CHAPTER II
EXPERIMENTAL PROCEDURE AND TECHNIQUES

2.1 Introduction. We are concerned here with the study of \( K^- \) nucleon interactions in various nuclei and some properties of the hypernuclei produced in these captures. A \( K^- \) meson is captured in a nucleus either by a single nucleon or by a pair of nucleons. In the single nucleon capture mode a hyperon-pion pair is produced which carries away a major portion of the available energy, whereas in the two nucleon capture mode most of the available energy is shared by the hyperon-nucleon pair (Table 3). The remaining energy goes in the excitation of the capturing nucleus which subsequently disintegrates by evaporation.

Under favourable conditions a \( \Lambda \) hyperon may get bound to one of the evaporation products leading to the production of a hyperfragment. In order to study simultaneously the production and decay vertices of hyperfragments and the production and decay/interaction vertices of the \( \Sigma^+ \) hyperons produced in single nucleon capture reactions of \( K^- \) we require a detector of high stopping power and spatial resolution and for which accurate range-energy relations are available. The above conditions are well satisfied by nuclear emulsions. In addition, nuclear emulsions are capable of providing precise estimates of the range and ionization of charged fragments.

Nuclear emulsions are composed of a gelatin base in which small crystals of silver halide are embedded along with a small percentage of other elements. The main target nuclei which are available for interaction are C, N, O and Ag, Sr groups. This is an
advantage since interactions in nuclei having widely different properties can be studied simultaneously and especially so if a comparison of the natures of interaction in the two groups is needed.

Many types of emulsions have been developed for different purposes. The most sensitive emulsions, capable of recording minimum ionizing tracks, are the 0-5 and K-5, manufactured by Ilford Ltd., England.

In the following sections we describe the relevant experimental procedures followed during the course of this work.

2.2 Exposure and Details of the Stack. A stack consisting of 150 K-5 emulsion pellets, each of size 10 cm x 15 cm and of nominal thickness 600 μm, was exposed to the 325 MeV/c separated K⁻ beam of the proton synchrotron at CERN. The total flux of K⁻ mesons in the stack was ∼ 2 x 10⁵.

For the kinematic analysis of events it is often necessary to follow tracks of charged particles from emulsion to emulsion till they stop, interact or leave the stack. To achieve the required alignment of the various pellets the edges of the stack were milled before exposure and grids with reference to the milled edges were printed on the various pellets after the exposure. The thickness of each pellicle was measured to an accuracy of 1 μm at six different places before processing. The pellets were mounted on glass plates and developed according to standard procedures.

2.3.1 Scanning Procedure and Selection of Events for Hyperfragment Analysis

Area scanning under a magnification of ×500 was
one in the central regions of the collision particles where most of the K\(^-\) mesons were brought to rest. K\(^-\) stars with \(N_h \geq 1\) were recorded, where \(N_h\) is the number of non-relativistic charged particles produced in an interaction. A total of \(\sim 1,60,000\) such K\(^-\) stars were recorded and they were all re-seen under high magnification (1500x) for double stars (DS). A DS is an event in which at least one prong originates from a center other than the primary center, the two centers being connected by a track. All the tracks coming from the K\(^-\) stars were followed in the same plate in order to reduce the loss of long range DS type of events. Double star events which were clearly due to one of the following processes were eliminated:

a) a scattering of a particle,
b) an interaction of a fast particle, and
c) capture of a slow meson or hyperon, omitted from the primary star.

If the connecting track is \(\sim 15 \mu\text{m}\) or more, it is easy to identify processes (b) and (c). Contamination due to (a) is eliminated by planarity test. The identification of scattering events becomes difficult if the connecting track or one of the scattered tracks is \(< 10 \mu\text{m}\). Thus in events in which the connecting tracks are \(> 20 \mu\text{m}\) contamination due to (a), (b) and (c) has been removed almost completely. For events in which the connecting track is \(< 20 \mu\text{m}\) those which are clearly due to (a), (b), (c) have been eliminated. The remaining contamination has been estimated to be small\(^73\) for
non-mesic HFs of range $\geq 5\mu$m. Events were noted as single prong HFs only when they were clearly not due to processes (a), (b) and (c). Out of a total of $\sim 1,60,000$ stars observed, 6517 events were accepted as HFs. All tracks from the decay of these HFs were followed till they were brought to rest, interacted or left the emulsion stack. Pions were identified by comparing range versus ionization measurements with standard curves and by an examination of their endings. By this procedure we identified 1312 $\pi^-$-mesic and 3 $\pi^+$-mesic HFs. The remaining 5202 events were due to non-mesic and $\pi^0$-mesic modes of HFs. 1273 $\pi^-$-mesic and 1721 non-mesic HFs were of range $> 5\mu$m; these HFs have mass numbers $\leq 16$.

2.3.2 Selection of Events for the Study of the $K^-$-nucleon Interaction

About 20,000 $K^-$ stars were reexamined and those associated with only one heavy prong (with the exception of a possible recoil of range $< 5\mu$m) were noted. These prongs were followed till they stopped in the emulsion, upto a maximum range of 5 mm; this corresponds to an upper limit for the range of charged $\Sigma$ hyperons produced in single nucleon capture of $K^-$ mesons in nuclei (see Table 3). If the particle came to rest before 5 mm or seemed as though it would, even if it decayed or interacted in flight, its ending was carefully examined under high magnification in order to identify hyperons by their decay and capture modes. A $\Sigma$ hyperon was considered positively identified if it came to rest and gave rise to a visible star (defined as one which has one prong of range $> 200\mu$m or at least two prongs longer than $5\mu$m). A
$\Sigma^+$ hyperon was considered identified if it came to rest and gave rise to a decay proton of the proper range (within limits set by straggling). If a $\Sigma$ hyperon appeared to come to rest and decayed into a pion it was tentatively classified as $\Sigma^+ (\rightarrow n\pi^+)$.

However, since it is not practicable to follow the decay pions and ascertain their range, it is clear that such a sample of $\Sigma^+ (\rightarrow n\pi^+)$ events will contain a contamination of in-flight $\Sigma^+ (\rightarrow n\pi^+)$ decays where the hyperon has decayed in the last $\sim 200 \mu$m of its range. Such a view is confirmed by the number of such events given in Table 4. If no contamination existed the number of $\Sigma (\rightarrow n\pi^+)$ events would be the same (within statistical fluctuations) as the number of $\Sigma^+ (\rightarrow p\pi^0)$ events.

Hyperons which clearly decayed in flight into a proton or a pion were classified as $\Sigma^+ p$ and $\Sigma^{\pm} \pi^+$ events respectively.

The production centers of all these $\Sigma$ events were seen under high magnification (1500x) to detect the presence of:

a) a lightly ionising track due to a pion,
b) a short recoil (1 \leq R \leq 5 \mu m),
c) an Auger electron,
d) a blob, which could be due to an Auger electron or a very short recoil (R < 1 \mu m).

An electron track was identified as an Auger electron if it consisted of at least three grains, the first being within 2 \mu m of the K$^-$ capture center. The minimum Auger electron energy corresponding to this criterion is about 13 keV.

Events with a blob or those in which neither an Auger
Table 4
Raw Numbers of Various Types of Events in which a $\Sigma$ Hyperon is Produced in a $K^-$ Capture Star

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Auger</th>
<th>Recoil</th>
<th>Clean</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma^-$ + $\pi^+$</td>
<td>46</td>
<td>74</td>
<td>91</td>
<td>211</td>
</tr>
<tr>
<td>$\Sigma^-$ no $\pi^+$</td>
<td>26</td>
<td>24</td>
<td>37</td>
<td>87</td>
</tr>
<tr>
<td>$\Sigma^+ (\rightarrow \rho\pi^0) + \pi^-$</td>
<td>39</td>
<td>107</td>
<td>114</td>
<td>260</td>
</tr>
<tr>
<td>$\Sigma^+ (\rightarrow \rho\pi^0)$ no $\pi^-$</td>
<td>27</td>
<td>23</td>
<td>21</td>
<td>73</td>
</tr>
<tr>
<td>$\Sigma^+ (\rightarrow n\pi^+) + \pi^-$</td>
<td>64</td>
<td>135</td>
<td>152</td>
<td>351</td>
</tr>
<tr>
<td>$\Sigma^+ (\rightarrow n\pi^0)$ no $\pi^-$</td>
<td>41</td>
<td>35</td>
<td>33</td>
<td>109</td>
</tr>
<tr>
<td>$F_{\Sigma^+ p}$ $\rightarrow \pi^-$</td>
<td>10</td>
<td>20</td>
<td>17</td>
<td>47</td>
</tr>
<tr>
<td>$F_{\Sigma^+ p}$ no $\pi^-$</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>$F_{\Sigma^0 n}$ $\rightarrow \pi^+ \pi^-$</td>
<td>24</td>
<td>36</td>
<td>31</td>
<td>91</td>
</tr>
<tr>
<td>$F_{\Sigma^0 n}$ no $\pi$</td>
<td>15</td>
<td>5</td>
<td>6</td>
<td>26</td>
</tr>
</tbody>
</table>
electron nor a recoil were present have been classified as "clean".

The raw numbers of the various types of events are listed in Table 4. This completes the selection of events for our work.

2.4 Measuremental techniques. During the course of our work the only quantities measured experimentally were the ranges of tracks of charged particles emitted from an interaction center and the angles between tracks emitted from the same center. We describe below the method of measuring these quantities.

2.4.1 Range Measurements. The passage of a charged particle through unprocessed nuclear emulsion results in an ionization along the path followed by the particle. This process of ionization stops when the energy of the particle is reduced to a few keV. Upon development this path of ionization is rendered visible as a track which terminates at the point where ionization had stopped. The length of the track along its trajectory from its point of origin to the last developed grain is defined as the residual range of the particle. The residual range is determined by measuring the range $R_p$ of the track projected on the plane of the emulsion and the dip angle of the track with respect to this plane. The projected range and dip angle are measured by means of a calibrated eyepiece graticule and a vertical gauge. As the emulsion thickness shrinks after development the true vertical displacement is found by multiplying the observed displacement by the shrinkage factor (the ratio of thickness before development to the thickness after deve-
development). If $\Delta z$ is the actual vertical displacement over a projected length $R_p$, then the dip angle is given by $\tan^{-1}(\Delta z/R_p)$

2.4.2 Determination of Space Angle between two Tracks.

The space angle between two tracks emitted from a point is determined by a knowledge of the dip angles of the tracks and the projected angle between them. The measurement of dip angles has already been described in the previous section. The projected angle was measured to an accuracy of about $0.25^\circ$ by means of a "Goniometer" fixed to the eyepiece.

If $\theta_1$ and $\theta_2$ are the dip angles of the two tracks and $\theta_{12}$ is the projected angle between them, the space angle $\phi$ is given by

$$\phi = \cos^{-1} \left( \cos \delta_1 \cdot \cos \delta_2 \cdot \cos \theta_{12} + \sin \delta_1 \cdot \sin \delta_2 \right)$$

In the case of three tracks having dip angles $\delta_1$, $\delta_2$, and $\delta_3$ and projected angles $\theta_{12}$ and $\theta_{13}$ between tracks 1 and 2 and 3 respectively, the volume contained by the three tracks is

$$V = \cos \delta_1 \cdot \cos \delta_2 \cdot \cos \delta_3 \left( \sin \theta_{12} \cdot \tan \delta_3 - \sin \theta_{13} \cdot \tan \delta_2 + \sin(\theta_{13} - \theta_{12}) \cdot \tan \delta_1 \right)$$

2.4.3 Measurement and Other Errors in the Determination of Ranges and Angles.

Errors in the determination of residual range consist of:

a) Measuremental errors: For short tracks (range $\sim 10\mu$m) where the range is confined to a single field of view the percentage error in range is $\sim 4\%$. When the range is greater than one field of view the total range is determined by displacing the graticule through its own length, in the direction of the
track, an appropriate number of times. In making such displacements it is necessary to find a grain or other distinctive feature which coincides with one end of the graticule and use it as reference point when moving the stage. Some error is introduced in this process which can be minimised by repeated measurements. The error in long tracks is estimated to be about 1%.

b) **Straggling Errors:** Due to the random nature of the ionisation process ranges of particles with the same initial energy are not exactly the same but are spread over a certain interval. This spread is known as range straggling. The range straggling is $\sim 3\%$ for 20 MeV pions and $\sim 1.5\%$ for protons of the same energy. For alpha particles and other multiply charged fragments the straggling error is much smaller ($\approx 0.4\%$).

The errors in space angle and volume are determined from the knowledge of errors on projected and dip angles. The error in projected angles is caused by the finite width of the tracks and depends on the length of track available for measurement. From repeated observations it was found that the error was $\sim 1^\circ$ for tracks of range $\geq 20\mu m$, $\sim 3^\circ$ for tracks of range between 10$\mu m$ and 20$\mu m$ and $\sim 5^\circ$ for shorter tracks. Errors in dip angle were estimated to be $\sim 3^\circ$, $\sim 5^\circ$ and $\sim 10^\circ$ for the above three categories of tracks respectively.

2.4.4 **Range-Energy Relations.** For a particle of given mass and charge its energy can be determined from a knowledge of its residual range in a medium of known density. Generalized
range-energy relations for ions of mass $M$ and charge $Z$ have
been deduced by Barkas$^{53,54}$ and Heckman et al.$^{55}$ for nuclear
emulsions of density $1.315$ gm/cc, hereafter referred to as
"standard density". For convenience $M$ and $Z$ are expressed in
units of proton mass and charge respectively. These range-
energy relations are

$$R = \frac{M}{Z^2} \lambda + R_{\text{ext}} \quad (2.8)$$

$$T = M Z \quad (2.8a)$$

$$R_{\text{ext}} = M Z^{2/3} c_2(\beta/z) \quad (2.9)$$

where $\lambda$, $T$ and $\beta$ are the range, kinetic energy and ve-
locity respectively of a particle of proton mass and charge
and $T$ is the kinetic energy of the particle. The term $R_{\text{ext}}$
takes care of the extension in range of a positive particle
due to reduction of its effective charge as a result of pick-
up of electrons as it nears the end of its range. Thus the
range of a particle of given velocity $\beta$ can be determined if
$\lambda$ and $R_{\text{ext}}$ are known. For an estimation of these terms
Barkas$^{54}$ fitted a polynomial of the type

$$\log_{10} \lambda = \sum_{n=0} a_n (\log_{10} \beta)^n \quad (2.10)$$

to his experimental data of $\lambda$ vs $Z$ using the least
squares method. The values of the coefficients are $a_0 =
1.1428530, a_1 = 1.4761584, a_2 = 0.1976753, a_3 = -0.0998061$
and $a_4 = 0.0324486$. The term $R_{\text{ext}}$ was determined as a fun-
tion of $(M/z^2) \lambda$ by using the above relations and Heckman's$^{55}$
range energy relations for multiply charged particles.
universal curve of $g_2 = R_{ext}/W^{2/3}$ vs $137\beta/z$ (velocity expressed in terms of the velocity of the electrons in K-orbit) was obtained and a polynomial of the type

$$g_2 = \sum_{n=0}^{5} b_n (137\beta/z)^n$$

for $137\beta/z < 2.4$

$$= 0.22$$

for $137\beta/z \geq 2.4$  

(2.11)

was fitted to the above data; the constants $b_n$ have the values $b_0 = -0.0000510, b_1 = 0.0432293, b_2 = 0.1386108, b_3 = -0.0751569, b_4 = 0.0109471$ and $b_5 = -0.0000281$.

Making use of the relations (2.8) through (2.11) range-energy relations for $H^1, He^4, Li^7, Be^9, C^{12}, N^{14}$ and $O^{16}$ were obtained. For identical initial velocity a simple manipulation is sufficient to determine the energy of any of the isotopes of the above ions if we know its range. The relations used are

$$\frac{R_{\text{isotope}}}{R_{\text{ion}}} = \frac{M_{\text{isotope}}}{M_{\text{ion}}} = \frac{E_{\text{isotope}}}{E_{\text{ion}}}$$

(2.12)

where $R, E$ and $M$ refer to the range, mass and kinetic energy of the particles.

A convenient form of representing the range-energy relation for each of the above ions is obtained by fitting a polynomial of the type

$$\log_{10} E = \sum_{n=0}^{5} A_n (\log_{10} R)^n$$

(2.13)

to the range energy data of the above ions by the method of least squares. The values of the coefficients $A_n$ for each of the above ions for $E$ values ranging from 0.1 to 30 MeV are given in Table 5(a). By feeding these values as input data of a computer program we can calculate the energies for all possible identities of a prong of given range.

Since the energies of multiply charged fragments in the
<table>
<thead>
<tr>
<th>Identity</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^1$</td>
<td>-1.1163355</td>
<td>1.5897613</td>
<td>-0.9228738</td>
<td>0.4458415</td>
<td>-0.1067592</td>
<td>0.0099061</td>
</tr>
<tr>
<td>He$^4$</td>
<td>-0.8141977</td>
<td>1.9733587</td>
<td>-1.0215354</td>
<td>0.3845874</td>
<td>-0.0706154</td>
<td>0.0047790</td>
</tr>
<tr>
<td>Li$^7$</td>
<td>-0.5496027</td>
<td>1.7082944</td>
<td>-0.5496537</td>
<td>0.1224456</td>
<td>-0.0178404</td>
<td>0.0027855</td>
</tr>
<tr>
<td>Be$^9$</td>
<td>-0.3582423</td>
<td>1.5885062</td>
<td>-0.4205375</td>
<td>0.0814655</td>
<td>-0.0138497</td>
<td>0.0022955</td>
</tr>
<tr>
<td>B$^{10}$</td>
<td>-0.2100525</td>
<td>1.5219040</td>
<td>-0.3948175</td>
<td>0.1222207</td>
<td>-0.0492447</td>
<td>0.0103025</td>
</tr>
<tr>
<td>C$^{12}$</td>
<td>0.1089723</td>
<td>0.5328245</td>
<td>1.1827628</td>
<td>-1.0500721</td>
<td>0.3712929</td>
<td>-0.0485263</td>
</tr>
<tr>
<td>N$^{14}$</td>
<td>0.2085064</td>
<td>0.5604256</td>
<td>0.9728113</td>
<td>-0.7963735</td>
<td>0.2596941</td>
<td>-0.0316340</td>
</tr>
<tr>
<td>O$^{16}$</td>
<td>0.3179026</td>
<td>0.3590888</td>
<td>1.2409119</td>
<td>-0.9261220</td>
<td>0.2812402</td>
<td>-0.0316721</td>
</tr>
<tr>
<td>E (MeV)</td>
<td>$A_0$</td>
<td>$A_1$</td>
<td>$A_2$</td>
<td>$A_3$</td>
<td>$A_4$</td>
<td>$A_5$</td>
</tr>
<tr>
<td>--------</td>
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<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>1 - 14</td>
<td>-1.1234411</td>
<td>1.6628835</td>
<td>-1.0868952</td>
<td>0.5865055</td>
<td>-0.1578796</td>
<td>0.0165328</td>
</tr>
<tr>
<td>14 - 55</td>
<td>-0.5213276</td>
<td>0.4129263</td>
<td>0.1059671</td>
<td>-0.0255709</td>
<td>0.0019482</td>
<td>0.0000287</td>
</tr>
<tr>
<td>55 - 260</td>
<td>-0.0395347</td>
<td>0.1854312</td>
<td>0.0755715</td>
<td>0.0075271</td>
<td>-0.0040823</td>
<td>0.0003509</td>
</tr>
<tr>
<td>260 - 600</td>
<td>-0.9134579</td>
<td>0.6187756</td>
<td>0.0576965</td>
<td>-0.0165215</td>
<td>0.0008027</td>
<td>0.0000751</td>
</tr>
</tbody>
</table>
mesic decay of PF is low (\(< 30 \text{ MeV}\)) a single polynomial fit of the type (2.13) yields sufficiently accurate results over the small energy region. However, for singly charged particles the energy interval is much larger and therefore a single polynomial fit did not yield sufficiently accurate results over the entire energy region. For singly charged particles, therefore, the energy interval (0.1 to 600 MeV) was divided into four parts (viz. \(0.1 \text{ to } 14 \text{ MeV}\), \(14 \text{ to } 55 \text{ MeV}\), \(55 \text{ to } 260 \text{ MeV}\) and \(260 \text{ to } 600 \text{ MeV}\)) and a polynomial was fitted for each energy interval independently. The coefficients \(A_n\) for the four regions are given in Table 5(b).

2.4.5 Calibration of the stack. The range energy relations determined in the previous section are valid for emulsions of a standard density. If we are to use these relations we have to determine the density of our stack the details of which are given below.

The range of non-energetic charged particles depends only upon the density of the material through which they pass. Thus a knowledge of the ranges of such particles in our stack and in emulsions of standard density will enable us to calibrate our stack. Protons emitted from \(\Sigma^+\) decays at rest were used for this purpose; the energy of the proton in the decay mode \((\Sigma^+ \rightarrow p + \pi^0)\) is 18.84 MeV; the range of these protons in emulsions of a standard density is \((1677 \pm 2) \mu\text{m}^{56}\).

Residual ranges of 118 protons, from \(\Sigma^+\) decay at rest were measured in our stack. In all these events the entire proton range was contained in a single emulsion pellicle. The mean value of the proton range was found to be \((1688 \pm 3) \mu\text{m}\).
We therefore corrected all pion and proton ranges by a factor

\[ c(\beta) = 1 - \gamma(\beta) \times 0.0083 \quad (2.14) \]

where the values of \( \gamma(\beta) \) based on "additivity of volume" are taken from the work of Barkas et al\(^57\) and the numerical coefficient 0.0083 represents the fractional decrease of density of the stack with respect to emulsions of standard density.

### 2.4.6 Additional possible errors in Range Measurements and their Removal

In addition to the measurement and straggling errors in range measurements, error due to scrubbing of emulsion surface can exist. The emulsion surface of each pellicle is scrubbed in order to remove small surface deposits that occurred during processing. This could lead to an underestimation of range of flat tracks of particles traversing more than one pellicle. The effect of scrubbing on a flat track is detected by noting the shift in its position with respect to a reference track (which is steeply dipping or makes a projected angle of \( \sim 90^\circ \) with the track under consideration) in two consecutive plates. Under such circumstances the real range would be the visible range plus the shift so observed. However, the same effect could be produced if there had been an air gap between the two pellicles at the time of exposure, and in such a case no correction would be required. In order to investigate this point we measured the proton ranges from \( \Sigma^+ \) decays at rest. We selected \( n \) 118 events in which the entire range of the proton was contained in a single emulsion pellicle and...
(b) 116 events in which the proton traversed two or more pellicles. The mean range of protons of class (a) was found to be $(1688 \pm 3) \mu$m and that of the protons of class (b) was found to be $(1671 \pm 3) \mu$m when only the visible track was considered. When the range of class (b) protons was determined after correcting for the shift with respect to the reference track the mean value found was $(1687 \pm 3) \mu$m. The good agreement of this value with that for protons of class (a) clearly shows that the shift in position of a track with respect to the reference track is almost entirely due to scrubbing. All range measurements of tracks were therefore carried out in this manner in the present work. This type of correction for scrubbing is very important only when the tracks are long ($\sim$ a few cms) and their dip angles are small ($\leq 20^\circ$).