^0$. The prompt photon and the photons from the decay products of $\Sigma^0$ were detected for each reconstructed event; the neutron was also detected in a small fraction of the events.


I. INTRODUCTION

The study of radiative decays of hyperon excited states can be used to investigate the configuration of the constituents of these states. The decay widths of excited hyperons, such as those from $\Sigma^0(1385) \rightarrow \Sigma^0 \gamma$ or $\Lambda(1405) \rightarrow \Sigma^0 \gamma$, can provide information on the SU(3)$_f$-breaking or SU(6)-breaking mechanisms, or on possible $qgq(q\bar{q})$ components. Many quark models have been developed to explain the structure of the excited states, and a number of these models are summarized in Ref. [1]. All of these involve the capture of kaons at rest. Unfortunately, no theoretical calculations exist for the in-flight capture of kaons by a proton leading to the $\Sigma \gamma$ final state. For capture at rest, numerous calculations have been made to predict the resonance radiative widths or the branching ratios involving reactions, including $K^- p \rightarrow \Sigma^0 \gamma$ or $K^- p \rightarrow \Lambda \gamma$. These reactions are some of the simplest ones that involve a strange quark. The calculations are made within the framework of different models, such as the nonrelativistic constituent quark [2,3], MIT bag [3], chiral bag [4], cloudy bag [5], chiral constituent quark [6], relativized constituent quark [7], soliton [8], and Skyrme [9] models, as well as those that use lattice-quenched QCD [10], the heavy-baryon chiral perturbation approach (HB$\gamma$PT) [11], and an algebraic model [12]. Predictions of the radiative widths using the $\Sigma^0 \gamma$ channel, for most models above, are around 20 keV for the $\Sigma^0(1385)$, between 2–155 keV for the $\Lambda(1405)$, and between 17–293 keV for the $\Lambda(1520)$. The predicted branching ratio for $K^- p \rightarrow \Sigma^0 \gamma$ is 2.3 × 10$^{-3}$ for a cloudy bag model [5], (1.8–2.6) × 10$^{-3}$ for a quark bag model [13], and (4–10) × 10$^{-3}$ for HB$\gamma$PT [11]. A pole model [14] calculation predicts values of (3.5–6.6) × 10$^{-4}$. 

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A previous experimental study [15] for $K^- p \rightarrow \Sigma^0 \gamma$ at rest found the branching ratio to be $(1.44 \pm 0.23) \times 10^{-3}$, while another earlier measurement [16] gave an upper limit of $4 \times 10^{-3}$. It is interesting to note that in these two studies, the reaction $K^- p \rightarrow \Lambda \gamma$ was also measured at rest, with smaller values found for this branching ratio. A complementary measurement [17] of the radiative widths of excited-state hyperons, made through photoproduction and subsequent decay into $\Lambda \gamma$, has also been performed, along with another experiment [18] using proton diffractive production reactions to look at $\Lambda \gamma$ with a spectrometer. Hyperon beams [19] have also been used to determine the radiative widths of charged excited-state hyperons. The current experiment has also measured the cross section [20] for $K^- p \rightarrow \Sigma^0 \gamma$. This report describes the first measurement of the total cross section for the $K^- p \rightarrow \Sigma^0 \gamma$ reaction.

II. DETECTOR, BEAM, AND HARDWARE

The measurement was made at the BNL Alternating Gradient Synchrotron (AGS), using the Crystal Ball (CB) detector, which consists of 672 NaI crystals arranged in a spherical shape and subtends a solid angle of 93% of $4\pi$ sr. The spaces for an additional 24 NaI crystals each at opposite poles were left empty to form two “tunnels” for the beam to enter and exit the detector. Each crystal is shaped like a truncated pyramid, with a length corresponding to 15.7 radiation lengths. The crystals point toward the target located at the center of the sphere and are assembled to form a spherical shell with an inner radius of 25.3 cm and an outer radius of 66.0 cm. Electromagnetic showers in the detector were measured with an energy resolution of $\sigma_E/E \sim 2.0\% [E(\text{GeV})]^{0.36}$. The angular resolutions of photons of energy 50–500 MeV were $\sigma_\phi \sim 2^\circ$–3$^\circ$ for the polar angle ($\theta$) and $\sigma_\phi \sim 2^\circ/\sin \theta$ for the azimuthal angle. The liquid-hydrogen target, shaped as a horizontal cylinder, 10.57 cm long and 10.27 cm diameter, with spherical end caps, was located at the center of the CB. It was surrounded by a set of four plastic-scintillator, charged-particle veto counters (veto barrel) in the form of a 120-cm-long rectangular cylinder. Additional beam-veto counters were located upstream of the detector to reject particles far from the nominal beam direction and downstream of the target to eliminate events in which the kaon did not interact with a proton.

A momentum-analyzed and separated beam of kaons was incident on the target. Eight momenta were used, ranging from 514 to 750 MeV/c, with a momentum spread of about 4% at each momentum. A beam particle was defined by the coincidence of signals from three plastic scintillation counters, all located upstream of the target. The first beam counter consisted of eight scintillator strips in a hodoscope, and the other two were spatially separated scintillators. The counters measured instantaneous beam intensities that ranged between 5 kHz at 514 MeV/c and 40 kHz at 750 MeV/c. A set of four multwire drift chambers, each consisting of either two or four wire planes, was located upstream to measure the beam trajectory. Beam contamination due to pions, muons, and electrons was between 7% and 20%, depending on the momentum [22]. None of these particles would produce photons that would reconstruct as signal events, but they affected only the number of incident kaons and were accounted for in beam normalization [22].

Several trigger types were recorded during data acquisition. A BEAM trigger consisted of a coincidence of signals from the three beam counters with no signal from the beam-veto counters. The time-of-flight separation between the kaons and pions in the beam allowed a rejection of pions from the BEAM trigger. A software analysis of the BEAM triggers showed that the kaon fractions in the beam, determined from the time-of-flight spectra over a 6.8 m flight path between the beam counters, were between 79% and 94% of the total number of beam particles, depending on the beam momentum. The main CB trigger consisted of a BEAM trigger and a summed total energy signal of at least 350 MeV deposited in the NaI counters. This main trigger signal was in anticoincidence with signals from the veto barrel counters and the other charged-particle veto counters, making it a neutral trigger.

Before and after taking data with the kaon beam, pion beam data were collected at a beam momentum of 750 MeV/c to determine the energy gains in each NaI counter. At this momentum, the reactions $\pi^- p \rightarrow \pi^0 n$ and $\pi^- p \rightarrow \eta n$ produced copious neutral pions and $\eta$’s that promptly decayed to pairs of photons. A distribution of the invariant mass of these photon pairs formed peaks at the $\pi^0$ and $\eta$ masses, as seen in Fig. 1. The calibration was done by adjusting the gains of the detectors to give the proper reconstructed $\pi^0$ and $\eta$ masses and by minimizing the widths of these mass peaks. More details on the experimental setup and calibrations can be found in Refs. [21] and [22].

![Invariant Mass of Two Photons from $\pi^- p$ Data](image-url)
III. $K^- p \rightarrow \Sigma^0 \gamma$ EVENT SELECTION

The procedure and the general philosophy of the analysis are very similar to that described in Ref. [22], and hence only the salient details will be given in this paper.

The process for neutral channels, $K^- p \rightarrow \Sigma^0 \gamma_1 \rightarrow (\Lambda \gamma_2) \gamma_1 \rightarrow (\pi\pi^0) \gamma_2 \gamma_1 \rightarrow n\gamma_4 \gamma_2 \gamma_1$, produces four photons and a neutron. Each photon or neutron interacting in the CB deposited energy in a “cluster” of crystals, whose sum gave the total energy deposited by the particle, as well as its angular position with respect to the target. A “photon” or “neutron” cluster is defined as a set of 13 contiguous crystals centered around a crystal in which at least 20 MeV of energy is deposited. Within this set of crystals, only those individual crystals that have at least 2 MeV deposited in them were added together to determine the total energy of the cluster.

Several conditions were applied in selecting events with good clusters. If any one of the following conditions existed, the event was rejected in the analysis: (1) Two or more clusters were detected near the entrance of the beam pipe. This requirement rejected events where any remaining charged beam particles traversed the CB. (2) Two or more clusters overlapped each other. In these cases, the energy cannot be reliably divided between the two clusters. (3) A cluster was centered on a crystal immediately adjacent to the tunnel. Photon energy measurements from such clusters were significantly less precise due to leakage of electromagnetic shower into the tunnel.

A further restriction on the data required that the beam trajectory, as measured using the upstream wire chambers, passed through the target. For a neutral trigger to be considered as a $K^- p \rightarrow \Sigma^0 \gamma$ candidate event for analysis, the final requirement was that the invariant mass of at least one pair of clusters should be within a window ($\pm 30$ MeV) centered around the $\pi^0$ mass. Only about 2% of the neutral triggers passed all of these requirements.

$K^- p \rightarrow \Sigma^0 \gamma$ candidate events that satisfied the above criteria produced four photon-induced clusters, and a fifth cluster was present if the neutron interacted within the CB. The probability of the neutron interacting with the NaI crystals and forming a cluster is approximately 20% [23]. The events were divided into two groups as four-cluster or five- (or more) cluster events. In five-cluster events, all five of the final-state particles are detected; whereas in four-cluster events, it is assumed that the four particles detected are the four photons. If there were less than four clusters, the event was rejected, because the event could not be reconstructed because of insufficient information. All events with five clusters or more were considered to be five-cluster event candidates and were analyzed using different combinations of five clusters at a time. If a five-cluster event did not completely reconstruct as a five-cluster $K^- p \rightarrow \Sigma^0 \gamma$ event, it was reanalyzed as a four-cluster event. Of the candidate events for analysis, 21% were five-cluster events and 79% were four-cluster events.

The following process was performed for all event types to identify and tag four clusters as possible candidates for the four photons, $\gamma_1$ to $\gamma_4$. The production photon $\gamma_1$ is identified as the one whose missing mass is closest, within a tight window ($\pm 5$ MeV), to that of the known mass of the $\Sigma^0(M_{\Sigma})$. The missing mass (MM) of each photon candidate (MM$_{\gamma_i}$) was determined from kinematics. Any other photons that could pass as $\gamma_1$ were considered as second or third choices and used later in the analysis. The $\gamma_2$ photon was selected so that the missing mass of the combined photons $\gamma_1$ and $\gamma_2$ (MM$_{\gamma_1 \gamma_2}$) was the mass of the $\Lambda(M_{\Lambda})$. At this point, the kinematics of the reaction yielded the vector momentum of the $\Lambda$. Identifying the $\gamma_2$ photon candidate left two or three remaining clusters. In a four-cluster event, the two remaining $\gamma$ candidates were tested to see if their invariant mass (IM$_{\gamma \gamma}$) was consistent with a $\pi^0$ mass. If they fall within a $\pi^0$ mass window of $\pm 10$ MeV, these were tagged as $\gamma_1$ and $\gamma_4$. In a five-cluster event, the last three clusters were taken, two at a time, to find the pair that gave the $\pi^0$ invariant mass that was within the $\pi^0$ mass window. The remaining cluster was then labeled as the neutron. The identification of the neutron cluster was further confirmed by predicting its direction using event kinematics and then comparing this with the measured direction of the neutron cluster. It was possible to have more than one combination of particle candidates in identifying the clusters as the photons $\gamma_1$ to $\gamma_4$ for an event. This process was repeated for all combinations of clusters, and each combination was used in the subsequent analysis.

To complete the identification of the particles outlined above, the angles of all the clusters with respect to the nominal beamline were required. The position of the primary interaction vertex, where the $K^-$ interacts in the liquid-hydrogen target, was found in the direction transverse to the beam from the projected beam-particle trajectory measured by the upstream wire chambers. The primary vertex position $z_1$ along the beam direction was initially assigned to $z_1 = 0$, the center of the target. The $\Lambda$ decay vertex was initially assumed to be at the same location as the primary interaction vertex. The appropriate cluster angles were calculated with respect to these two vertex positions.

Event kinematics were used to determine the longitudinal location along the beam direction of the primary interaction $z_1$ and the $\Lambda$ decay vertex $z_2$ via a $x^2$-type function $F$ in which these two coordinates were free parameters. The form of the $F$ function for four-cluster events is shown in the following equation:

$$F = w_\Sigma (MM_{\gamma_1} - M_\Sigma)^2 + w_\Lambda (MM_{\gamma_1 \gamma_2} - M_\Lambda)^2 + w_\pi (IM_{\gamma_3 \gamma_4} - M_\pi)^2 + w_\eta (IM_{\gamma_1 \gamma_2 \gamma_3 \gamma_4} - M_\eta)^2. \quad (1)$$

A similar form is used for five-cluster events:

$$F = w_\Sigma (MM_{\gamma_1} - M_\Sigma)^2 + w_\Lambda (MM_{\gamma_1 \gamma_2} - M_\Lambda)^2 + w_\pi (IM_{\gamma_3 \gamma_4} - M_\pi)^2 + w_\eta (IM_{\gamma_1 \gamma_2 \gamma_3 \gamma_4} - M_\eta)^2 + w_\theta (\theta_{\text{meas}} - \theta_{\text{calc}})^2 + w_\phi (\phi_{\text{meas}} - \phi_{\text{calc}})^2. \quad (2)$$

In these expressions, $M_{\pi^0}$, $M_{\Sigma^0}$, $M_\Lambda$, and $M_\eta$ are the masses of $\pi^0$, $\Sigma^0$, $\Lambda$, and neutron, respectively, and $\theta_{\text{meas}}$ and $\phi_{\text{meas}}$ are the polar and azimuthal angles (determined from the cluster positions relative to the decay vertex) of the direction of the $\Lambda$. The angles $\theta_{\text{calc}}$ and $\phi_{\text{calc}}$ are those of the neutron calculated from kinematics. The parameters $w_\pi$, $w_\Sigma$, $w_\Lambda$, $w_\eta$, $w_\theta$, and $w_\phi$ are weighting factors for each term. These weights were
determined from Monte Carlo simulations of \( K^- p \rightarrow \Sigma^0\gamma \) events. For example, to determine the variance \( 1/w_\Sigma \) of the \( \Sigma \) mass distribution, the term involving \( \Sigma \) mass was removed from the \( F \) function, and a minimization was performed as described below for the data. The variance was determined from the resulting \( \Sigma \)-mass distribution after a cut on \( F \). The other weights were also determined in a similar fashion.

The missing mass terms (\( \text{MM}_{\gamma}, \text{MM}_{\pi^0}, \text{MM}_{\Lambda\pi^0}, \text{MM}_{\Sigma^0\pi^0} \)), the invariant mass term (\( \text{IM}_{\gamma\gamma} \)), and the angles \( \theta_{\text{mean}}, \phi_{\text{mean}} \) in the above \( F \) function are determined from the cluster energies and the locations of the interaction and decay vertices. With the cluster energies already determined from the energy deposited in the crystals as described earlier, the net result is that the magnitude of the \( F \) function depends on the knowledge of the locations of the two vertices \( (x_1, y_1, z_1) \) and \( (x_2, y_2, z_2) \). The \( z \) coordinates of the kaon interaction point \( (x_1, y_1) \) were measured by the in-beam wire chambers, and the \( x \) and \( y \) coordinates of the \( \Lambda \) decay point \( (x_2, y_2) \) were determined from its momentum vector. The \( \Lambda \) momentum vector was calculated from the kinematics of the interaction. This leaves only two variables, \( z_1 \) and \( z_2 \), on which the \( F \) function depends. As these two parameters get closer to the true locations of the vertices, all the “measured” masses and angles move toward their true values, giving a minimum value to the \( F \) function.

To determine \( z \) coordinates of the two vertices, the \( F \) function was minimized by changing the positions of the interaction vertex \( z_1 \) and the decay vertex \( z_2 \), and by correctly reconstructing the masses of all the particles involved in the decay. The minimization was performed using the CERN routine \textsc{minuit}. All valid combinations of previously assigned cluster combinations were tried, and the combination giving the minimum value of \( F \) was adopted as the optimum candidate for the event. Once this candidate event was selected, along with the associated vertices, cuts were applied on the invariant and missing masses, on the direction of the neutron (for five-cluster events), and on \( F \). These cuts were designed to minimize the background from the other kaon-induced reactions. If the event did not pass all the cuts, the cluster combination with the next best \( F \) value for that event was chosen, and the process was repeated. This \( F \)-function minimization method has been used very successfully in the analysis of \( K^- p \rightarrow \Sigma^0\pi^0 \) data [22].

IV. SIMULATIONS AND ACCEPTANCE

The detector acceptance was obtained from a Monte Carlo simulation based on \textsc{geant} 3.21 [24]. A detailed description of the simulation is given in Ref. [22]. Because no previously measured differential cross sections were available for the reaction \( K^- p \rightarrow \Sigma^0\gamma \), events were generated isotropically. Using a total of 300000 Monte Carlo events, the acceptance was determined as the fraction of the simulated events passing the cuts to those generated. The typical acceptance for the reaction was determined to be approximately 7–8%, for all the kaon beam momenta.

Figure 2 compares the reconstructed \( \Sigma^0 \) mass obtained from data and that obtained from Monte Carlo simulation.

![FIG. 2. Plot of reconstructed missing mass (MM\( \gamma \)) off the production photon showing the excellent agreement between data (solid circles) and the Monte Carlo simulation (line). The peak of the data spectrum corresponds to the mass of \( \Sigma^0 \) with a small uncertainty (sigma).](image)

As described in the next section, the \( \Sigma^0 \) mass from Monte Carlo simulation included contributions from all backgrounds weighted according to their total cross sections. The figure is generated after a cut on the \( F \) value that was used to optimize the signal/background ratio, as described in the next section. The cut removed 80% of the candidate events. Figure 2 shows that the Monte Carlo simulation is in excellent agreement with the data, verifying the validity of the simulation.

V. BACKGROUNDS

Backgrounds to the detected signal were caused by beam interactions in the target flask and insulation and by other kaon-induced reactions in the liquid hydrogen. To determine the contribution to the signal from events in an empty target flask, data with cold hydrogen gas in the flask were taken at each momentum. These empty-target data were analyzed with the same cuts as the full-target data, normalized appropriately, and subtracted from the number of full-target \( K^- p \rightarrow \Sigma^0\gamma \) events. The number of empty-target events are listed in Table 1 for each momentum, and the largest contribution was about 3% at 750 MeV/c.

The kaon-induced backgrounds were studied by using Monte Carlo events generated using \textsc{geant}. For each of the main background reactions, \( K^- p \rightarrow \Sigma^0\pi^0 \), \( K^- p \rightarrow \Lambda\pi^0 \), and \( K^- p \rightarrow K^0n \), 1.2 \times 10^6 events were generated from the measured differential cross sections [20,22,25]. The simulated background reactions were analyzed in the same manner as \( K^- p \rightarrow \Sigma^0\gamma \) events. For the Monte Carlo “signal” events, 22% of the neutral triggers passed the initial event selection criteria listed above, whereas for the three \( K^- p \) background channels, only 9%, 4%, and 5% of the neutral triggers,
respectively, satisfied the requirements. Of these Monte Carlo events, 90% of the signal events passed a cut on the function value $F$, given by the kinematic fit described earlier. For the three backgrounds, only 37%, 44%, and 19%, respectively, survived the fit requirements. Even though a fairly large number of background events passed the kinematic fit, this occurred at the expense of other physical parameters (e.g., location of the interaction vertex) as described in the next paragraph. A background contribution from the reaction $K^{-}p \rightarrow \Sigma^{0}\gamma$ was also studied, but the cuts imposed in the analysis completely eliminated this background.

As seen in Fig. 3, the minimization of the $F$ function returned values of the primary vertex location, $z_1$, for the background events that most often were outside the physical boundary of the hydrogen target ($-5 < z_1 < 5$ cm). By requiring the primary vertex to be located within the target volume, most of the remaining background reaction candidate events were removed. The background channel with the largest number of events passing the $z_1$ cut was $K^{-}p \rightarrow \Sigma^{0}\pi^{0}$. This can be explained as follows: if one of the photons from the decay of the $\pi^{0}$ is not detected (i.e., if the photon goes out the exit hole in the CB or if it does not deposit enough energy to be above threshold), the reaction can very closely mimic $K^{-}p \rightarrow \Sigma^{0}\gamma$.

The backgrounds can be further reduced by studying the reconstructed $\Sigma^{0}$, $\Lambda$, $\pi^{0}$, and neutron mass peaks and the neutron angles (for five-cluster events). In Fig. 4, the reconstructed mass of $\Sigma^{0}$ is shown from the Monte Carlo data for $K^{-}p \rightarrow \Sigma^{0}\gamma$ and from the three main background reactions. Cuts on the masses ($\pm 5$ MeV on the mass of $\Lambda$, and $\pm 7$ MeV on the mass of the neutron) and the neutron angle ($\pm 14^\circ$ in $\theta$ and $\pm 18^\circ$ in $\phi$), further suppressed events in these three background channels. In the end, all the above requirements suppressed the three backgrounds by factors of 25, 100, and 300, respectively.

In summary, the final event selection was made by making cuts on the following quantities: (1) the $F$ value, (2) the mass of the $\pi^{0}(IM_{\gamma\gamma\gamma})$, (3) the mass of $\Sigma^{0}(MM_{\gamma\gamma})$, (4) the mass of $\Lambda(MM_{\gamma\gamma\gamma\gamma})$, (5) the mass of the neutron ($MM_{\gamma\gamma\gamma\gamma\gamma}$), and (6) the position of the primary interaction vertex $z_1$. All of these cuts were chosen to maximize the signal-to-background ratio.

### Table I. Comparison of the number of $K^{-}p \rightarrow \Sigma^{0}\gamma$ events passing all the requirements for the target full of liquid hydrogen and for the empty target containing cold hydrogen gas at each measured kaon momentum.

<table>
<thead>
<tr>
<th>Beam momentum (MeV/c)</th>
<th>Full target</th>
<th>Empty target (normalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>647</td>
<td>23</td>
</tr>
<tr>
<td>714</td>
<td>576</td>
<td>7</td>
</tr>
<tr>
<td>687</td>
<td>383</td>
<td>9</td>
</tr>
<tr>
<td>659</td>
<td>234</td>
<td>8</td>
</tr>
<tr>
<td>629</td>
<td>216</td>
<td>3</td>
</tr>
<tr>
<td>581</td>
<td>139</td>
<td>3</td>
</tr>
<tr>
<td>560</td>
<td>87</td>
<td>0</td>
</tr>
<tr>
<td>514</td>
<td>35</td>
<td>0</td>
</tr>
</tbody>
</table>

![Figure 3](image1.png)

**FIG. 3.** Difference between the optimized primary vertex $z_1$ and the actual location of the vertex obtained from Monte Carlo, for the $K^{-}p \rightarrow \Sigma^{0}\gamma$ signal and for the three background channels $K^{-}p \rightarrow \Sigma^{0}\pi^{0}$, $K^{-}p \rightarrow \Lambda\pi^{0}$, and $K^{-}p \rightarrow K^{0}n$. The background channels most often return values of $z_1$ that are outside the target. The dashed lines show the boundaries of the target.

Figure 5 shows how the number of signal events (after subtracting the background) changed as a function of the cut number applied for the 750 MeV/c data, with the cuts being applied in the order listed above. A seventh cut on the $z$ position of the decay vertex $z_2$ was applied, but this cut did not improve the signal-to-background ratio. Hence it was not used in the subsequent analysis.

Figure 6 shows the effects of the cuts on the signal-to-background ratio for the data. Even though these cuts reduced the number of signal events, they resulted in significant improvement in suppressing the background and improved the signal-to-background ratio by a factor of nearly 5. Figure 7 shows the effect of the cuts on the total cross section at 750 MeV/c. Similar trends in the number of events and the total cross sections are observed at other beam momenta. The cross section is shown to be insensitive to the applied cuts, but the cuts served to reduce the uncertainties in the cross section.

**VI. EXPERIMENTAL RESULTS**

The total cross sections for $K^{-}p \rightarrow \Sigma^{0}\gamma$ at each of the eight measured kaon momenta were computed from the number of good events after background subtractions, the
corrected number of incident kaons, and the effective target length. The total cross sections are given in Table II, along with the total number of reconstructed events in the signal and the different background channels for all eight momenta. The contributions from the background channels were weighted using the total cross sections of the background reactions. For $K^- p \to \Sigma^0 \gamma$, the cross sections measured by the Crystal Ball experiment [22] were used; whereas for the backgrounds, $K^- p \to \Lambda \pi^0$ and $K^- p \to K^0 n$, the results published in 1970 by Armenteros et al. [26] were used. The differences between using the CB results and those of Armenteros et al. for the background estimates were not significant. The total cross sections as a function of the kaon momenta are shown in Fig. 8. The uncertainties quoted in Table II are due to statistics only. There is an overall 10% systematic uncertainty [22] associated with the normalization of the cross sections. As mentioned earlier, the acceptance was determined assuming an isotropic distribution. If the angular distribution of the photons is not isotropic this would affect the cross sections reported. The effect of $P$ and $D$ wave contributions to the cross sections were studied by simulating the $K^- p \to \Sigma^0 \gamma$ reaction using the measured angular distribution of $K^- p \to \Sigma^0 \pi^0$ at 750 MeV [22]. For this reaction, the angular distribution has contributions from several partial waves. The net result

### Table II

$K^- p \to \Sigma^0 \gamma$ total cross section as a function of the incident kaon momentum. The uncertainties listed are statistical only. If the cross section is consistent with zero within experimental uncertainties, only an upper limit is given. Also shown are the number of signal events and the estimated number of events from each background reaction.

<table>
<thead>
<tr>
<th>Beam momentum (MeV/c)</th>
<th>Number of detected events in different channels</th>
<th>Total cross section ($\mu$b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Sigma^0 \gamma$</td>
<td>$\Sigma^0 \pi$</td>
</tr>
<tr>
<td>750</td>
<td>214</td>
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</tr>
<tr>
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<td>49</td>
</tr>
<tr>
<td>514</td>
<td>1</td>
<td>22</td>
</tr>
</tbody>
</table>

FIG. 4. Missing mass (Monte Carlo) off $\gamma_1$ for the $K^- p \to \Sigma^0 \gamma$ signal and for the three background channels. A peak at 1193 MeV corresponding to the mass of $\Sigma^0$ identifies signal events. Cuts (shown by the dashed lines) are placed on this mass to optimize the signal-to-background ratio.

FIG. 5. The number of signal events (reconstructed events – background) surviving the data cuts at 750 MeV/c, as a function of the applied cut number described in the text, showing how the number of events changed with successively tighter requirements.
is a drop in acceptance or an increase in the total cross section by 20%, implying a +20% systematic uncertainty in the total cross sections. An alternative method for estimating this systematic uncertainty is to use only $S$, $P$, and $D$ wave distributions and combine them to obtain the acceptance. Unfortunately at present there is no guidance from theory on how to weight them appropriately, and we did not pursue it. Consequently, the overall systematic uncertainty in the total cross section is $\pm 22\%$ and $-10\%$.

Using the total $K^- p \to \Sigma^0 \gamma$ cross sections, the branching ratio $R_{\Sigma^0 \gamma} = \left[ \frac{K^- p \to \Sigma^0 \gamma}{K^- p \to \text{anything}} \right]$ was calculated to be $(3.6 \pm 0.7) \times 10^{-3}$ at 750 MeV/c. The branching ratios at other beam momenta are listed in the Table III.

### Table III. $K^- p \to \Sigma^0 \gamma$ branching ratios at different incident kaon momenta.

<table>
<thead>
<tr>
<th>Beam momentum (MeV/c)</th>
<th>Branching ratio ($\times 10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>$3.6 \pm 0.7$</td>
</tr>
<tr>
<td>714</td>
<td>$3.8 \pm 0.6$</td>
</tr>
<tr>
<td>687</td>
<td>$1.1 \pm 0.7$</td>
</tr>
<tr>
<td>659</td>
<td>$\leq 0.7$</td>
</tr>
<tr>
<td>629</td>
<td>$1.6 \pm 0.9$</td>
</tr>
<tr>
<td>581</td>
<td>$\leq 1.2$</td>
</tr>
<tr>
<td>560</td>
<td>$\leq 1.7$</td>
</tr>
<tr>
<td>514</td>
<td>$\leq 1.6$</td>
</tr>
</tbody>
</table>

VII. SUMMARY

We have reported the first direct observation of the $K^- p \to \Sigma^0 \gamma$ reaction in flight as a function of the kaon momentum between 514 and 750 MeV/c. As seen in Table III, the branching ratios as a function of excitation energy show little increase until 714 MeV/c, where there is an apparent rise above the rather uniform small values below this kaon momentum. The only other reported measurement of this reaction [15], with kaon capture at rest, yielded a branching ratio of $(1.44 \pm 0.23) \times 10^{-3}$, which is not in disagreement with this branching ratio up to 687 MeV/c. At 714 and 750 MeV/c, the branching ratios exceed the one at rest by approximately three standard deviations.

Moreover, we have reported the measurement of the absolute cross section for this reaction over the kaon momentum range, 514–750 MeV/c. Only very few events were detected at momenta below 714 MeV/c. A rise in the cross section observed at 714 and 750 MeV/c may be an indication that additional channels have become important at these higher momenta.
excitation energies. We expect that these results for radiative decay in this hyperon sector will complement studies of hyperon photoproduction elsewhere [17].

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