2.5 Low Energy Kaon Scattering: Present Status and Open Possibilities

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Abstract

An overview of the experimental results on low energy scattering of charged and neutral Kaons is given. Emphasis is put on the still missing information, which could be essential to provide a thorough description of the $\overline{K}N$ interaction close to threshold as well as below it, and that could be achieved by exploiting the unique features of a high intensity K_L^0 beam.

1. **Neutral Kaon Scattering: Properties and Cross Sections Measurements at Low Energies**

The low energy cross section data for the interaction of charged Kaons with protons or neutrons (in deuterium targets) are rather few and imprecise. Below 350 MeV/c incident momentum only old measurements exist, which date back to the Eighties and earlier years, and were performed in bubble chamber experiments or with emulsions [1]. This low energy region could still be fruitfully explored by the DAΦNE machine in Frascati, and proposals were put forward some years ago in this respect [2].

For neutral Kaons the situation is even worse. Few data exist down to 130 MeV/c with a statistical accuracy limited to 10-20% for the K_L^0p scattering, and a little better for K_L^0d [3]. The trend of low momentum K_L^0p total cross section, from Ref. [3], is reported in Fig. 1: a typical total cross section at low momenta for K_L^0 induced scattering on protons is around 70 mb, and twice as large on deuterons.

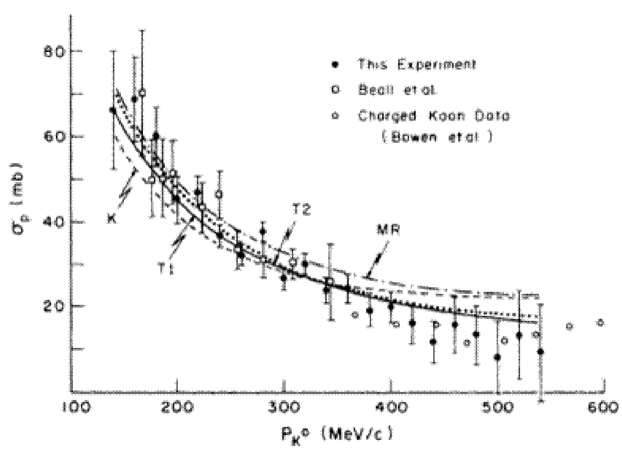

Figure 1: Total K_L^0p cross section. From Ref. [3]. The superimposed curves are the trends expected on the basis of different solutions for the K^-p scattering lengths (see text).

It is useful to recall that neutral Kaons behave as two different kinds of particles depending on the interaction they are subject to. The weakly interating particles, CP-eigenstates K_S^0

and K_L^0, are linear combinations (of almost equal strenght, at the precision level of scattering measurements) of the strangeness eigenstates, K^0 and $\overline{K^0}$. These are the relevant particles for evaluating the effect of the strong interaction in the scattering. According to the strangeness of the meson, however, its behavior as hadronic probe is largely different.

The Kaons with strangeness $S = +1$, *i.e.*, K^+ and K^0, have just a mild interaction with the medium. The cross sections are small, of the order of 10 mb, and are dominated by the elastic channel with a small contribution from Charge Exchange. The relevance of these scattering processes is mainly related to the possible formation of exotic pentaquark systems ($q^4\overline{q}$), that however have never been observed so far (anyway, if ever existing, these states are not likely to show up at low energies). In the K^+p scattering a sizeable contribution, almost as large as the one due to strong interaction, comes from the electromagnetic interaction, relevant especially at small angles [4]. The K^+p system is a pure isospin $I = 1$ state, and its S-wave scattering length, which will be described in more detail in Sec. 2.5.1.a, has been determined with good ($\sim 1\%$) precision.

On the other hand, Kaons with strangeness $S = -1$ are strongly absorbed. The interaction cross sections are larger than 50 mb, and several baryonic resonances (formerly known as Y^*), both with isospin 0 and 1, may be excited even below threshold. The $\overline{K}N$ system is therefore strongly coupled, via these resonances, to several channels, like $\Lambda\pi,\ \Sigma\pi,\ Y\eta,\ Y\pi\pi$ *etc*. The different behavior of the two K_L^0 components implies that the interaction of such a beam with dense matter basically kills the $\overline{K^0}$ amplitude, which is almost completely absorbed. However, if the interaction of K_L^0 occurs on protons, final states are produced resulting from both K^0 and $\overline{K^0}$ interactions with different amplitudes: from their interference one might extract information on the relative sign of the K^0N and $\overline{K^0}N$ potentials. While the K^0p system is a mixture of $I = 0$ and $I = 1$ amplitudes, the $\overline{K^0}p$ is in pure $I = 1$: the information the latter can provide is complementary to what can be obtained by the study of K^+p, but without any Coulomb interaction. Moreover, the final states which can be produced in a $\overline{K^0}p$ scattering are the charge conjugate of those reachable in a K^-n interaction; therefore, they carry the same information but don't require the use of deuterium as a target, which inevitably introduces three-body interactions between the target and the projectile that need to be properly taken into account.

It is also worthwhile to notice that on the basis of charge symmetry one can assume that $\sigma_{tot}(K^0p) = \sigma_{tot}(K^+n)$ and $\sigma_{tot}(\overline{K^0}p) = \sigma_{tot}(K^-n)$. These equalities were proved to be valid at least to the precision level of old bubble chamber experiments, and were often used to indirectly assess unmeasured cross sections [5].

The existence of resonant states prevents the use of perturbative theories to describe the $\overline{K}N$ interaction close to threshold. To this purpose, non-perburbative chiral based coupled channel approaches are usually applied, adapting the models to all the available experimental observations, including, besides elastic and inelastic cross sections, also measurements of hadronic branching ratios close to threshold, resonances lineshapes, and inputs from Kaonic atom levels shifts due to strong interaction and their widths. Several models have been elaborated in the years to reproduce the K^-N experimental data [6]; more new inputs would of course be welcome not only to improve the data description, but also to provide a more reliable prediction of the below-threshold behavior, that is relevant for the study of sub-threshold baryonic resonances and the possible existence of multinucleon-antiKaon aggregates, as will be discussed in Sec. 2.5.2.a.

(a) **Low energy scattering parameterizations**

An old fashioned simple but useful way to describe the low energy interaction of particles is to parametrize the scattering cross sections in terms of S-wave *scattering lengths* [7]. Assuming the reaction energy to be low enough to allow only the S-wave to be involved, and the “zero-effective range" approximation to be appliable, the scattering length $A = a + ib$, that in general is a complex number, can be used to describe univoquely the phase-shift in each channel of given isospin and strangeness through the relationship $\cot\delta = 1/kA$, where δ is the phase-shift and k the projectile wave number. In a definite isospin-strangeness channel, the scattering cross section may then be expressed by the general formula:

$$\sigma = \frac{a^2 + b^2 + b/k}{k^2a^2 + (1 + kb)^2}. \tag{2}$$

The efforts of the first experiments measuring K^- scattering was mainly to extract the real and imaginary part of the scattering lengths for the two isospin sources from the available cross sections [8]. Due to the lack of data and the loose constraints provided, however, these assessments were far from being precise and several equally good solutions were often found, with large ambiguities which survived until recently, when precise measurements of Kaonic atom levels were performed and could be used as precise additional inputs.

The S-wave K^0_Lp scattering cross sections may be expressed, in zero-range approssimation, through four parameters: the isospin I=0 and I=1 real scattering lengths a_0 and a_1 for the $S = +1$ channels, and the complex (absorptive) $\overline{A} = \overline{a}_1 + \bar{b}_1$ scattering length for the $S = -1$, $I = 1$ channel [9]. By means of these parameters the low-energy cross sections have the following simple expressions:

total cross section

$$\sigma_{tot} = 2\pi\left[\frac{1}{2}\frac{a_0^2}{1+k^2a_0^2} + \frac{1}{2}\frac{a_1^2}{1+k^2a_1^2} + \frac{\overline{a}_1^2 + \overline{b}_1^2 + \bar{b}_1/k}{k^2\overline{a}_1^2 + (1+k\bar{b}_1)^2}\right];$$

elastic cross section

$$\sigma(K^0_Lp \to K^0_Lp) = \pi\left|\frac{1}{2}\frac{a_0}{1-ika_0} + \frac{1}{2}\frac{a_1}{1-ika_1} + \frac{\overline{a}_1 + i\bar{b}_1}{k^2\overline{a}_1^2 + (1+k\bar{b}_1)^2}\right|^2;$$

regeneration cross section

$$\sigma(K^0_Lp \to K^0_Sp) = \pi\left|\frac{1}{2}\frac{a_0}{1-ika_0} + \frac{1}{2}\frac{a_1}{1-ika_1} - \frac{\overline{a}_1 + i\bar{b}_1}{k^2\overline{a}_1^2 + (1+k\bar{b}_1)^2}\right|^2;$$

one nucleon absorption cross section

$$\sigma(K^0_Lp \to Y\pi) = \frac{2\pi}{k}\frac{\bar{b}_1}{k^2(\overline{a}_1^2 + b_1^2) + 2k\bar{b}_1 + 1}.$$

In the following a short account of the existing measurements of the above cross sections at low momenta will be given.

i. **$K_L^0 p \to K_S^0 p$ regeneneration cross section**
The main purpose of the first measurements of the regeneration cross sections [10] was the investigation of the features of the Y_1^* resonances (in particular, the $\Sigma(1385)$), and the search for the possible existence of exotic $I = 0$, $S = +1$ Z^* states. The amplitude may be written by the sum of the $I = 0$ and $I = 1$ $K^0 N$ terms, and the $I = 1$ $\overline{K^0} N$ one: $T = \frac{1}{4}(Z_0 + Z_1) - \frac{1}{2} Y_1$; the resulting cross section derives from the interference between the $S = -1$ and $S = 1$ amplitudes. Regeneration cross sections were measured down to 300 MeV/c [11], and at the lowest momenta they amount to about 5 mb. Fig. 2 reports the available experimental data with, superimposed, a few parameterizations deduced from different solutions for the $K^- n$ scattering length value (via the application of the charge symmetry assumption). The differential cross sections exhibit moreover a marked backward peaked trend as a function of the K_S^0 emission angle in the reaction center of mass [12].

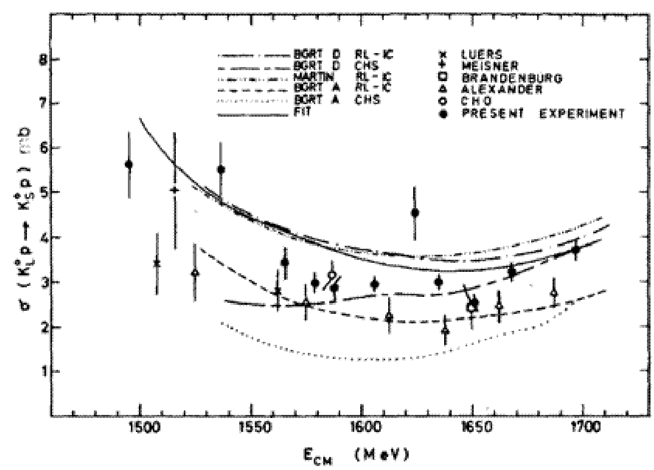

Figure 2: Low momentum K_L^0 regeneration cross section, from Ref. [10].

ii. **Inelastic Cross Sections and Hyperon Production Yields**
The relevant reactions for the K_L^0 induced production of baryonic resonances at low energies are $K_L^0 p \to \Lambda\pi^+$, $\Sigma^0\pi^+$ and $K_L^0 p \to \Lambda\pi^+\pi^0$. An assessment of the ratio of regeneration to elastic yields, $R = \frac{\sigma(K_S^0 p)}{\sigma(\Lambda\pi^+)+2\sigma(\Sigma^0\pi^+)}$, was used by early experiments [13, 14] to discriminate among the expected trends, as a function of K_L^0 momentum, from different sets of solutions for the $K^- p$ scattering length. As shown in Fig. 3 (left), none of the trends expected for R on the basis of different solution sets could reproduce in a satisfactory way the observed yields.
Figures 3 center and right show, respectively, the inelastic cross sections for the reactions $K_L^0 p \to \Lambda\pi^+$ (about 5 mb at 300 MeV/c) and $K_L^0 p \to \Sigma^0\pi^+$ (~ 3 mb). The $K_L^0 p \to \Lambda\pi^+\pi^0$ channel is less relevant (< 1 mb) [15], and is mainly dominated by the $\Sigma^0(1385)$ production.

2. **Low Energy $\overline{K}N$ Dynamics: Open Problems**

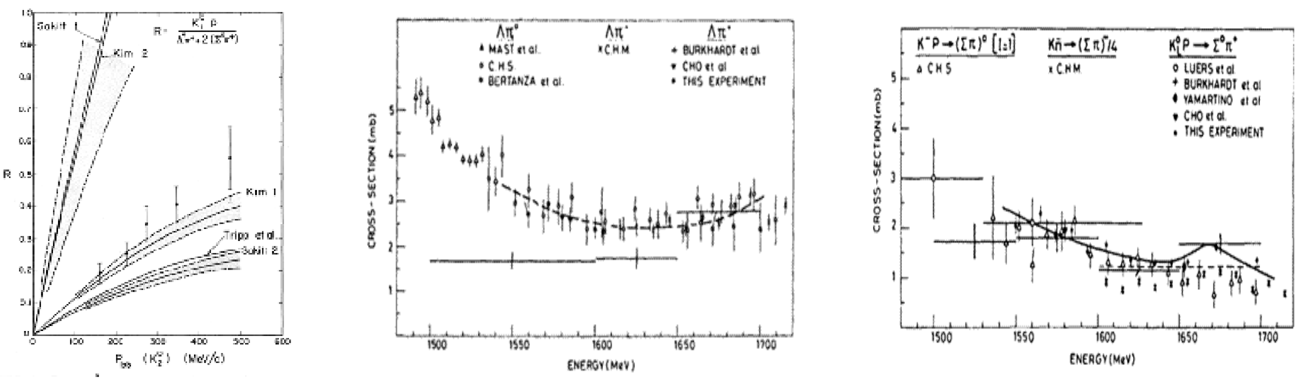

Figure 3: Left: ratio, as a function of K_L^0 momentum, of the yields for regeneration to inelastic scattering. The lines represent the expected trends on the basis of different solutions chosen for the K^-p scattering length, from Ref. [13]. Center: $K_L^0 p \to \Lambda\pi^+$ cross section; Right: $K_L^0 p \to \Sigma^0\pi^+$ cross section. When existing, the data are compared to cross section measurements in the charge conjugated channels. The last two pictures are from Ref. [15].

The $\overline{K}N$ interaction still presents some obscure aspects which only few more accurate data will be able to shed light on. The basic fact is the strong attractiveness of the interaction close to threshold and even below it, that manifests itself with the existence of a baryonic quasi-bound $\overline{K}N$ state, the $\Lambda(1405)$, embedded in the $\pi\Sigma$ continuum. This means that a strong coupled-channel dynamics between $\overline{K}N$ and $\Sigma\pi$ exists; to reproduce this behaviour a below-threshold extrapolation of the trend of the $\overline{K}N$ amplitude based on observed data must be exploited. However, the relatively scarce precision of the presently available experimental data close to threshold has severe drawbacks on the accuracy of the sub-threshold extrapolations. For this reason, new experimental inputs would certainly be welcome, especially if characterized by fixed quantum numbers (like the Coulomb free $I = 1$ $K_L^0 p$ interaction).

Several chiral inspired coupled-channels models have been elaborated over the years [6]. The most recent ones [16] are able to reproduce satisfactorily most of the existing data through global fits, especially since when the newest measurement of the Kaonic hydrogen $1S$ level performed by the SIDDARTHA Collaboration [17] was included in the data set. We recall that the energy shift ΔE and width Γ of the $1S$ Kaonic hydrogen line are directly related to the $a(K^-p)$ scattering length value through the Trueman-Deser formula (including second order isospin corrections): $\Delta E - i\Gamma/2 = -2\alpha^3\mu_T^2\, a(K^-p)\,[1 + 2\alpha\mu_T(1-\log\alpha)a(K^-p)]$, where α is the strong coupling constant, and μ_T the reduced mass of the K^-p system. The new measurement performed by the SIDDARTHA Collaboration fixes the inconsistencies emerging from the previous experiments on Kaonic hydrogen, and is fully compatible with all the existing scattering data. Unfortunately, the experiment was not sensitive enough to perform also a measurement of the $1S$ Kaonic deuterium level, that could allow the determination of the K^-n scattering length; however, an upgrade was proposed to this purpose and is foreseen to run at DAΦNE in the near future.

The Kaonic hydrogen new measurement is very useful to provide much more stringent constraints for the determination of the scattering lengths in the two different isospin channels [18]. Calculations have been performed also to assess the extent of the K^-n (fixed $I = 1$) scattering length [19], but the evaluation is still rather imprecise due to the large uncertainty of the experimental inputs (especially of the scattering data in the $\Lambda\pi$ channel). As shown in Ref. [20] the $I = 1$ $\overline{K}N$ interaction is expected to be weaker as compared to the $I = 0$ source; therefore, data from Kaonic deuterium or from $K^0_L p$ scattering would be useful in this respect.

(a) **Subthreshold behavior: the $\Lambda(1405)$ case and the case for possible nuclear-Kaonic aggegates**

The measurement of the Kaonic hydrogen ΔE and Γ provides a single experimental point to constrain the behavior of the below-threshold real and imaginary part of the K^-p elastic scattering amplitude, as shown in Fig. 4 from Ref. [21]. This result is just one typical snapshot of the outcomes of several equivalent high-quality below-threshold extrapolations: $Re(a(K^-p)) = -0.65 \pm 0.10$ fm, and $\Im m(a(K^-p)) = 0.81 \pm 0.15$ fm. In spite of the uncertainty of the prediction, represented by the grey band around the best fit result, basically all models agree on the existence of the $\Lambda(1405)$ resonance, to be interpreted as a $I = 0$ $\overline{K}N$ system bound by 27 MeV. This resonance is dinamically generated by the interplay of two poles in the second Riemann sheet, one at higher mass ($1424 - i26$ MeV) coupled to the $\overline{K}N$ channel, and the second at a lower mass value ($1381 - i81$ MeV) dominated by the $\Sigma\pi$ coupling [19].

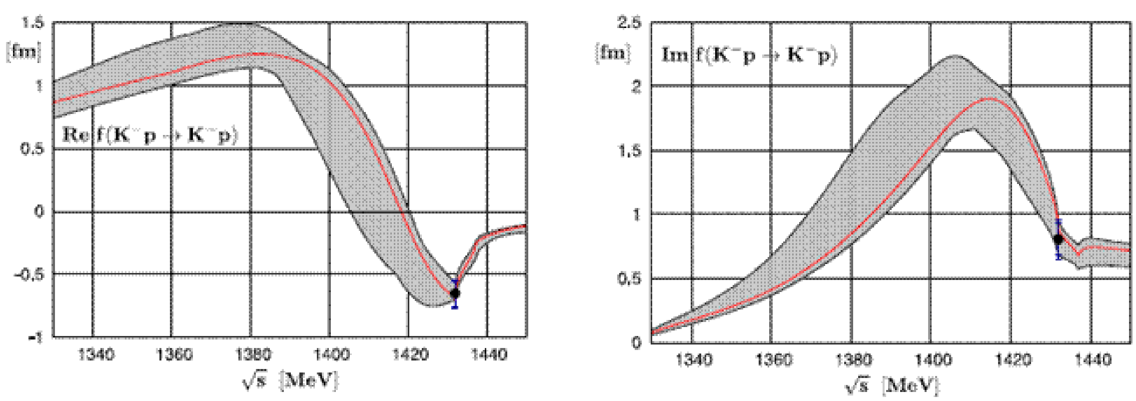

Figure 4: Solutions for the real and imaginary part of the K^-p elastic scattering amplitude, based on the chiral inspired model of Ref. [19]. The best fit to the experimental data is represented by the continuous line, while the grey area shows the uncertainty of the model, determined by the precision of the available experimental data used for the fit. The two data points correspond to the assessment of the real and imaginary parts of the K^-p scattering length derived from the experimental measurement of the Kaonic hydrogen $1S$ level by the SIDDARTHA Collaboration.

From the experimental point of view the observations of the $\Lambda(1405)$ were often hindered by the existence, in the same mass region, of the $\Sigma(1385)$ baryon, which shares with the $\Lambda(1405)$ the charged $\Sigma\pi$ decay mode. The decays in charged $\Sigma\pi$ pairs were studied by early experiments on deuterium targets [22]. The first observations were confirmed, with higher statistics, by second generation experiments which were also able to measure the $\Sigma^0\pi^0$ decay channel, which is mostly important as it is only allowed for the decay of the $\Lambda(1405)$, but is prevented to $\Sigma(1385)$. The latter, on the other hand, may only decay to $\Lambda\pi^0$ (channel excluded for $\Lambda(1405)$). The most complete data-set collected so far defining the $\Lambda(1405)$ lineshape comes from the CLAS experiment, based on photo- and electroproduction of the $\Sigma\pi$ final states [23]. The best fit of the data suggests the lineshapes of the three charge combinations of the $\Sigma\pi$ invariant mass systems to be reproduced by introducing a dominant $I = 0$ contribution (at $m = 1338 \pm 10$ MeV/c^2, with $\Gamma = 85 \pm 10$ MeV), plus two $I = 1$ amplitudes, one of which is most probably related to the $\Sigma(1385)$ broad resonance ($m = 1394 \pm 40$ MeV/c^2, $\Gamma = 149 \pm 40$ MeV), while the second, narrower and at higher mass ($m = 1412 \pm 10$ MeV/c^2, $\Gamma = 52 \pm 10$ MeV), has a still uncertain nature. Its necessity, to provide a good description of the data, has been remarked by theoretical models [24]; for its interpretation, the possibility that it might be due to a new, exotic pentaquark baryonic state [25] is still open.

Related to the existence of the $\Lambda(1405)$ is the case of the so-called (anti)Kaon-nuclear clusters. Following the hypothesis suggested by Akaishi and Yamazaki in 2002 [26], the $\Lambda(1405)$ could be the founding block based on which more complex aggregates, composed by an anti-Kaon deeply bound to two or more nucleons, could exist. Even though the existence of such states is not ruled out in most of the chiral inspired models elaborated so far [27], very few of them agree on their observability as narrow states mainly decaying via the non mesonic channel ($\Sigma\pi$ and $\Lambda\pi$ being prevented by their strong binding and by isospin conservation). Most of the models, in fact, foresee for the $\overline{K}N$ potential rather shallow wells, so a mild binding. In the initial formulation, on the contrary, these states are expected to be narrow, bound by more than 100 MeV and forming very compact systems, with a density more than three times as large as compared to ordinary nuclear matter. The medium in which their formation could more likely occur is also a controversial point: while according to the starting hypothesis the observation in light targets could be easier, other calculations [28] indicate that heavy targets should be preferred. If this were the case, however, probably large Final State Interaction effects would spoil completely their observability as narrow states.

From the experimental point of view, the situation is still rather confused and a few observations claimed so far [29] still need a sound confirmation. For the latest findings of this search using a ^{3}He target (E15 experiment running at J-PARC) the reader may refer to Ref. [30].

The search for such states has been performed so far only relative to the $K^-NN(N)$ systems; no measurement were ever attempted with neutral Kaon beams. Therefore, provided a ^{3}He or ^{4}He (or even heavier) target could be exploited, the search for such states could represent a completely new field of investigation to be pursued with K^0_L as projectiles (again, free from Coulomb interactions and related to the binding properties of $I = 1$ $\overline{K}N$ systems only).

3. **Possible Measurements with K^0_L Beams and Experimental Reach**

With a liquid hydrogen/deuterium target, the following reactions could be measured at low momenta, to improve the present knowledge on the scattering cross sections:

elastic scattering $K^0_L p \to K^0_L p$, $K^0_L d \to K^0_L d$ (coherent), $K^0_L d \to K^0_L np$ (quasi-elastic scattering on n);

inelastic scattering on protons with Y formation $K^0_L p \to \Lambda\pi^+,\ \Sigma^0\pi^+,\ \Sigma^+\pi^0,\ \Lambda\pi^+\pi^0$;

inelastic scattering on deuterons for below-threshold Y resonances production $K^0_L d \to \Lambda(1405)N$;

charge exchange reactions $K^0_L p \to K^+ n$;

regeneration reaction $K^0_L p \to K^0_S p$.

One or two measurements of low momentum cross sections below 350 MeV/c at the 10% precision level would be highly desireable to complement the experimental data set on which close-to-threshold $\overline{K}N$ interaction studies are based. Differential information, for instance as a function of the emission angle, could be fruitfully explored as well.

A few experimental possibly critical drawbacks have however to be taken into account. Among them:

(a) The K^0_L beam intensity at low momentum. As shown by experiments exploiting the K^0_L production by means of photoproduction on a Be target, K^0_L's are produced with a continuum momentum spectrum [31,32]. The low momentum portion is roughly some 10^{-3} of the total integrated K^0_L momentum spectrum, for a maximum photon energy of around 10 GeV [32], close to that foreseen for the 12 GeV CEBAF machine. This could still allow to have a fair number of low momentum K^0_L (some Hz), provided they can be effectively discriminated from neutrons even at these low energies;

(b) The capability of detecting low momentum particles in the final state. The momentum resolution is not a crucial problem in a few body reaction, but the curling of low momentum particles in a high intensity magnetic field could prevent them from reaching the position sensitive detectors and therefore impair the observation of the mentioned reactions. A careful study on how to increase the apparatus acceptance to low momentum particles would most likely be required in the planning of such measurements.

A tentative yield evaluation, with some optimistic but reasonable detection efficiencies (assuming that all the emitted particles enter the apparatus acceptance), indicates that for an elastic cross section measurement with a precision at the level of 10% some hours of data taking could be enough, while a few days at most would be required for the less frequent inelastic channels.

(a) **Hypernuclei formation studies**

A completely new research field, that could be explored with a K^0_L beam and for which no experimental result exist so far, is the production of hypernuclei in $\overline{K^0}$ induced reactions. The spectroscopy of the formation pion, in reactions on ^{A}Z nuclei like $^A\mathrm{Z}(\overline{K^0},\pi^+)^A_\Lambda(\mathrm{Z}-1)$ or $^A\mathrm{Z}(\overline{K^0},\pi^0)^A_\Lambda\mathrm{Z}$, requires a very high momentum resolution (on the order of a few per mil), which, however, is probably out of scope for an apparatus conceived for hadron spectroscopy like GlueX. This information might be of unprecedented value for the investigation of the so-called Charge Symmetry Breaking effect, which consists in a sizeable difference between the binding energies of the ground states of mirror hypernuclei. So far, the effect has been observed in light mirror hypernuclei pairs (like ${}^{4}_{\Lambda}$He vs ${}^{3}_{\Lambda}$H), and is supposed to be due to a strong $\Lambda\Sigma$ mixing [33]. While in this case the binding energies differ of about 250 KeV, for heavier (P-shell) hypernuclei the difference is expected to decrease. Studies of mirror light hypernuclei production would be welcome to investigate this interesting effect in deeper detail.

4. **Conclusions**

With a beam of low momentum K^0_L new tools to improve the knowledge of the $\overline{K}N$ interaction, never exploited so far, could be available. It is important to recall that with a K^0_L beam the isospin $I = 1$ source of the $\overline{K}N$ amplitude may be selected: its features are largely unknown as, with charged Kaons, this information may only be pursued using deuterium as a target, which involves a complicated treatment due to the inherent few-body interaction. Moreover, the $K^0_L p$ interaction is free from any Coulomb-related effect.

Data on $K^0_L p$ scattering might improve the present knowledge of $I = 1$ scattering length, providing complementary information to the already planned measurements of Kaonic deuterium. An extension of the charged Kaon scattering database to neutral Kaon induced reactions would be important to improve the precision of $\overline{K}N$ models especially regarding their below-threshold extrapolations, that are crucial to improve the understanding of some still critical subjects, like the nature of the $\Lambda(1405)$ as a true baryonic resonance.

With targets heavier than deuterium, the study of more complex systems like Kaon-nuclear bound states or hypernuclei produced in K^0_L induced reactions could potentially be feasible, and thorougly yet unexplored research topics could be opened.

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