BNL-42105

CONF-881024--1

STRANGENESS PRODUCTION IN $\overline{P}$–NUCLEUS INTERACTIONS

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DE89 004892

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Invited talk presented by C. B. Dover

at the Conference on HADRONIC MATTER IN COLLISION

Tucson Arizona

October 6 – 12, 1988

**Supported in part under contract DE–AC02–76ER13001 with the U. S. Department of Energy.

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1. INTRODUCTION

The annihilation of antinucleons ($\bar{p}, \bar{n}$) or antinuclei ($\bar{d}$, $^3\overline{\mathrm{He}}$) in nuclei leads to a large energy deposition in the system, opening up numerous possibilities for the study of the dynamical evolution of hot hadronic matter. The study of such multiparticle systems in an unusual realm of density ρ and temperature T is potentially very useful in probing the equation of state of heated nuclear matter and studying mechanisms of energy dissipation and the approach to thermodynamic and chemical equilibrium. An intensive search for manifestations of a transition to the quark gluon plasma (QGP) phase is taking place in the arena of relativistic heavy ion collisions, with experiments at Brookhaven and CERN. Although a $\bar{p}$-nucleus annihilation event produces initially a more localized "hot spot" than in a central heavy ion collision, one might still ask whether the subsequent evolution of the system, which ultimately leads to the emission of 10's of nucleons and other fragments, passes through the QGP phase. For instance, one can tag on charged

*Supported by the U. S. Department of Energy under contract DE-AC02-76CH00016.

**Supported in part under contract DE-AC02-76ER13001 with the U. S. Department of Energy.

particle multiplicity to emphasize internal rather than surface $\bar{p}$ annihilation. This would enhance the possibility of observing anomalous strangeness production[1,2], which is perhaps indicative of QGP formation. For lab momenta $p_L < 1.5\,\mathrm{GeV/c}$ or so, hyperon production (Λ, Σ) in $\bar{p}$–nucleus annihilation involves two or more nucleons, whereas kaons $(K_s, K^{\pm})$ can be generated in a process $\bar{p}N \to \overline{K}KX$ on a single nucleon N. Ratios like $R = \left(N(\Lambda) + N(\Sigma^0)\right)/N(K_s)$ are then indicative of the relative importance of multinucleon processes. Rafelski[3] has argued that the large $\Lambda + \Sigma^0$ production cross section observed in the $\bar{p}$ + Ta system[4] at 4 GeV/c reflects QGP formation. However, it has often been pointed out, for instance by Cugnon and Vandermeulen[5] for the $\bar{p}$ case, that strangeness enhancements are not necessarily signatures of the creation of "quark–gluon soup," but also occur in a conventional hadronic picture once one includes multinucleon ($\overline{N}NN$ and higher order) absorption reactions. It is the goal of this paper to try to understand the data on strange particle production in $\bar{p}$–nucleus interactions in terms of a conventional hadronic picture, in which strangeness is produced and redistributed by a combination of direct and sequential (final state interaction) processes. Our conclusion is that the main features of the data, namely the energy and A dependence (or lack thereof) of R, as well as the absolute cross section for Λ production in $\bar{p}$–nucleus collisions for $p_L \leq 4\,\mathrm{GeV/c}$, can be understood without invoking the notion of an intermediate QGP phase.

The paper is organized as follows: In chapter 2, we briefly review some of the essential features of strangeness production in $\overline{N}N$ collisions. The simplest nuclear case, namely $\bar{p}d$, is considered in chapter 3. Antinucleon annihilation in complex nuclei is examined in chapter 4. The emphasis throughout is on the interpretation of strange particle production cross sections in terms of conventional direct and multistep hadronic processes, with particular focus on the energy and A dependence of such reactions.

2. STRANGENESS PRODUCTION IN $\overline{N}N$ COLLISIONS

In $\overline{N}N$ annihilation at rest, the production of $\overline{K}K$ pairs, in conjunction with any number of pions, constitutes about 5 – 7% of the total number of events[6]. As the energy increases, the ratio of strange/nonstrange production increases slowly. In terms of a statistical phase space model[7], where annihilation is described in terms of two–body processes $\overline{N}N \to M_1M_2$, followed by the decay of the mesons M_1 and M_2, the production of strange (relative to nonstrange) particles is suppressed by a factor $C_{\bar{s}s} \approx 1/6$. A similar suppression factor $C_{\bar{s}s} \approx 0.15 - 0.3$ is also observed for a variety of reactions (pp, $K^{\pm}p$, ep, e^+e^-, νp, $\bar{\nu}p$) at higher energy[8]. One of the main motivations for studying $\overline{N}$–nucleus annihilations is that strangeness production is enhanced due to the effects of the medium, beyond the level expected on the basis of "direct" formation of strange particles in first order $\overline{N}N$ collisions.

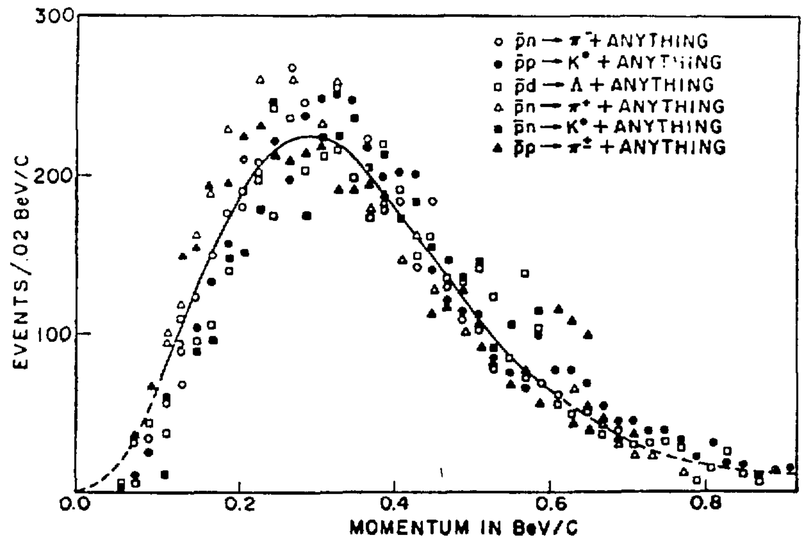

Fig. 1. Momentum spectra for $\pi^{\pm}$, K^0, and Λ particles produced in $\bar{p}N$ and $\bar{p}d$ annihilation at rest, taken from Roy[9].

An interesting feature of $\overline{N}N$ annihilation is the fact that the momentum spectra of π's and K's, as well as Λ's produced in $\bar{p}d$ annihilation, are essentially the same. This is shown in Fig. 1, taken from Ref. 9. The average momentum $< k_\pi >$ of pions is observed to be about 350 MeV/c for $\bar{p}p$ annihilation at rest. This is the value expected if we share the total energy $\sqrt{s}$ equally among the mean multiplicity $< N_\pi >$ of pions, i.e.,

$$< k_\pi > \approx \left[\left(\frac{\sqrt{s}}{< N_\pi >} \right)^2 - m_\pi^2 \right]^{1/2} . \qquad (1)$$

For $< N_\pi > \approx 5, \sqrt{s} = 2m_N$, we obtain $< k_\pi > \approx 350$ MeV/c, in agreement with experiment. In the region $2m_N \leq \sqrt{s} \leq 4m_N$, we have[10] $< N_\pi > \approx 5 + (\sqrt{s} - 2m_N)$, with $\sqrt{s}$ in units of GeV/c^2. Then for a lab momentum $p_L = 4$ GeV/c, we expect

$< N_\pi > \approx 8$, $< k_\pi > \approx 600$ MeV/c. The average pion from annihilation is thus below the threshold of 890 MeV/c for Λ production via the $\pi N \to K\Lambda$ reaction. This is relevant for our later discussion of $\bar{p}+$ Ta annihilation.

Since the π, K, and Λ spectrum all have about the same shape (although the average momenta[9] for K and Λ are a bit higher than for π), the effective temperature T obtained from fitting to the form[11]

$$\frac{d^3\sigma}{d^3k} = C\frac{k^2}{w^3}e^{-w/T} \ , \tag{2}$$

where $w = \left(m_\pi^2 + k^2\right)^{1/2}$, will differ for particles of different mass. For π's, one obtains[9,11] $T \approx 120$ MeV while for K and Λ, we have $T \approx 85,\ 55$ MeV, respectively. One should not ascribe too much significance to these differing temperatures, i.e., in terms of early emission of π's from a "hot plasma", and later emission of K's and Λ's from a cooler system. A similar caution applies to the interpretation of π, K, and Λ spectra from $\bar{p}$–nucleus annihilation! The effective parameter T in Eq. (2) can be understood in terms of the tendency of the decaying system to emit particles of roughly the same mean momentum $< k >$, independent of their mass. Thus, the temperature T_i of species i satisfies the approximate constraint

$$T_i w_i\left(< k >\right) \approx C \ . \tag{3}$$

For $< k >= 400$ MeV/c, we obtain $C = 0.054\,\mathrm{GeV}^2$ for π and K, $0.064\,\mathrm{GeV}^2$ for Λ, using the T values of Roy[9].

For our later discussion, we will require the cross sections for Λ, $\overline{\Lambda}$, and K_s production in $\bar{p}p$ collisions. The thresholds for the reactions $\bar{p}p \to \Lambda X$ relevant to Λ inclusive production are $p_L = \{1.44,\ 1.94,\ 2.20,\ 2.35,\ 2.60\,\mathrm{GeV/c}\}$ for $X = \{\overline{\Lambda},\ \overline{\Sigma}^0,\ \overline{\Sigma}^0\,(1385)\,,\ K\overline{N},\ \overline{\Lambda}\,(1520)\}$, respectively. The Λ cross section for $p_L \leq 10\,\mathrm{GeV/c}$ can be parametrized as

$$\sigma\left(\bar{p}p \to \Lambda X\right) \approx \sigma_0\left(s - s_0\right)^\alpha \ , \tag{4}$$

with $\sigma_0 \approx 0.22$ mb, $\alpha \approx 0.58$, and $s_0 = 4m_\Lambda^2$ (units of GeV^2). Equation (4) reproduces the value 0.53 mb measured by Noguchi *et al*[12] at 4 GeV/c. Up to $p_L \approx 2.5\,\mathrm{GeV/c}$, the above cross section is mostly $\Lambda\overline{\Lambda}X$. From C invariance, we have $\sigma\left(\bar{p}p \to \Lambda X\right) = \sigma\left(\bar{p}p \to \overline{\Lambda}X\right)$.

Between $2-10\,\mathrm{GeV/c}$, the inclusive K_s cross section remains essentially constant[13]:

$$\sigma(\bar{p}p \to K_s X) \approx 2\ \mathrm{mb}\ . \tag{5}$$

At lower momenta, the K_s cross section rises slightly: Cooper *et al*[14] give 2.6 mb at 760 MeV/c, for instance. Below 4 GeV/c, the K_s's arise almost entirely from annihilation processes[13]. The non–annihilation K_s production ($\bar{p}p \to KY\overline{N}X$) rises rapidly above 3 GeV/c, becoming comparable (at ~ 1 mb) to the annihilation part at around 10 GeV/c. Note that the non–annihilation K_s cross section is comparable for $\bar{p}p$ and pp collisions. Observe also that the ratio $\sigma(\bar{p}p \to K_s X)/\sigma_A$, where σ_A is the total inelastic cross section, increases with p_L, indicating the increased relative importance of strange particle production at higher energies. A similar trend holds for e^+e^- annihilation[15].

3. STRANGENESS PRODUCTION IN $\bar{p}d$ ANNIHILATION

Abundant data are available on Λ and K_s production in $\bar{p}d$ collisions[16–19]. In all the experiments on nuclear targets, Λ's produced via $\Sigma^0 \to \gamma\Lambda$ decay ($\tau_{\Sigma^0} \approx 5.8 \times 10^{-20}$ sec) are not separated from directly produced Λ's. We introduce the symbol $\tilde{\Lambda} \equiv \Lambda + \Sigma^0$ to remind ourselves to compare the data to models which include strong production of <u>both</u> Λ and Σ^0. As we shall argue later, the amount of Σ^0 production is significant, and one obtains an erroneous comparison[18,20] of second order reaction mechanisms with the data by assuming $\tilde{\Lambda} = \Lambda$.

In Fig. 2, we display some of the $\bar{p}d$ data of Parkin *et al*[19]. At the top of the figure, the ratio R defined by

$$R = \frac{\sigma\left(\bar{p}d \to \tilde{\Lambda}X\right)}{\sigma(\bar{p}d \to K_s X)} \tag{6}$$

is plotted as a function of $\bar{p}$ lab momentum, while at the bottom is shown the cross section difference

$$\Delta\sigma = \sigma\left(\bar{p}d \to \tilde{\Lambda}X\right) - \sigma\left(\bar{p}d \to \tilde{\bar{\Lambda}}X\right) \tag{7}$$

multiplied by the branching ratio $B = BR\left(\Lambda \to p\pi^-\right) = 0.642$. In Fig. 2, Refs. 1, 2, 5, 7 refer to the work of Camerini *et al*[21], Oh *et al*[17,22], Mandelkern *et al*[18], and Bizzarri *et al*[16], respectively. In the region below 2.5 GeV/c, we have

$$R \approx 0.2$$
$$\Delta\sigma \approx 0.55\ \mathrm{mb}\ . \tag{8}$$

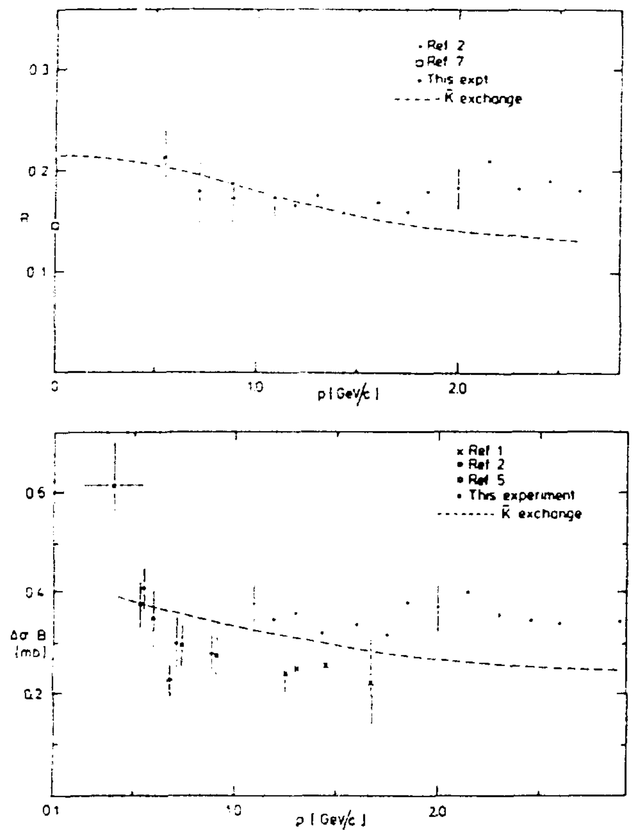

Fig. 2. The ratio of $\bar{\Lambda}$ to K_s inclusive production in $\bar{p}d$ collisions, as a function of $\bar{p}$ lab momentum, is shown at the top, from Parkin *et al*[19]. The plot is not corrected for neutral decay modes of the Λ and K_s, and should be multiplied by $BR\left(K_s \rightarrow \pi^+\pi^-\right)/BR\left(\Lambda \rightarrow p\pi^-\right) \approx 1.069$ to obtain the ratio R of Eq. (6). The cross section difference $\Delta\sigma \cdot B$, where $B = BR\left(\Lambda \rightarrow p\pi^-\right)$ and $\Delta\sigma$ is given by Eq. (7), is shown at the bottom.

The constancy of R and $\Delta\sigma$, both below and above the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ threshold, suggests that a simple mechanism dominates the production of the excess Λ's. Below the $\bar{\Lambda}\Lambda$ threshold, Λ production must involve both nucleons of the deuteron. Several possible second order processes are shown in Fig. 3. These have been studied by various authors[16–19,23]; the treatment of Parkin *et al*[19] is the most detailed. For low momentum, the top graphs in Fig. 3 involving $\bar{\Lambda}$ or π production are kinematically suppressed, since the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ or $\pi N \rightarrow K\Lambda$ reactions are essentially subthreshold. The sequential process $\bar{p}N \rightarrow \overline{K}KX$ followed by $\overline{K}N \rightarrow \pi Y$ dominates. The cross section is approximately

$$\sigma\left(\bar{p}d \rightarrow \tilde{\Lambda}X\right) = \sigma\left(\bar{p}d \rightarrow K\overline{K}X\right)\frac{<\sigma\left(\overline{K}N \rightarrow \tilde{\Lambda}X\right)>}{\sigma_d} \tag{9}$$

where $< \sigma\left(\overline{K}N \rightarrow \tilde{\Lambda}X\right) >$ is an average strangeness exchange cross section, and $\sigma_d = 4\pi / < 1/r^2 >_d \approx 200$ mb is obtained from the Hulthen wave function of the deuteron. For the $\bar{p}$ momentum range 0.4 – 0.9 GeV/c, Parkin *et al*[19] give $< \sigma\left(\overline{K}N \rightarrow \tilde{\Lambda}X\right) > \approx 20$ mb (note that both Λ and Σ^0 are included!). If we now assume that all $\overline{K}K$ charge states are equally produced, we have $\sigma\left(\bar{p}d \rightarrow K_s X\right) \approx \frac{1}{2}\sigma\left(\bar{p}d \rightarrow K\overline{K}X\right)$, and hence

$$R \approx \frac{2 < \sigma\left(\overline{K}N \rightarrow \tilde{\Lambda}X\right) >}{\sigma_d} \approx \frac{1}{5}\,, \tag{10}$$

which agrees well with the data shown in Fig. 2. The inclusive cross section for K_s production is

$$\sigma\left(\bar{p}d \rightarrow K_s X\right) \approx \left(1 - \frac{w_i}{2}\right)\left[\sigma\left(\bar{p}p \rightarrow K_s X\right) + \sigma\left(\bar{p}n \rightarrow K_s X\right)\right]\left(1 - \frac{\bar{w}}{2}\right) \tag{11}$$

where $\bar{w}$ is a final state absorption probability for the K_s given by

$$\bar{w} \approx \frac{< \sigma\left(\overline{K}N \rightarrow YX\right) >}{\sigma_d} \approx \frac{1}{6}\,, \tag{12}$$

where $Y = \{\Lambda,\ \Sigma^0,\ \Sigma^{\pm}\}$, and $w_i \leq 1$ represents a "screening" correction due to initial state interactions. Parkin *et al*[19] give $\sigma\left(\bar{p}d \rightarrow K_s X\right) \approx 2.2$ mb (correcting for double counting of $K_s K_s$ events). If we assume $\sigma\left(\bar{p}n \rightarrow K_s X\right) \approx \sigma\left(\bar{p}p \rightarrow K_s X\right)$ and use Eq. (5), we would predict $\sigma\left(\bar{p}d \rightarrow K_s X\right) \approx 3.7\ (1 - w_i/2)$ mb from Eq. (11), suggesting $w_i \approx 0.8$.

Other tests of the simple second order rescattering model are provided by the fractions f_π or f_K of the $\bar{p}d \rightarrow N + \pi$'s or $\bar{p}d \rightarrow NK\overline{K} + \pi$'s events in the "non–spectator" region (defined by Oh and Smith[17] as transverse lab nucleon momentum $p_T > 200$ MeV/c). The p_T spectra of Λ's and nucleons are remarkably similar in shape[17], suggesting that the same sort of double scattering mechanism is operating. We expect

$$f_\pi \approx \frac{< \sigma_{\pi N} >}{\sigma_d}\quad , \qquad f_K \approx \frac{< \sigma_{\overline{K}N} >}{\sigma_d}\,. \tag{13}$$

For reasonable values $< \sigma_{\pi N} > \approx 60$ mb, $< \sigma_{\overline{K}N} > \approx 40$ mb, we obtain $f_\pi \approx 0.3$, $f_K \approx 0.2$, in agreement with the values $f_\pi = 0.32$ (three– and four–prong events) or 0.28 (five – six prong) cited by Zemany *et al*[23], and $f_K \approx 0.16$ from Oh *et al*[22].

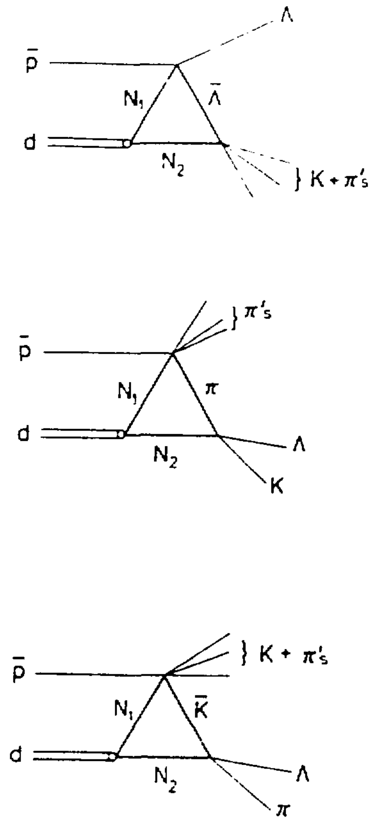

Fig. 3. Mechanisms for Λ production in $\bar{p}d$ collisions.

The double scattering mechanism (Fig. 3) involving $\overline{K}$ exchange has also been used to predict[17,19] the distribution of p_L and p_T for the Λ, and well as the angular distribution of the Λ in the $\bar{p}d$ center of mass system. The Λ lab momentum spectrum[17] is peaked near $\left(p_T^2 + p_L^2\right)^{1/2} \approx 500$ MeV/c, with a full width of 500 MeV/c, essentially independent of the incident $\bar{p}$ momentum (in the range $1.1 - 2.9$ GeV/c). The peak in the p_T distribution is centered near $250 - 300$ MeV/c. Detailed $\overline{K}$ exchange calculations[19] agree well with the observed p_T spectrum of the K_s's, but disagree with the relative slopes of the K_s and Λ spectra. The angular distribution of the Λ is predicted[19] to be strongly peaked in the backward hemisphere, whereas the data show only a modest peaking.

The predictions of the second order $\overline{K}$ exchange model[19] for R and $\Delta\sigma$ of Eqs. (6) and (7) are shown as dashed lines in Fig. 2. Although the agreement is very good below 1.5 GeV/c, R and $\Delta\sigma$ are predicted to decrease somewhat with increasing momentum, a trend not displayed by the data. This reflects the onset of the "direct" $\left(\bar{p}p \to \bar{\Lambda}\Lambda X\right)$ and associated production $(\pi N \to K\Lambda)$ mechanisms above 1.5 GeV/c.

4. STRANGENESS PRODUCTION IN $\bar{p}$–NUCLEUS ANNIHILATION

In this chapter, we summarize the essential features of the experimental data, mention a variety of approaches for describing $\bar{p}$–nucleus annihilation, and discuss several simple models for the energy and A dependence of Λ/K_s ratios and absolute cross sections for Λ and $\bar{\Lambda}$ production.

4.1. Theoretical Approaches

The intranuclear cascade (INC) model has been frequently applied to an analysis of the $\bar{p}$–nucleus annihilation process[24–30]. A fluid dynamics approach has been studied by Strottman[31]. The possibility that a droplet of quark gluon plasma might be formed in $\bar{p}$–nucleus annihilation has been suggested by Rafelski and collaborators[2,3]. Recently, several informative reviews[32,33] have appeared.

For particle spectra in the INC approach, there are both "hot" and "cold" components, characterized by different slopes in the momentum distribution. For pions, the "hot" component displays an effective temperature T close to that characteristic of $\overline{N}N$ annihilation (see Eq. (2)). These pions escape the nucleus without much energy loss. The "cold" pions have transferred significant energy to the nucleus, giving rise to numerous spallation nucleons. The multiplicity and momentum spectrum[34] of π's and N's, as well as the distribution of residual nuclei[35], are well described in the INC approach. The search for new phenomena[2,3] has thus been focused in the domain of strange particle production. However, as has been emphasized by Cugnon and Vandermeulen[5], "strangeness enhancement" is not necessarily a signature of quark gluon plasma formation, but also occurs if one includes the annihilation of baryon number $B = 1$ "fireballs" (i.e., $\overline{N}NN$) in addition to the $B = 0$ annihilation processes usually included in the INC. This "enhancement" is not of dynamical origin, but is a consequence of phase space.

4.2. Experimental Data

The data on strange particle production in $\bar{p}$–nucleus collisions[4,36–38] is rather limited. Condo *et al*[36] have measured the yield Y of Λ's per incident $\bar{p}$ at low momentum to be $Y \approx 0.02$, essentially independent of A (but with sizable errors of 20 – 30%). There are also limits[37] of $Y < 4-5\times10^{-4}$ for the production of doubly strange $\Lambda\Lambda$, ΛK^- or K^+K^+ systems in $\bar{p}A$ annihilation. Miyano *et al*[4] have published cross sections for $\Lambda, \bar{\Lambda}$, and K_s production in $\bar{p}+$ Ta collisions at 4 GeV/c, and reported preliminary values[39] at 3 GeV/c:

$$\sigma(\bar{p}+\mathrm{Ta}\to K_s X) = \begin{cases} 43.4\pm10.2 \text{ mb} \ \ (3\,\mathrm{GeV/c}) \\ 82\pm6 \text{ mb} \ \ (4\,\mathrm{GeV/c}) \end{cases}$$
$$\sigma(\bar{p}+\mathrm{Ta}\to \Lambda X) = \begin{cases} 145\pm20 \text{ mb} \ \ (3\,\mathrm{GeV/c}) \\ 193\pm12 \text{ mb} \ \ (4\,\mathrm{GeV/c}) \end{cases} \quad (14)$$
$$\sigma(\bar{p}+\mathrm{Ta}\to \bar{\Lambda} X) = \begin{cases} 4.9\pm2.7 \text{ mb} \ \ (3\,\mathrm{GeV/c}) \\ 3.8\pm2 \text{ mb} \ \ (4\,\mathrm{GeV/c}) \end{cases}$$

At 600 MeV/c, Balestra *et al*[38] give

$$\begin{aligned} \sigma(\bar{p}+\mathrm{Ne}\to K_s X) &= 5.4\pm1.1 \text{ mb} \\ \sigma(\bar{p}+\mathrm{Ne}\to \Lambda X) &= 12.3\pm2.8 \text{ mb} \,. \end{aligned} \quad (15)$$

The yield $Y = (1.95\pm0.43)\times10^{-2}$ of Λ's is consistent with that measured by Condo *et al*[36]. The Λ/K_s ratio is

$$R = \begin{cases} 2.3\pm0.7 \ \ (\bar{p}+\mathrm{Ne} \text{ at } 600\,\mathrm{MeV/c}) \\ 2.4\pm0.3 \ \ (\bar{p}+\mathrm{Ta} \text{ at } 4\,\mathrm{GeV/c}) \\ 3.3\pm0.9 \ \ (\bar{p}+\mathrm{Ta} \text{ at } 3\,\mathrm{GeV/c}) \,. \end{cases} \quad (16)$$

These values are an order of magnitude larger than the ratio $R \approx 1/4$ for $\bar{p}p$ at[12,13] 4 GeV/c or $R \approx 0.3$ for $\bar{p}d$ at[22] 2.9 GeV/c. The question is whether this order of magnitude enhancement in R is the signal of new physics, for instance the formation of quark gluon plasma[1–3], or whether it simply reflects the increased probability $\bar{w}$ for $\overline{K}N \to \pi Y$ strangeness exchange (or $\pi N \to KY$ associated production) in a complex nucleus, compared to the deuteron. We argue for the latter interpretation here. The data suggest that R is approximately independent of incident $\bar{p}$ momentum p_L and target mass (note that $\bar{p}$ annihilation at rest is a special case[38], since R for $\bar{p}+$Ne drops by a factor of 10 with respect to Eq. (16), due to the fact that the $\bar{p}N$ annihilation products are not kinematically focused in the forward direction, and hence $\bar{w}$ decreases). This feature emerges naturally from the rescattering model considered here. In a quark gluon plasma picture, one expects a significant dependence of R on p_L and A, but this has not been worked out in detail.

4.3. Simple Estimates of Λ, $\bar{\Lambda}$, and K_s Cross Sections

In this section, we use conventional models to take account of initial and final state interactions. The strange particles produced in the primary $\bar{p}N$ interaction are redistributed through higher order reaction processes in the nuclear medium, which are described by probabilities like $\bar{w}$ in Eq. (12). We now consider the various cross sections in turn.

4.3.1. The $\bar{\Lambda}$ cross section. At 4 GeV/c we have the ratio[4]

$$R_{\bar{\Lambda}} = \frac{\sigma\left(\bar{p} + \mathrm{Ta} \to \bar{\Lambda}X\right)}{\sigma\left(\bar{p}p \to \bar{\Lambda}X\right)} \approx 7.9 \pm 4.2 \tag{17}$$

In a simple Glauber model, worked out for inelastic processes by Kōlbig and Margolis[40], $R_{\bar{\Lambda}}$ for a target with $A = N + Z$ is given by

$$R_{\bar{\Lambda}} = \frac{Z\sigma\left(\bar{p}p \to \bar{\Lambda}X\right) + N\sigma\left(\bar{p}n \to \bar{\Lambda}X\right)}{\sigma\left(\bar{p}p \to \bar{\Lambda}X\right)} P\left(\sigma\right) \ , \tag{18}$$

where $P(\sigma)$ is the "survival probability" defined by

$$P\left(\sigma\right) = \frac{1}{A}\int_0^{\infty} e^{-\sigma T(b)} T\left(b\right) d^2b \ ,$$
$$T\left(b\right) = \int_{-\infty}^{+\infty} dz \rho\left(r\right) \ , \tag{19}$$

where σ is the total cross section averaged over initial state $\bar{p}p$ and $\bar{p}n$ and the final state $\bar{\Lambda}p$ and $\bar{\Lambda}n$ interactions, and $\rho(r)$ is the nuclear density (normalized to the mass number A). For a Gaussian density $\rho(r)$, with $< r^2 >^{1/2} = r_0 A^{1/3}$, we obtain

$$R_{\bar{\Lambda}} \approx \left(\frac{Z + \alpha N}{A}\right) \frac{2\pi r_0^2}{3\sigma} A^{2/3} \ . \tag{20}$$

For $r_0 = 0.97$ fm, which reproduces $< r^2 >^{1/2} = 5.48$ fm for Ta, $\sigma \approx 70$ mb (for $\bar{p}p$ at 4 GeV/c) and $\alpha \approx 0.9$ (estimated from $\sigma\left(\bar{p}p \to \bar{\Lambda}\Lambda\right)/\sigma\left(\bar{p}p \to \bar{\Lambda}X\right) \approx 0.1$ at 4 GeV/c), we obtain

$$R_{\bar{\Lambda}} \approx 8.5 \ , \tag{21}$$

which compares well with Eq. (17). Another estimate, which uses the measured ratio[41] $R_{\bar{n}} = \sigma(\bar{p} + A \rightarrow \bar{n}X) / \sigma(\bar{p}p \rightarrow \bar{n}n) \approx 3.8 \pm 0.6$ for Pb at 550 MeV/c, is

$$R_{\overline{\Lambda}} \approx R_{\bar{n}} \frac{\sigma_{\bar{p}p}(550 \text{ MeV/c})}{\sigma_{\bar{p}p}(4 \text{ GeV/c})} \approx 2.3 R_{\bar{n}} \approx 8.7 \ , \tag{22}$$

also consistent with Eq. (17). Thus, there appears to be nothing anomalous about the rate of $\overline{\Lambda}$ production in $\bar{p}$+ Ta collisions at 4 GeV/c.

4.3.2. The A dependence of the Λ yield. The data of Condo *et al*[37] indicate a weak A dependence for the Λ yield Y. For the low p_L in this experiment[37], the $\pi N \rightarrow K\Lambda$ and $\bar{p}p \rightarrow \Lambda X$ processes do not operate, and Λ's arise from secondary $\overline{K}N \rightarrow \pi Y$ interactions. Assuming for simplicity that all hyperons Y are detected as Λ's, either through $\Sigma^0 \rightarrow \Lambda\gamma$ decay or $\Sigma^\pm N \rightarrow \Sigma^0 N$, ΛN conversion, we may write

$$Y = \frac{\sigma(\bar{p}p \rightarrow \overline{K}X)}{\sigma_{\text{TOT}}(\bar{p}p)} P_{\overline{K}\pi} \quad , \qquad P_{\overline{K}\pi} \approx 1 - \frac{2\pi r_0^2}{3A^{1/3}} \frac{1}{<\sigma_{\overline{K}N \rightarrow \pi Y}>} \tag{23}$$

where $P_{\overline{K}\pi}$ is the conversion probability for $\overline{K}N \rightarrow \pi Y$, evaluated as in Eqs. (19) and (20). Using $r_0 = 1.07$ fm for ^{12}C and 0.93 fm for Pb (to reproduce $<r^2>^{1/2}$), $<\sigma_{\overline{K}N \rightarrow \pi Y}> \approx 40$ mb, twice the value given by Parkin *et al*[19] for $\Lambda + \Sigma^0$ at low p_L, and $\sigma(\bar{p}p \rightarrow \overline{K}X) / \sigma_{\text{TOT}}(\bar{p}p) \approx 0.035$, we obtain predictions varying from $Y = 0.026$ for ^{12}C to 0.032 for ^{208}Pb, consistent with the experimental values[37] of 0.023 ± 0.006 and 0.027 ± 0.11, respectively. More accurate data are required to test the rather weak A dependence of the form $(1 - C/A^{1/3})$, where $C \approx 1/2$, predicted by Eq. (23). The A dependence is weak because we are in the strong absorption regime for which $P_{\overline{K}\pi}$ is close to unity even for rather light nuclei.

4.3.3. The cross section for K_s production. There are two components to the K_s production cross section: a "direct" part σ_{DIR} reflecting the reaction $\bar{p}N \rightarrow K_s X$, and a part σ_{AP} generated by the sequential process $\bar{p}N \rightarrow \pi$'s, followed by $\pi N \rightarrow K_s Y$ associated production:

$$\sigma(\bar{p}A \rightarrow K_s X) = \sigma_{\text{DIR}}(K_s) + \sigma_{\text{AP}}(K_s) \ . \tag{24}$$

At low p_L, σ_{DIR} dominates, and is given by

$$\sigma_{\text{DIR}}(K_s) \approx A_{\text{eff}} \sigma(\bar{p}p \rightarrow K_s X) \approx 5.4 \text{ mb} \tag{25}$$

for $\bar{p}$ + Ne at 600 MeV/c, where the effective mass number $A_{\text{eff}} \approx 2Z_{\text{eff}} \approx 2$ is taken from the $(\bar{p}, \bar{n})$ measurements of Bressani *et al*[41]. We use the value $\sigma(\bar{p}p \to K_s X) \approx 2.7$ mb obtained by Cooper *et al*[14] at 750 MeV/c. The value $\sigma_{\text{DIR}}(K_s)$ reproduces the measured value[37] of $\sigma(\bar{p}\text{Ne} \to K_s X)$ from Eq. (15). For $\bar{p}$+ Ta at 3 GeV/c, we estimate

$$A_{\text{eff}} \approx \frac{2\pi r_0^2}{3\sigma} A^{2/3} \approx \frac{20\,\text{mb}}{\sigma} A^{2/3} \approx 17 \tag{26}$$

using $\sigma \approx \sigma_{\text{TOT}}(\bar{p}p)/2 \approx 38$ mb. A similar result $A_{\text{eff}} \approx 15$ is obtained by scaling the value $A_{\text{eff}} \approx 7.5$ observed[41] for $(\bar{p}, \bar{n})$ on Pb at 550 MeV/c by the ratio of $\sigma_{\text{TOT}}(\bar{p}p)$ values at 550 MeV/c and 3 GeV/c (a factor 2). Thus we predict

$$\sigma_{\text{DIR}}(K_s) \approx 34 \text{ mb} \quad (\bar{p} + \text{Ta at } 3\,\text{GeV/c}) \tag{27}$$

which is only slightly smaller than the experimental value of Eq. (14), indicating that $\sigma_{\text{AP}}(K_s)$ is not large at 3 GeV/c. Note that the "geometric" formula $\sigma_{\text{DIR}}(K_s) = A^{2/3}\sigma(\bar{p}p \to K_s)$ used by Miyano *et al*[4] is incorrect because it omits the factor $2\pi r_0^2/3\sigma$, leading to an overestimate of $\sigma_{\text{DIR}}(K_s)$ by about a factor of 2 at 3 GeV/c. Note also that Eq. (26) is not valid for small A. At 4 GeV/c, we expect $A_{\text{eff}} \approx 18$ and $\sigma_{\text{DIR}}(K_s) \approx 36$ mb. Comparing with Eq. (14), we see that

$$\sigma_{\text{AP}}(K_s) \approx 46 \text{ mb} \quad (\bar{p} + \text{Ta at } 4\,\text{GeV/c}) \tag{28}$$

4.3.4. The cross section for Λ production. In the $\bar{p}d$ case, a detected Λ could have arisen from the strong production of either Λ or Σ^0 in second order reactions involving two nucleons. In a complex nucleus, Λ's can also arise via second order production of $\Sigma^{\pm}$, followed by $\Sigma^{\pm}N \to \Sigma^0 N, \Lambda N$ conversion on a third nucleon. This conversion probability is denoted by P_c, and is approximately given by $1 - 2\pi r_0^2/3A^{1/3}\sigma_c$, where $\sigma_c = \langle \sigma(\Sigma^{\pm}N \to \Lambda N + \Sigma^0 N) \rangle \approx 80$ mb for 400 – 500 MeV/c Σ's. We split the $\tilde{\Lambda} = (\Lambda + \Sigma^0 + P_c\Sigma^{\pm})$ cross section into several parts,

$$\sigma\left(\bar{p}A \to \tilde{\Lambda}X\right) = \sigma_{\text{DIR}}\left(\tilde{\Lambda}\right) + \sigma_{\text{AP}}\left(\tilde{\Lambda}\right) + \sigma_{\text{SE}}\left(\tilde{\Lambda}\right) \tag{29}$$

in terms of direct (DIR), associated production (AP) and strangeness exchange (SE) contributions. The direct part $\sigma_{\text{DIR}}\left(\tilde{\Lambda}\right)$ is

$$\sigma_{\text{DIR}}\left(\tilde{\Lambda}\right) = A_{\text{eff}}\left[\sigma(\bar{p}p \to \Lambda X) + \sigma\left(\bar{p}p \to \Sigma^0 X\right) + \sigma\left(\bar{p}p \to \Sigma^{\pm} X\right) P_c\right] . \tag{30}$$

Using the estimate $\sigma(\bar{p}p \to \Sigma^{\pm}X) = 2\sigma(\bar{p}p \to \Sigma^0 X) = \sigma(\bar{p}p \to \Lambda X)$, and the values $\sigma(\bar{p}p \to \Lambda X) = 0.35$ mb (3 GeV/c) and 0.53 mb (4 GeV/c), and $P_c \approx 0.95$, we find $\sigma_{\rm DIR}(\tilde{\Lambda}) \approx 19$ mb (3 GeV/c) and 32 mb (4 GeV/c) for $\bar{p}$+ Ta. Further, we have

$$\sigma_{\rm SE}\left(\tilde{\Lambda}\right) = A_{\rm eff}\sigma_A(\bar{p}p) \sum_{i=\overline{K},\overline{K}^*} Y_i P\left(i\,N \to \pi\tilde{\Lambda}\right) , \tag{31}$$

where $\sigma_A(\bar{p}p)$ is the total inelastic $\bar{p}p$ cross section, Y_i is the yield of meson i per $\bar{p}p$ annihilation, and $P\left(i\,N \to \pi\tilde{\Lambda}\right)$ is the probability of the strangeness exchange reaction $i\,N \to \pi\tilde{\Lambda}$ occurring in the final state. We ignore possible double counting problems in Eq. (31). For the $\overline{K}$ contribution, we expect

$$\sigma_{\rm SE}^{\overline{K}}\left(\tilde{\Lambda}\right) \approx A_{\rm eff}\sigma\left(\bar{p}p \to \overline{K}X\right) P_{\overline{K}\pi} \approx 65 \text{ mb} \tag{32}$$

for $\bar{p}$+ Ta at 4 GeV/c, using Eq. (23).

The associated production cross section is

$$\sigma_{\rm AP}\left(\tilde{\Lambda}\right) = A_{\rm eff}\sigma_A(\bar{p}p) \sum_{i=\{\pi,\rho,\omega,\eta\}} P\left(i\,N \to K\tilde{\Lambda}\right) \tag{33}$$

where $P\left(i\,N \to K\tilde{\Lambda}\right) = P\left(i\,N \to K\Lambda + K\Sigma^0\right) + P_c P\left(i\,N \to K\Sigma^{\pm}\right)$. Using $A_{\rm eff}$ $\sigma_A(\bar{p}p) \approx 900$ mb and $Y_i \approx 8$ at 4 GeV/c, and

$$P\left(\pi N \to K\tilde{\Lambda}\right) \approx \rho_0 < \sigma\left(\pi N \to K\tilde{\Lambda}\right) >< R > \tag{34}$$

where $\rho_0 \approx 1/6$ fm^{-3}, $< R > \approx (\pi/6)^{1/2} < r^2 >^{1/2} \approx 4$ fm for Ta. Equation (34) is obtained by expanding Eq. (19) for small $< \sigma >$ (compare to Eq. (23), which is valid for large $< \sigma >$). For $\tilde{\Lambda} = \Lambda$, we have $< \sigma(\pi N \to K\Lambda) > \approx 0.2\, P_>$ mb, where the factor $P_> \approx 1/3$ is the probability[20] that the π is above threshold; this gives $\sigma_{\rm AP}^{\pi}(\Lambda) \approx 32$ mb, in agreement with the value 29 mb calculated by Ko and Yuan[20]. For $\pi N \to K\Sigma$, the thresholds are around $1.02 - 1.035$ GeV/c, so $P_>$ is smaller than for Λ. However, we have $< \sigma(\pi N \to K\Sigma) > / < \sigma(\pi N \to K\Lambda) > \approx 1.6$ at 1.23 GeV/c, 3.3 at 1.5 GeV/c, summed over Σ charge states. We estimate that Λ and Σ production are comparable, i.e., $P\left(\pi N \to K\tilde{\Lambda}\right) \approx 2P(\pi N \to K\Lambda)$, so we obtain

$$\sigma_{\rm AP}^{\pi}\left(\tilde{\Lambda}\right) \approx 64 \text{ mb} \quad (\bar{p} + \text{Ta at } 4\,\text{GeV/c}) \;. \tag{35}$$

The contributions of vector mesons to $\sigma_{\rm AP}\left(\tilde{\Lambda}\right)$ are much more model dependent. Ko and Yuan[20] have given an estimate of $\sigma^{\omega}_{\rm AP}(\Lambda) \approx 12$ mb. For the ρ, we have

$$\sigma^{\rho}_{\rm AP}\left(\tilde{\Lambda}\right) \approx 60\; Y_\rho P_\rho < \sigma\left(\rho N \to K\tilde{\Lambda}\right) > \tag{36}$$

where we expect[6] $Y_\rho \approx 1$ and P_ρ is the probability that the ρ, once produced in $\overline{N}N$ annihilation, strikes a second nucleon before decaying:

$$P_\rho = 1 - \exp\left(-\frac{c\tau_0}{<r>}\,\frac{\beta}{\left(1-\beta^2\right)^{1/2}}\right) \tag{37}$$

where $c\tau_0 = c/\Gamma_\rho \approx {}^4\!/_3$ fm, $\beta = (v/c)_\rho$ and $<r>$ is the mean spacing between nucleons. At low $\bar{p}$ momentum, the ρ's are rather slow and are produced in the far surface of the nucleus, so $P_\rho \ll 1$. Thus, for $\bar{p}$+ Ne at 600 MeV/c, for instance, we expect that $\sigma^{\rho}_{\rm AP}$ is negligible. Indeed, the K_s cross section in this case is fully consistent with a direct production mechanism, as per Eq. (25). At 4 GeV/c, on the other hand, the average ρ momentum is higher, and $\overline{N}N$ annihilation occurs further inside the nucleus, where $<r>$ is decreased. For ρ lab momenta in the range 500 – 700 MeV/c, typical for 4 GeV/c $\bar{p}$ annihilation, and $<r>= 1.5$ fm, Eq. (37) yields $P_\rho \approx {}^1\!/_2$.

The remaining ingredient is $< \sigma\left(\rho N \to K\tilde{\Lambda}\right) >$. We note that the ρN system at rest has a mass distributed around 1.71 GeV/c, while $K\Lambda$ and $K\Sigma$ correspond to masses of 1.61 and 1.69 GeV/c, respectively. Thus, the $\rho N \to K\tilde{\Lambda}$ processes are exoergic, and the cross section will display a ${}^1\!/_v$ behavior at low momentum, in contrast to $\pi N \to K\tilde{\Lambda}$, which has a threshold. Assuming that s–channel baryon resonances dominate the $MN \to KY$ cross sections, we note that the $N(1710)$, a ${}^1\!/_2{}^+$ p–wave state, couples significantly to $\pi N, \eta N, \rho N, \Lambda K$, and ΣK. The $N(1710)$ lies at the ρN threshold and corresponds to a pion momentum of 1.07 GeV/c, i.e., close to the peak of the $\pi N \to K\Lambda$ cross section. Thus, a simple model is

$$\frac{< \sigma\left(\rho N \to K\tilde{\Lambda}\right) >}{< \sigma\left(\pi N \to K\tilde{\Lambda}\right) >} \approx \frac{BR\left(N(1710) \to \rho N\right)}{P_> \cdot BR\left(N(1710) \to \pi N\right)} \approx \frac{1}{P_>} \approx 3 \tag{38}$$

or $< \sigma\left(\rho N \to K\tilde{\Lambda}\right) > \approx 1.3$ mb. Note that $BR\left(N(1710) \to \rho N\right)$ is very uncertain. Similarly, from $BR\left(N(1710) \to \eta N\right) \approx BR\left(N(1710) \to \pi N\right)$, we obtain $< \sigma\left(\eta N \to K\tilde{\Lambda}\right) > \approx 1$ mb. Thus, we have, using[6] $Y_\eta \approx 0.05$,

$$\sigma^{\rho}_{\rm AP}\left(\tilde{\Lambda}\right) \approx 40 \text{ mb}\;, \quad \sigma^{\eta}_{\rm AP}\left(\tilde{\Lambda}\right) \approx 1.5 \text{ mb}\;. \tag{39}$$

Gathering all these terms together, we estimate at 4 GeV/c,

$$\sigma_{\rm AP}\left(\tilde{\Lambda}\right) \approx 118 \text{ mb} , \quad \sigma\left(\bar{p} + \text{Ta} \to \tilde{\Lambda}X\right) \approx 215 \text{ mb} . \tag{40}$$

The latter value agrees well with the experimental result[4] of 193 ± 12 mb from Eq. (14). Note that $\sigma_{\rm AP}\left(\tilde{\Lambda}\right)/\sigma_{\rm AP}\left(K_s\right) \approx 2.6$, much the same as the ratio $\sigma_{\rm SE}\left(\tilde{\Lambda}\right)/\sigma_{\rm DIR}\left(K_s\right)$, so that overall we get R values in agreement with Eq. (16).

We conclude that the absolute cross section for Λ production in $\bar{p}+$ Ta collisions at 4 GeV/c can be understood in terms of conventional hadronic multistep processes. The bulk of the Λ cross section arises from strangeness exchange $\left(\overline{K}N \to \pi Y\right)$ and associated production $(\pi N \to KY,\ \rho N \to KY)$ induced by the annihilation pions and kaons which traverse the nuclear medium.

4.4. Future Prospects

As we have argued, the inclusive cross sections for $\bar{p} + A \to \Lambda X, K_s X$ do not require an exotic explanation. More challenging quantities to explain are the semi–inclusive cross sections[4] for $\bar{p} + A \to \Lambda K_s X,\ K_s K_s X,\ \Lambda\Lambda X$, etc. These will tell us in more detail how the strangeness is redistributed after its production in first order $\overline{N}N \to \overline{K}KX,\ K\Lambda X,\ \overline{\Lambda}\Lambda X$, etc., processes. The cross sections for $\bar{p}+A \to K^- X,\ \Sigma^\pm X$, which have not been measured, are important as a test of the extent to which we have approached the strong absorption limit (i.e., $P_{\overline{K}\pi}$, $P_c \to 1$ for $\overline{K}$ or $\Sigma^\pm$ conversion). The mechanisms for the production of multiply–strange systems ($\Lambda\Lambda$, Ξ^-, Ω^-, and even the H dibaryon!) are of particular interest. The ratio $N(\Lambda\Lambda)/N(\Lambda) \approx 0.035$ seen[4] in $\bar{p}+$ Ta at 4 GeV/c, for instance, may be explainable in terms of a third order process, or it could be more economical to use the notion of emission from a $B = 2$ fireball $\left(\overline{N} + 3N \to \Lambda\Lambda X\right)$, in which phase space considerations are dominant, and the memory of cross sections and intermediate states in a multistep reaction is lost. These matters will be taken up in a subsequent paper[42].

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