(pre)Letter of Intent

The case of deeply bound kaonic nuclear states

Proposal of an international facility at \( DA\Phi\)NE2

September 2005

DEAR/SIDDHARTA Collaboration

Manifestation of interest from Institutions of:
- Austria
- Canada
- France
- Germany
- Hungary
- Italy
- Japan
- Poland
- Romania
- Russia
- Sweden
- USA
- ...
Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

Frank Wilczek “QCD made simple”
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From exotic atoms to exotic nuclei
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## 1 Introduction

The objective of this (pre)Letter of Intent is to attract attention on one of the hottest topics of hadron physics, the case of deeply bound kaonic nuclear states, also called kaonic nuclear clusters or $\bar{K}$-nuclear clusters. To do this, we show that, if they would exist, a new paradigm in strangeness nuclear physics is created. It has many impacts and leads very far-away: because $\bar{K}$-nuclear clusters represent indeed the ideal conditions for investigating the way in which the spontaneous and explicit chiral symmetry breaking pattern of low-energy QCD changes in the nuclear environment. Cold dense matter is formed, a phase transitions from hadronic matter to a quark-gluon phase could be expected.

*Our aim is as well that to explain why DAΦNE2 is a good place to study kaonic nuclear clusters.*

The hypothesis of deeply bound kaonic nuclear states is only three years old, in the structured form of a phenomenological model (Akaishi and Yamazaki). A successful example of deeply bound pionic atomic states did already exist, after their observation at GSI in 1996 (Yamazaki, Kienle, et al.). The deeply bound states in pionic atoms have become an important tool to test partial chiral symmetry restoration in hadronic matter.

Some experimental indications of $\bar{K}$-nuclear clusters have been recently produced mainly at KEK, and also at DAΦNE (FINUDA), GSI (FOPI) and BNL-AGS (E930).

The future of the field speaks essentially Japanese, although at GSI, with FOPI, a campaign has just started, and will last until the big new complex FAIR will progressively absorb all the existent.

We demonstrate in Chapter 6 that DAΦNE2, with its special features and a dedicated setup to study $\bar{K}$-nuclear clusters in nuclei, would be the only facility in
the world where the method suggested by the authors of the original hypothesis, the more direct and unambiguous, namely $K^-$ induced reactions at rest, can be applied. DAΦNE2, moreover, would be the only European laboratory where kaonic nuclei are investigated.

We identified the methods, described in Chapter 7, to study the characteristics features of $\overline{K}$-nuclear clusters both in the production stage and in the decay. This turns out in the necessity of a $4\pi$ dedicated detector, capable of detecting all charged and neutral particles, which will allow, for the first time, the complete determination of all formation and decay channels.

The scientific programme of the new initiative at DAΦNE2, described in Chapter 8, consists of precision spectroscopy studies of a number of light kaonic nuclei as a function of their baryonic number and isospin.

Finally, by recalling the interest raised by the kaonic atoms experiments at DAΦNE and the subsequent formation of the large international collaboration DEAR/SIDDHARTA, we claim in Section 9 the legitimacy in expecting a similar interest towards kaonic nuclei, especially at the light of the unique role that the new Frascati facility might play in Europe and at world level. Preliminary contacts with the international community support this expectation.

2 The scientific case of kaonic nuclear clusters

2.1 A new paradigm in strangeness nuclear physics

A new paradigm in strangeness nuclear physics is represented by the recently studied “Nuclear $\overline{K}$ bound states in light nuclei” by Y. Akaishi and T. Yamazaki [1], whose first experimental indications have been produced at KEK [2, 3 ,4], LNF [5], GSI [6] and BNL [7].
In a few-body nuclear system, in fact, the isospin I=0 $\bar{K}N$ interaction plays an important role: it favours discrete nuclear bound states of $\bar{K}$, while contracting the nucleus thus producing a cold dense nuclear system.

Many important impacts then follow:

- such compact exotic nuclear systems are formed with binding energies so large (100-200 MeV) that their widths turn out very narrow, less than (20-30 MeV), since the $\Sigma\pi$ decay channel is closed energetically and, additionally, the $\Lambda\pi$ channel is forbidden by isospin selection rule;

- high-density cold nuclear matter would be formed around $K^-$, which could provide information concerning a modification of the kaon mass and of the $\bar{K}N$ interaction in the nuclear medium. How hadrons behave and how their properties change in nuclear medium is interesting and important from the viewpoint of spontaneous and explicit symmetry breaking of QCD [8]. The masses of light hadrons are largely of dynamical origin and reflect the symmetry pattern of QCD.

- kaonic nuclear clusters could provide information on a transition from the hadronic phase to a quark-gluon phase [9]. At low baryon densities matter exists in aggregates of quarks and gluons with their colour charges combined to form neutral (colour-singlet) objects. This is a domain of low-energy QCD, the physics of the hadronic phase in which mesons, baryons and nuclei reside. In this phase, the QCD vacuum has undergone a qualitative change to a ground state characterized by strong condensates of quark-antiquark pairs and gluons, as shown in the QCD phase diagram of Fig. 1. At large quark densities and Fermi momenta, another sector of the phase diagram, it is expected that Cooper pairing of quarks sets in and induces transitions to a complex pattern of superconducting and superfluid phases. Information on changes of vacuum properties of QCD and quark condensate could therefore also be obtained.
empirical information could be obtained on whether \textit{kaon condensation} can occur in nuclear matter, with implications in \textit{astrophysics}: \textit{neutron stars, strange stars}.

- \textit{nuclear dynamics under extreme conditions (nuclear compressibility, etc)} could be investigated.

![QCD phase diagram](image)

Fig. 1. Illustration of the QCD phase diagram.

## 2.2 Production mechanisms

At present, different production mechanisms have been investigated:

1. \textit{Stopped K reactions on light nuclei}, with ejection of a proton or a neutron as \textit{spectators}, detected in \textit{missing mass spectra}. Example: $^4\text{He} \ (K_{\text{stopped}}^-, n)$ reaction, which is a nuclear Auger process.

2. \textit{In-flight reactions}, with detection of the outgoing particles in \textit{missing mass spectra}.

\begin{itemize}
  \item 2.1 \textit{Knock-out reactions ($K^-, N$)}, where one nucleon is knocked out in the formation stage.
\end{itemize}
2.2 \((K^-, \pi^-)\) reactions in proton-rich systems, to produce bound nuclear states on unbound systems.

3. **Nucleus-nucleus and proton-nucleus collisions**, where $$\bar{K}$$ clusters are identified via invariant mass spectroscopy of their *decay products*.

1. Stopped \(K^-\) reactions were studied in the original proposal of Akaishi and Yamazaki for three light nuclei: \(^3\text{He}\), \(^4\text{He}\) and \(^8\text{Be}\) [1]. *The actual experimental indications of deeply bound \(\bar{K}\) nuclear states have been all obtained with that approach* [2, 3, 4].

   The formation of the exotic state proceeds in this way (see Fig. 2 referred to the \(^4\text{He}(K^-\text{stopped}, n)\) reaction):
   - the \(K^-\) is stopped in an atomic orbit of \(^4\text{He}\) forming the exotic atom \(K^-\text{He}^4\);
   - after decay of the kaonic atom, the \(K^-\) interacts with the nucleus and forms the deeply bound kaonic nuclear state \(K^-\text{ppn}\) by expelling a spectator neutron. The branching ratio for the formation of the state is expected to be at least 2% (see Section 3.3).
   - eventual peaks in the missing mass spectra of the spectator nucleons indicate the formation of the nuclear states and allow to deduce mass and width of the state.

2.1 The production of kaonic nuclei can be also achieved with in-flight \((K^-, N)\) reactions [10, 11], schematically shown in Fig. 3. The nucleon is knocked out in the forward direction, leaving a kaon scattered backward in the vertex where the \(K+N\rightarrow K+N\) reaction takes place. The reaction can thus provide a virtual \(K^-\) or \(K^0\) beam which excites the \(K\) nuclear states. The momentum transfer which characterizes the reaction depends on the binding energy \(B\) of the kaon in the nucleus: to excite states well bound in a nucleus \((B \approx 100 – 200\text{ MeV})\) the momentum transfer is of the order of \(0.3 – 0.4\text{ GeV/c}\) and does not appreciably depends on the incident kaon momentum \((P_{K^-} = 0.5 – 1.5\text{ GeV/c})\).
2.2 The “strangeness exchange reactions” (K⁻, π⁻) would lead to the production and detection of K⁻ bound states [12]. One of the advantages of this reaction is to produce very exotic K⁻ bound systems on proton-rich “nuclei”, such as p-p, that are unbound without the presence of K⁻. The p-p system (³He) does not exist, the K⁻ attracts the two protons to form a bound state with estimated B = 48 MeV and Γ = 61 MeV. The state is lying more deeply than Λ(1405), but still above the Σπ threshold. In this production mechanism, one needs a kind of trapping process for the incoming energetic K⁻. In this respect, the abundant production of Λ(1405) and Λ(1520) in K⁻ induced reactions, which was observed in past bubble-chamber experiments, [13, 14, 15] gives a hint on the production of exotic K⁻ nuclei.

With reference to the exotic K⁻pp system, of particular interest is the study of the K⁻+d reaction, which was investigated in deuterium bubble chamber [14, 15] obtaining information on the elementary process:

\[ K^- + "n" \rightarrow \Lambda(1405) + \pi^- \]  \hspace{1cm} (2.1)

In this case the Λ(1405) acts as a doorway state to produce K⁻ bound state, as shown in Fig. 4. Once a Λ(1405) is formed in a target nucleus Λ=(B+n) in an elementary “hard” process (2.1), it remains in the nucleus B and serves as a “seed” of strong attraction to produce a K⁻ bound state in the core nucleus C. While propagating in the residual nucleus B, the Λ(1405) either decays to (Σπ)⁰ or gets “dissolved”, because of its “soft” character, into a K⁻ bound nuclear state.

An intriguing question is of course whether or not the (K⁻, d) bubble chamber experiments [14, 15] showed any evidence for the presence of a K⁻ pp bound state.
Fig. 2. Energy level diagram of the $\bar{K}^- + ^3\text{He}$ system. The $T = 0$ state can be excited and signaled with a neutron emission from stopped $K^-$ on $^4\text{He}$. The neutron spectral distribution is also shown. Isospin in nuclei is indicated by $T$, following the usual convention.
Fig. 3. Diagram for the formation of kaonic nuclei via the \((K^-, N)\) reaction. The kaon, the nucleon, and the nucleus are denoted by the dashed, thin solid, and multiple lines, respectively. The kaonic nucleus is denoted by the multiple lines with the dashed line. The filled circle is the \(K N \rightarrow KN\) amplitude while the open circles are the nuclear vertices. The bubbles represent distortion.

Fig. 4. Diagram for the production of \(K\) bound states in \((K^-, \pi^-)\) reactions through \(\Lambda(1405)\) as a doorway.
3.1 Protons of 3.5 – 4.5 GeV on a deuteron target can produce $K^-pp$ nuclear cluster through the elementary reactions

$$p + "n" \rightarrow \Lambda^* + K^0 + p \quad (2.2)$$
$$p + "p" \rightarrow \Lambda^* + K^+ + p \quad (2.3)$$

where “n” and “p” are a neutron and a proton in a target nucleus and $\Lambda^* \equiv \Lambda(1405)$. The elementary cross sections, although not well known, can be estimated to be around 20 µb by using the experimental spectra of $\Lambda$, $\Sigma$, and $(\Sigma(1385) + \Lambda(1405))$ at 3.5 GeV/c proton momentum taken by DISTO at Saclay [16], in combination with the NN cross section for $\Lambda K^0N$ (around 200 µb). In the reaction on deuterium, $p\Lambda^*$ serves as a doorway to form $K^-pp$:

$$p + d \rightarrow [p + \Lambda^*] + K^0 + p_s \rightarrow K^-pp + K^0 + p_s \quad (2.4)$$

where $p_s$ denotes a spectator proton which comes from the target d. In this reaction a missing mass spectrum for $K^-pp$ can be constructed from the energies and momenta of the incident $p$ and the emitted $K^0(\rightarrow \pi^+ + \pi^-)$ and $p_s$.

Once the $K^-pp$ is identified in the formation channel (missing mass spectrum) its decay pattern can be studied. Simultaneously, an invariant mass spectrum for the decaying $K^-pp$ can be reconstructed. Thus, full kinematical constraints in both the formation and decay channels will be obtained.

3.2 Using heavy-ion collisions, a new type of experiment to identify $\overline{K}$ clusters as residual fragments (“$\overline{K}$ fragments”) in nuclear collisions [17] can be performed. Since high–density fireballs with large strangeness content are provided in heavy-ion reactions, the predicted $\overline{K}$ clusters are expected to be abundantly produced, but so far are hidden and untouched from observation. $K^-$ mesons in a fire ball act as deep trapping centers to form these clusters in coalescence with other nucleons. The thermal equilibrium model [18] predicts substantial populations of $\overline{K}$ clusters [19], as is shown in Fig. 5.

$\overline{K}$ clusters are produced and identified by detecting both $K^0$ mesons, from the invariant mass of $\pi^+ + \pi^-$, and $\Lambda$ hyperons from the invariant mass of $p + \pi^-$. As
a further step, one has to reconstruct invariant mass spectra from all the charged trajectories of the decay particles of the $\bar{K}$ clusters:

\[
\begin{align*}
K^-pp (T = \frac{1}{2}) & \rightarrow \Lambda + p \\
K^-npp (T = 0) & \rightarrow \Lambda + d \\
K^-ppp (T = 1) & \rightarrow \Lambda + p + p
\end{align*}
\] (2.5) (2.6) (2.7)

The yields (multiplicities) for $K^-pp$, $K^-ppp$ and $K^-pnpp$ are about 1%, and thus invariant mass spectroscopy is applicable. Once the $\bar{K}$ clusters are established, they can be used to study the reaction dynamics of heavy-ion fireballs.

Fig. 5. Theoretical estimates of typical $\bar{K}$ cluster yields in heavy ion reactions based on the thermal equilibrium model [19].

3 From low-energy $K^-N$ interactions to $\bar{K}-nuclear bound states

Akaishi and Yamazaki constructed a quantitative $\bar{K}N$ interaction model [1] on a phenomenological basis so to simultaneously reproduce: 1) the low-energy $K^-N$ scattering data, 2) the kaonic hydrogen shift of the ground state and 3) the binding energy and decay width of $\Lambda(1405)$, asserted to be an I=0 quasi-bound state of $\bar{K}N$. 

Then they used the $g$-matrix method to study the structure of $\bar{K}$ nuclear clusters in light nuclei, $^3\text{He}$, $^4\text{He}$ and $^9\text{Be}$ and predicted discrete $\bar{K}$-bound states, $\bar{K}^-$ppn, $\bar{K}^-$ppnn, $\bar{K}^-2\alpha$, which showed the following characteristics:

1. The $I=0$ $\bar{K}N$ interaction is strong enough to shrink the nucleus against the nuclear incompressibility.

2. The binding energies are extremely large due to the strong attractive potential, helped by the nuclear shrinkage effect, so that the bound states lie below the threshold of the main decay channel $\Sigma\pi$, thus inferring the presence of quasi-stable discrete bound state (width $\Gamma < \text{binding energy B}$). It is worthy to recall that such possibility of deeply bound kaonic nuclear states in presence of a strong $\bar{K}N$ attractive potential was already indicated by S. Wycech in 1986 [20, 21].

There is already a successful example of deeply bound mesonic states, represented by the discovery, in 1996, of deeply bound pionic atomic states: the observation of narrow $1s$ and $2p$ states of $\pi$ in $^{207}\text{Pb}$ and $^{205}\text{Pb}$ [22]. These states, have become an important tool for testing chiral pion-nucleus dynamics and the quest for fingerprints of partial chiral symmetry restoration in baryonic matter [23, 24, 25]. However, the mechanism at work in forming deeply bound states of pionic atoms are quite different from the one thought to be responsible for the formation of kaon-nuclear bound states [8]. Binding a negatively charged $s$-wave pion at the surface of a heavy nucleus is a matter of subtle balance between Coulomb attraction and the repulsion resulting from the pion-nuclear strong interaction.

Wolfram Weise has recently addressed this basic question [8]: “to what extent does our present knowledge of low-energy $\bar{K}N$ interactions support the hypothesis of narrow $\bar{K}$-nuclear states introduced by Akaishi and Yamazaki?”

In this Section, we discuss the experimental foundation of the phenomenological model of Akaishi and Yamazaki and, in particular, we show how strictly the prediction of deeply bound kaonic nuclear states depends on features of kaonic atoms, a field in which the proponents of this proposal at DAΦNE2, the DEAR/SIDDHARTA collaboration, play a major role at world level.
3.1 Antikaon-nucleon optical potential

It is well known that the s-wave $K^-$nucleon scattering length is repulsive (the real part is negative), as it comes out from all $K^-$ nucleon scattering data extrapolated at threshold [26]. Moreover, a measurement of kaonic hydrogen performed at KEK [27], recently confirmed by the DEAR experiment at DAΦNE [28], has shown that the energy shift of the $1s$ atomic orbit of kaonic hydrogen is of “repulsive type”.

It is, however, possible that the actual $Kp$ interaction is attractive, although it appears repulsive from the scattering data and from the energy shift of the kaonic hydrogen. This occurs if the s-wave, isospin $I=0$, $\Lambda(1405)$ resonance is a bound state of $KN$. Since $\Lambda(1405)$ lies just below the $Kp$ threshold, scattering through this resonance gives rise to a repulsive contribution to the scattering amplitude at threshold [29].

In addition, for nuclei heavier than hydrogen, a systematic re-analysis of all the existing data of $K^-$ atoms, suggested a strong non-linear dependence on the nuclear density $\rho$ of the real part of the $K^-$ nuclear optical potential [30]. This turns out in a sign change, from repulsive to attractive, of the optical potential at rather low density in medium as compared to its value in free space [31].

This effect is readily understood by analogy to the proton-neutron (p,n) scattering [32]. The interaction between the proton and the neutron is attractive, but the scattering length in the deuteron channel ($I=0$, $S=1$) is repulsive, due to the existence of the deuteron as a bound state. In nuclear matter, however, the deuteron disappears, largely due to Pauli blocking, and the true attractive nature of p-n interaction emerges.

Simple arguments from low-energy scattering show that the existence of a bound state below threshold always leads to a repulsive scattering length [33].

In the bound state picture of $\Lambda(1405)$, analogously to the deuteron case, the scattering through the resonance gives rise to a repulsive contribution and the change of sign of the optical potential can be simply understood as the effect of the Pauli blocking of the proton inside the $\Lambda(1405)$ (the kaon, being a boson, is not
affected by the Pauli blocking), which leads to an *upward shift* of the resonance. Also in this case, the “dissolving” of the bound state allows the true nature of the K̅ − p interaction to emerge. All this is represented in Fig. 6 from ref. [1] where, just below the threshold corresponding to the atomic states, the dominant I=0 s-wave scattering amplitude f₁ changes from repulsion in free space to attraction in the medium, *due to the dissolution of Λ(1405)*. At threshold (E_{KN} = 0) the scattering amplitude is equal to the scattering length a₁ (definition of scattering length). When E_{KN} falls below the Σπ threshold, the imaginary part of f^{I=0} vanishes and gives no contribution to the decay of a very bound state in a nucleus.

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**Fig. 6.** Calculated scattering amplitudes f^{I=0} of K̅ N in free space and in nuclear matter versus the interval energy E_{KN}.
3.2 The kaonic hydrogen case

The measurement of kaonic hydrogen performed at KEK [27] solved the long standing “kaonic hydrogen puzzle”, by confirming the scattering data, since the energy shift of the 1s atomic level turned out of “repulsive type”.

The same upward shift of the ground state was obtained recently by the DEAR experiment on DAΦNE [28], which measured shift and width in kaonic hydrogen with unprecedented precision.

Presently, new accurate K–p threshold data of DEAR are becoming a paradigm for a revisitation of low-energy kaon-nucleon interactions. Indeed these data, together with existing information on K–p scattering, the πΣ mass spectrum and measured K–p decay ratios at threshold, set tight constraints on the theory and have consequently revived the interest in this field. We cite here: Meissner, Raha and Rusetsky [34]; Boraso, Nissler and Weise [35, 36]; Weise [8]; Ivanov [37]. Moreover, apparent incompatibilities between DEAR kaonic hydrogen results and previous K–p scattering data might open a new scenario and suggest even more precise kaonic hydrogen measurements:

B. Boraso, R. Nissler and W. Weise wrote in [35]:

“In conclusion, the present updated analysis of low-energy K–proton interactions, combining the next-to-leading order chiral SU(3)effective Lagrangian with an improved coupled-channels approach, emphasizes the importance of the constraints set by the new accurate kaonic hydrogen data from the DEAR experiment. At the same time this analysis points to questions of consistency with previously measured sets of K–p scattering data. Developments aiming for a precision at the level of a few electron volts in the shift and width of kaonic hydrogen, foreseen at DAΦNE in the near future, will further clarify the situation.”

This precision measurement constitute the SIDDHARTA programme at DAΦNE [38], to be performed in 2007 and 2008. The kaonic hydrogen
measurement with about 200 pb$^{-1}$ of integrated luminosity, can reach a few eV precision.

Kaonic deuterium will be also measured, so to obtain both $\bar{K}N$ isospin dependent scattering lengths, to be compared with the values from scattering data. A precise determination of $\bar{K}N$ scattering lengths is fundamental in the strangeness sector of hadron physics [39] and is crucial in the investigation of deeply bound kaonic nuclear states. The kaonic deuterium case is much less known: both the yield of the $2p\rightarrow 1s$ transition and the strong interaction shift and width of the $1s$ state are evaluated within large uncertainties [39, 40]. We estimated that a 10 eV precision in shift might be reached with about 500 pb$^{-1}$ of integrated luminosity.

It is worthy to underline that DAΦNE is the only laboratory in the world where such precision measurements can and will be performed. The other existing facilities with kaon beams do not have in their programmes such measurements, due to the fact that they are employing extracted beams of relatively high momenta (up to 2 GeV/c), so that the study of kaonic atoms is very inefficient.

3.3 The kaonic helium case

There is a crucial information about the formation of a specific deeply bound kaonic nuclear state – precisely, the $K^-\text{He}^3$ system – which depends on the result of the measurement of the X ray transitions in the $K^-\text{He}^4$ atom [41]. The branching ratio for the formation of the nuclear state can be calculated as ratio of the partial and total absorption widths of the atomic states of kaonic helium. The total width $\Gamma_{\text{tot}}^{\exp}$ is not well known. There are three experiments which observed kaonic helium atomic transitions from $3d$ to $2p$ levels [42-44]. The latter two experiments are known to show evidence for an anomalous energy shift and width of the $2p$ state. If the experimental average is used, $\Gamma_{\text{tot}}^{\exp} = 55 \pm 34$ eV. By estimating the partial width of the order of 1eV, the formation branching ratio turns out about 2%. The
experimental absorption width could however have a large ambiguity, because it is
significantly less than the experimental resolution.

Moreover, all the theoretical widths are around $\Gamma_{\text{tot}}^{\text{th}} = 2-4 \text{ eV}$ [45]. Analogous
discrepancy between experiments and theoretical estimates exists for the shifts [46].
This is what is dubbed “the kaonic helium puzzle”.

The relevance of the solution of the kaonic helium puzzle for the understanding
of deeply bound kaonic nuclear states has been explicitly stressed [47]. The
measurement will provide a crucial information on the nature of the two strange
tribaryons, $S^0(3115)$ and $S^+(3140)$, recently discovered by the E471 collaboration at
KEK, via $K^-$ capture in $^4\text{He}$. Presently, the $^4\text{He}$ kaonic atom is going to be measured
in a test experiment (E570) at KEK, just before its closure, using SDD detectors.
Given the nature of the “kaonic helium puzzle”, where experiments disagree each
other and differ by more than one order of magnitude from theories, a precision
measurement is compelling. This can be done, and will be done, on $^4\text{He}$ and $^3\text{He}$, to
look also at isotopic effects, by SIDDHARTA on DAΦNE in the future kaonic
atoms campaign [38]. Preliminary Monte Carlo simulations, performed for the
SIDDHARTA setup with a gaseous $^4\text{He}$ target show that a measurement with a
precision of few eV can be performed at DAΦNE with about 200 pb$^{-1}$ of integrated
luminosity. Similar estimations hold for the $^3\text{He}$ case.

Finally, it must be recalled that the capability to detect kaonic helium X-rays
transitions might turn out extremely useful in implementing an $X$-ray trigger to
reduce the background in the measurement of kaonic nuclear states in a dedicated
facility at DAΦNE2.

3.4 Low-energy kaon-nucleon scattering

Another key ingredient of the phenomenological model of Akaishi and
Yamazaki is represented by the bulk of low-energy kaon-nucleon scattering data
[26].
The updated analysis of low-energy K⁻ - proton interactions of Borasoy, Nessler and Weise, which combines the next-to-leading order chiral SU(3) effective Langragian with an improved coupled-channels approach [35], emphasizes the importance of the constraints set by the new accurate data of DEAR, but as well points to questions of consistency with previously measured sets of K⁻p scattering data.

To check the depth of these inconsistencies, namely if a physics case does indeed exist, one can perform with SIDDHARTA a still more accurate measurement of kaonic hydrogen [38]. At the same time, the attention must be focused on the bulk of scattering data. It is then worthy to examine the state-of-the art of the field and the perspectives [48].

3.4.1 Status of the field

The season of systematic investigation of kaon-nucleon interactions suffered an abrupt ending around 1980, with the closing down of most of machines and of the beam lines dedicated to this branch of hadronic physics.

Despite many valiant efforts to resurrect the field (the European Hadron Facility and KAON at TRIUMF, just to name the bravest), the few remaining kaon beam lines have been barely sufficient to keep hypernuclear physics alive.

So many of the statements on the successes of flavour SU(3) – just to mention one single case in the physics of the Standard Model – so abundant in particle physics textbooks are in reality based on a handful of old, low-statistics, low-resolution experiments, performed using kaon beams with momenta hardly less than some hundreds MeV/c, that nobody would even think today of proposing to a selecting committee.

Of course kaon beams have problems not presented by pion beams (which indeed have continued to be in – relative – availability), but the physics to be performed with them can not be replaced by anything else.

It is enough to mention that, while $G_{\pi NN}^2$ is known to a few percent, uncertainties on $G_{KNA}^2$ and $G_{KNZ}^2$ are at the levels, respectively, of about ten and
thirty percent, not to speak of pion-hyperon coupling, “known” via $\bar{K}N$ phase shift coupled-channel analysis, where standard dispersive techniques yield errors of order 100%!

Also, a cursory glance at the PDG tables shows that there are a lot of “missing” $\Lambda$ and $\Sigma$ states (not to mention the even more missing $\Xi$’s and $\Omega$’s).

### 3.4.2 Recent hopes for progress: KLOE, FINUDA and a new facility at DAΦNE2

In a kinematical range not available to conventional fixed-target experiments, $\Phi$-factories such as DAΦNE in Frascati can prove invaluable, being sources of almost monochromatic $K^+$, $K^-$ and $K_L$ of about 100 MeV/c, which can be degraded down to few tens of MeV/c.

KLOE, while doing its job of collecting neutral kaon decays looking for the tiny effects of CP violation, and in the meanwhile also reaping a good harvest of more conventional hadronic physics (cross sections, radiative decays, etc), has collected many tens of thousands of interactions of the kaons with the helium filling the huge wire chamber.

The design of FINUDA should also allow the observation of kaon-nucleon interactions, and in particular the collaboration plans to take data on charge – exchange of $K_L$’s on the hydrogen of plastics scintillators.

A proposal of Art Olin to study kaon-nucleon interactions in a liquid hydrogen target around the interaction point of FINUDA already exists.

In a $\Phi$-factory, the kaon beam is intrinsically clean, a situation unattainable with a fixed target machine. There, the minimum beam momentum is limited by the distance from the experiment to the production target and by the consequences of kaon decay in flight. The kaons have to be energetic enough to survive the trip. The several hundred MeV/c momentum beams require the use of moderators, thereby enhancing the beam contamination, especially pions, at the experiment.
A new facility at DAΦNE2 to study $\bar{K}$ - nuclear clusters with a $4\pi$ detector, should include in its scientific program $K^\pm$ scattering on nucleons to build up a high quality set of data.

3.5 The $\Lambda(1405)$

The third ingredient of the phenomenological model of Akaishi and Yamazaki [1] is the existence of the $\Lambda(1405)$ resonance, asserted to be an $I=0$ bound state of the $\bar{K}N$ system, with a binding energy $E_{\bar{K}N} = -29.5$ MeV from the $I=0\bar{K}N$ threshold ($-27$ MeV from the $\bar{K}\cdot p$ threshold).

The assertion is supported by studies of Weise et al. based on chiral SU(3) theory [31], which show that the $I=0\bar{K}N$ interaction is attractive enough to form the $\Lambda(1405)$. As well, the Juelich group using a boson exchange potential [49], showed that all the $\omega$, $\rho$, $\sigma$ mesons work coherently to give a strong attraction between a $\bar{K}$ and a $N$ which accommodates a $\bar{K}\cdot p$ bound states, identified as $\Lambda(1405)$.

Another possibility is that the $\Lambda(1405)$ is a three-quark state (or an admixture of the two interpretations) [50]. If this would be the real scenario, one of the strongest arguments of the Akaishi and Yamazaki model is substantially weakened.

Establishing which is the dominant component of $\Lambda(1405)$ has therefore a strong impact on the hypothesis of $K$ nuclear clusters.

Precise $\bar{K}N$ measurements at threshold, foreseen in the SIDDHARTA programme [38], will substantially improve the knowledge of the sub-threshold $\bar{K}N$ dynamics and contribute to clarify the nature of $\Lambda(1405)$.

More information can come from the measurement of two-body branching ratios in $K^-$ absorption at rest, which is precisely the kind of reactions to be studied in the proposed new facility at DAΦNE2. Specifically, one can investigate in-medium corrections to the branching ratios in $K^-$ absorption at rest and their effect.
on the charged $\pi^+$ spectrum [32]. The in-medium corrections are due to Pauli blocking, which arises if the $\Lambda(1405)$ is assumed to be a $\bar{K}$-nucleon bound state and leads to a density- and momentum-dependent mass shift of the $\Lambda(1405)$. Upward shift of the $\Lambda(1405)$ mass leads, as we have seen, to an attractive $\bar{K}N$ potential. The mass shift of $\Lambda(1405)$ is expected to appear most clearly if it is created in the nuclear medium with a small momentum. The $K^-$ absorption at rest is one possibility. For this reaction, the experimental charged pion spectra are available for several nuclear targets. The $\Lambda(1405)$ mass shift moves the $I=0$ amplitude upward in energy but does not affect the $I=1$ amplitude. It therefore modifies the relative phase and strength of $I=0$ and $I=1$ amplitudes leading to different branching ratios for the reactions $K^-p \rightarrow \pi^0\Lambda$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi^+\Sigma^-$, as compared to the free ones.

4 Actual experimental indications

E471, KEK

The first indication of deeply bound kaonic nuclear states must be ascribed to the experiment E471 at KEK [2,3,4]. In this experiment, along with the original proposal of Akaishi and Yamazaki, negative kaons were stopped in a superfluid helium target and the time-of-flight of neutrons/protons, detected by neutron-counter walls at ±2m from the target, was measured [41]. An overview of the experimental setup is shown in Fig. 7.

The results are shown in Fig. 8. In the missing mass spectrum of the $^4\text{He}(K_{\text{stopped}}^-, p)$ reaction (Fig. 8, top), a monoenergetic peak can be observed, with a statistical significance of 8.2$\sigma$. The peak is interpreted as the formation of the neutral tribaryon $S^0 (3115)$ with isospin $T=1$, and the following values for mass, width and binding energy:
\[
M_{S^0} = 3117.7^{+3.8}_{-2.0} \text{ (syst.)} \pm 0.9 \text{ (stat.) MeV}, \tag{4.1}
\]
\[
\Gamma_{S^0} < 21.6 \text{ MeV}, \tag{4.2}
\]
\[
B_{S^0} = -194 \text{ MeV with respect to } K^{-}p+n+n \text{ rest mass.} \tag{4.3}
\]

The state mainly decays to \(\Sigma NN\).

In the missing mass spectrum of the \(^4\text{He}(K^-_{\text{stopped}}, n)\) reaction (Fig. 8, bottom), experimental indication of another strange tribaryon \(S^+ (3140)\), with a statistical significance of 3.7\(\sigma\) was observed. The isospin is \(T=0\), with the following values for mass, width and binding energy:
\[
M_{S^+} = 3140.0^{+2.0}_{-1.0} \text{ (syst.)} \pm 2.3 \text{ (stat.) MeV}, \tag{4.4}
\]
\[
\Gamma_{S^+} < 21.6 \text{ MeV.} \tag{4.5}
\]
\[
B_{S^+} = -169 \text{ MeV with respect to } K^{-}p+p+n \text{ rest mass,} \tag{4.6}
\]
so the state is about 25 MeV higher than the previously observed \(S^0 (3115)\). The major decay mode is \(S^+ \rightarrow \Sigma^+ NN\).

Moreover, another candidate peak was found in the neutron spectrum at around 3117 MeV, where the isobaric analogue state of \(S^0 (3115)\), denoted \(S^+ (3115)\), is expected.
Fig. 7. An overview of the experimental setup of E471 at KEK. LC1, 2: Lucite Cerenkov counter, T0: beam timing counter, BDC: beamline drift chamber, VDC: vertex drift chamber, TC\textsubscript{thin} and TC\textsubscript{thick} (3 cm) trigger counter, NCV: neutron-counter charged-particle veto, NC: neutron-counter wall.
Fig. 8. Missing mass spectra of the $^4\text{He}(\text{stopped K}^-, p)$ reaction (top) and the $^4\text{He}(\text{stopped K}^-, n)$ reaction (bottom), measured at KEK by E471.
FINUDA, LNF (DAΦNE)

The “strangeness exchange reaction” $(K^-, \pi^-)$ was used by the FINUDA experiment at DAΦNE [5] to produce $\bar{K}$-bound states on proton-rich nuclei, such as p-p, which are unbound without the $K^-$. The process was $K^-$ absorption on very thin light targets ($^6\text{Li}$, $^7\text{Li}$ and $^{12}\text{C}$).

When a $K^-$ interacts with two protons, one expects that a hyperon-nucleon pair is emitted in the opposite direction. The measured angular correlation between $\Lambda$’s and protons in all targets indeed indicated the existence of this kind of reactions. Being so evident the correlation between a $\Lambda$ and a proton, it is naturally expected that the two particles are emitted from a “$K^-pp$” intermediate system.

If the process were simply two-nucleon $K^-$-absorption process, then the mass of the system should be close to the sum of the kaon mass plus the two protons mass, namely 2370 MeV. The invariant mass distribution of the $\Lambda$–p pairs, shown in Fig. 9, shows, however, a significant mass decrease with respect to the expected values, being peaked around

$$M_{\Lambda+p} = 2255 \text{ MeV.} \quad (4.7)$$

The peak in the $\Lambda+p$ invariant mass spectrum is interpreted as a kaonic bound nuclear state with binding energy and width:

$$B_{\Lambda+p} = -115^{+6}_{-5} \text{ (stat.)}^{+3}_{-4} \text{ (syst.) MeV} \quad (4.8)$$

$$\Gamma_{\Lambda+p} = 67^{+14}_{-11} \text{ (stat.)}^{+2}_{-3} \text{ (syst.) MeV.} \quad (4.9)$$

E930, BNL-AGS

At BNL, the in-flight knock-out $(K^-, N)$ approach was followed to produce kaonic nuclear states [7]. Specifically, the $(K^-, n)$ reaction on a water target was studied. Neutrons were measured by an array of neutron counters placed 6.8 m downstream of the target. The neutron momentum spectrum was obtained with the time-of-flight technique.

In Fig. 10, the missing mass spectrum of the $^{16}\text{O}(K^-, n)$ reaction is shown. Here the horizontal axis is the binding energy of $K^-$ to $^{15}\text{O}$. The distinct peak at zero
energy is the quasi-free peak of the reaction on proton. An appreciable amount of strength in the bound region can be seen. A peak at around 90 MeV corresponds to a kaonic nuclear state where the kaon is in the p-shell.

**FOPI, GSI**

Ni+Ni collisions at an incident energy of 1.93 AGeV at GSI were studied with the 4π detector FOPI [6]. Heavy-ion collisions at beam energies close to the strangeness production threshold could offer an alternative way to produce deeply kaonic nuclear states, observed so far only in kaon-induced reactions. The two-body final state Λ+d represents one of the possible decay channels of the kaonic nuclear cluster K−ppn.

The reconstructed invariant mass distribution Λ+d is shown in Fig. 11, in comparison with MonteCarlo simulations of signal and background. It was verified that a resonance introduced in Ni+Ni events can be reconstructed correctly (middle row), while no resonance-like structure is generated due to the method (lower row).

*The remaining excess in the data has a mean mass*

\[
M_{Λ+d} = 3160 \text{ MeV},
\]

(corresponding to a binding energy)

\[
B_{Λ+d} = -149 \text{ MeV},
\]

and a width

\[
Γ_{Λ+d} \approx 100 \text{ MeV}.
\]

*It can be interpreted as a $\overline{K}$ nuclear cluster.*
Fig. 9. Invariant mass spectrum of a $\Lambda$ and a proton measured by FINUDA at DAΦNE in a back-to-back correlation ($\cos\theta_{\text{Lab}} < -0.8$) from light targets before the acceptance corrections. The insert shows the result after the acceptance correction for the events which have two protons with well defined good tracks.

Fig. 10. Missing mass spectrum of the $^{16}\text{O}(K^-, n)$ reaction measured by E930 at BNL-AGS. See text for details.
Fig. 11. Distributions of invariant mass of Λ-d pairs measured with FOPI at GSI in data (top), signal-MonteCarlo (middle) and background-MonteCarlo (bottom).
5 Current and future experiments

5.1 Experiments at KEK

E549

The KEK facility will be closed in December 2005. Prior of its closure, a new experiment, E549, has taken data from May 2005 with the primary goal to confirm the existence of the two strange tribaryons observed by E471: the neutral $S^0(3115)$, $T=1$, in the proton spectrum, and the charged $S^+(3140)$, $T=0$, in the neutron spectrum.

In the proton spectrum, E549 has taken inclusive data with newly constructed proton tracking chambers and dedicated high resolution TOF counters. In the about one month scheduled running time, the $S^0(3115)$ statistics has been increased by a factor 10 and peak position/width/formation rate can be determined with much improved accuracy. Analysis is in progress.

E549/E570

For the neutron spectrum, in which evidence of the $S^+(3140)$ was observed, statistics can only linearly increase with the beam time. Therefore, neutron data will be taken continuously both in the running time of E549 and during data taking of the connected experiment E570, whose goal is to measure kaonic helium X rays.

The global neutron statistics should become close to that of the proton spectrum in E471. The experiment E570 is actually (September 2005) running. Analysis of neutron data from E549 is in progress.

5.2 Experiments at J-PARC

The 50 GeV PS of J-PARC will provide a unique playground for the study of deeply bound kaonic nuclear states [51]. The high kaon beam intensities ($\sim 10^6$ K$^+/s$) which can be obtained are planned to be used in dedicated experiments. Differently
from DAΦNE, the momentum of the kaon beam obtainable at J-PARC is rather high:
in one line is about 1 GeV/c (K1.1) and in another one 1.8 GeV/c (K1.8).

There are actually two Letters of Intent which propose scientific programmes
which are partially/totally dedicated to deeply bound kaonic nuclear states studies:

- **LoI 06**: “New Generation of Spectroscopy and of Hadron Many-Body Systems
  with Strangeness $S=-2$ and $S=-1$”, mainly dedicated to the study of the strangeness – 2 systems
  and to the $\gamma$-ray Hypernuclei spectroscopy, in which, in a short final note, is
  expressed a general interest towards the field of deeply bound kaonic states.

- **dedicated LoI 10**: “Study of Dense $K$ Nuclear Systems”, which considers two
  kinds of processes to produce kaonic nuclear cluster: $(K^-, N)$ and $(K^-, \pi^-)$, reactions.
  Moreover, the possibility of creating double-kaon bound states via $(K^-, K^-)$ and $(K^-, K^0)$
  processes is considered.

  - **Production of kaonic nuclear states with $(K^-, N)$ reactions** will be observed
    by the missing mass spectra of the $(K^-, p)$ and $(K^-, n)$ reactions. Outgoing
    protons will be measured by a spectrometer to be built by J-PARC. A
    standard detector system (plastic scintillators, drift chambers, Cherenkov
    counters) will equip the spectrometer. For neutron detection, a momentum
    resolution of 10 MeV/c will be required, which implies a combination of
    neutron counters with high time resolution and a time-of-flight length of 10 m.
    Light nuclear target, $d$, $^3$He, $^4$He, $^{12}$C and Si will be used in the first phase
    of the experiment.

  - **Production with the $(K^-, \pi^-)$ reaction.**
    The first step of the experimental program is the study of the process:
    \[
    K^- + d \rightarrow (K^-pp) + \pi^-.
    \]  
    (5.1)
    The experiment is proposed to be performed at the K1.1 beam line, with a
    beam line spectrometer and the SPES-II spectrometer. For the tagging of the
    decay products from the $K^-pp$ bound state, the Cylindrical Detector System
    (CDS), constructed for the BNL E906 experiment will be used. Once the
    existence of such a $K^-pp$ bound system is well defined, the study of the
$^4\text{He}(K^-, \pi)K\text{pppn}$ reaction will be performed, where the $K$-pppn system with the binding energy of $\approx 190$ MeV will be produced. It should exhibit an “enormous density around the $K^-$.”

- **Double-kaon nuclear states**

In a kaonic nuclear state the $K^-$ acts as a *contractor* on the surrounding nucleons with a shrinkage effect on nuclear matter which turns out in an increase of the average density up to 3 times the normal value. One can compress nucleons even further with double-kaon bound states, as shown in Fig. 12.

![Density distribution of ppn (= $^3\text{He}$) (left), $K^-\text{npp}$ (center) and $K^-K^-\text{npp}$ (right) obtained by a new framework of antisymmetrized molecular dynamics (AMD) [52].](image)

To excite two-kaon bound states several processes are possible, namely ($K^-$, $K^+$) and ($K^-$, $K^0$) reactions, as shown in Fig. 13. The kinematics are similar, so let’s discuss the first process as a model case.

- **Production with ($K^-$, $K^+$) reactions**

The ($K^-$, $K^+$) process can be performed by a single nucleon reaction. The second negative kaon is produced through virtual $\Phi$-production:
\[ K^- N \rightarrow K^- N \phi. \] (5.2)

The threshold momentum to produce \( \Phi \) on a single nucleon at rest is \( \approx 2.6 \) GeV/c. If one considers the direct \((K^-, K^+)-pair\) production
\[ K^- N \rightarrow K^+ K^- K^- N, \] (5.3)
the required incident momentum is getting smaller.

Anyway, the production of double-\( \bar{K} \) bound nuclear states via \((K^-, K^+)\) reactions requires an incident \( K^- \) momentum of \( \approx 2.1 \div 2.5 \) GeV/c. This momentum range exceeds that of the presently planned K1.8 beam line, unless the binding energy is very large \((300 \div 400 \) MeV). Rebuilding some critical magnets or constructing a new beam line might turn out necessary.

![Diagram of production processes of double-kaon nuclear states](image)

Fig. 13. Production processes of double-kaon nuclear states.

### 5.3 Experiments at GSI

**Al-Al, FOPI**

On the basis of the results obtained in Ni+Ni collisions [6], where a resonance structure in the \( \Lambda+d \) pairs invariant mass spectrum was observed with FOPI at 3160 MeV, search for kaonic nuclear clusters in 2 AGeV Al-Al collisions has taken data (August 2005). The aim was to reduce the combinatorial background and increase the statistics with respect to the previous measurement. More than
400 000 Λ’s have been collected and the analysis has started.

**p-d, FOPI**

By making use of the excellent capability of the FOPI detector in identifying both $K^0$ and $Λ$, a proposal to use 3-5÷4.5 GeV protons on a deuterium target was approved [53]. Formation of $Λ(1405)$ in a hard initial process and then use of the $Λ(1405)$ as a doorway to form the $K^-pp$ clusters, is the two-step process followed:

$$p + d \rightarrow [Λ(1405) + p] + K^0 + p \rightarrow K^- pp + K^0 + p$$

(5.4)

In this reaction, a missing mass spectrum of $K^-pp$ can be constructed by measuring $K^0$ and $p$.

Moreover, according to the decay pattern:

$$K^- pp \rightarrow Σ^\pm + π^\mp + p$$

(5.5)

or $\rightarrow Λ + p$

an invariant mass spectrum can also be built. This experiment is scheduled in October 2005. If successful, proton indirect reactions on C target will follow to produce kaonic nuclei with $A>2$. Dalitz analysis of 3-body decays will be developed.

## 6 The unique features of DAΦNE2

### 6.1 Why DAΦNE2 is a good place to study kaonic nuclear clusters

DAΦNE has proved to be a machine where hadronic physics in the strangeness sector can achieve important results. These results were obtained in dedicated measurements, which exploited the unique “kaon beam” coming from the decays of the $Φ$’s produced in $e^+e^-$ collisions.

DAΦNE2, characterized by a peak luminosity around $10^{33}$ cm$^{-2}$s$^{-1}$ [54], can play a special role in studying kaonic nuclear clusters in Frascati Laboratories. In fact, the future experiments in Japan (J-PARC) [51] will produce kaonic nuclear states
only with *K*-induced reactions in-flight \( (P_{K^-} = 1 \div 2 \text{ GeV/c}) \), either in \((K^-, N)\) or in \((K^-, \pi^-)\) processes. The alternative approach, followed at GSI, is represented by *nucleus-nucleus* and *proton-nucleus collisions* [53] at beam energies close to the strangeness production threshold.

*It follows, that a dedicated facility at DAΦNE2 can become the scientific pole for studying kaonic nuclear states with \(K^-\) induced reaction at rest.*

This can be also seen as part of a structured strategy to attack the multi-facets aspects of low-energy QCD.

The salient features of DAΦNE2 are:

- Low-momentum \((127 \text{ MeV/c})\), medium intensity charged kaons: \(\approx 1200/s\) at \(L \approx 10^{33} \text{ cm}^2 \text{s}^{-1}\);
- Low momentum spread (<0.1%);
- \(K^\pm\) pairs produced in a back-to-back topology;
- hadronic background intrinsically low – differently from an extracted beam.

It is clear, with the above mentioned features, that the sector to which DAΦNE2 can contribute, is the stopped kaons one. As already remarked, *no other facility in the world has a program for the sector of stopped kaons* – which, by the way, is that originally proposed by Akaishi and Yamazaki as ideal for this kind of physics, and that has produced significant experimental evidences of kaonic nuclei.

How DAΦNE2 characteristics can be exploited at best for the study of strongly bound kaonic nuclear states?

# kaons low-momentum and low-momentum spread give the possibility to use either *gaseous targets* (as proved by DEAR) or *thin targets* (as proved by FINUDA). *This simplifies the experimental apparatus* (and reduces costs). In the same time, the use of thin targets (Beryllium, Carbon, etc) greatly simplify the reconstruction/trigger features and reduces background.
Another great advantage of the use of a gaseous target is related to the neutron background generated by negative pion absorption. This was one of the crucial background sources in the E471 experiment at KEK where the first indications of kaonic nuclei were seen. As a result of a quasi-free hyperon production in $K^-$ induced processes and hyperon decay a large number of low energy $\pi^-$ is produced. The pions can stop quite easily in the materials of the frame which contains a liquid target and in the liquid itself. A pion of $\approx 50$ MeV/c stops in a few cm in a liquid helium target. Pions at rest react with nuclei in a two-nucleon absorption process which dominantly yields two neutrons in the final state: $\pi^- N N \rightarrow n n$. Unfortunately, the Q-value of the reaction is $\approx 140$ MeV and so the process produces neutrons of energy up to 70 MeV, which is exactly in the area of interest. The yield of these background neutrons depends on the equivalent $g/cm^2$ of the target, namely on density and thickness, and on the materials put around the target itself. All this will be reduced in the new facility at DAΦNE2 and therefore the neutron background substantially cut.

The back-to-back topology which characterizes $K^-$ production, can be used to trigger on $(K^-, K^+)$-pairs, so selecting $K^-$ induced events.

Another trigger system might be implemented by taking advantage of the X rays emitted in the decay of the kaonic atoms, created in the initial stage of the process. The effectiveness of this X-ray trigger will depend on the signal/background ratio.

### 6.2 Preliminary simulations

By assuming to use a dedicated setup on DAΦNE2, a simple extrapolation based on a MonteCarlo simulation was performed with the aim to show how the present experimental indications of kaonic nuclei would be seen by a dedicated setup on DAΦNE2.
6.2.1 KEK E471 results

In Figure 8, the missing masses spectra obtained in the E471 experiment at KEK for the $^4\text{He}(\bar{K}^-_{\text{stopped}}, p)$ and $^4\text{He}(\bar{K}^-_{\text{stopped}}, n)$ reactions, are shown. These results were obtained for a total number of stopped negative kaons inside the liquid helium target of about $2 \times 10^8$. The KEK E471 setup has the following features:
- acceptance for detection of charged particles: 34%;
- detection efficiency for neutron: 36%;
- solid angle for the neutron/proton detector: 8%.

From these numbers, one gets:
stopped kaons efficient for detection of the reaction products $\approx 10^6$.

In these conditions, the number of events in the missing mass spectra of the two reactions, were:
- about 450 events in the $(K^-, p)$ reaction for the $S^0(3115)$ neutral tribaryon, with a signal/background ratio about 1/8-1/10;
- about 120 events in the $(K^-, n)$ reaction for the $S^+(3140)$ charged tribaryon, with a signal/background ration about 1/10;
- about 70 events in the $(K^-, n)$ reaction for the $S^+(3115)$ charged tritybarion, with a signal/background ratio about 1/40.

The formation ratios for the considered reactions turned out of the order of $\sim 10^{-3}$.

6.2.2 Extrapolation from KEK to DAΦNE2

We have checked with a MonteCarlo simulation that more than 70% of kaons generated by $\Phi$–decay, with the specific characteristic of the DAΦNE2 “kaon beam”, can be stopped, with an optimized degrader, inside a gaseous helium target.

At DAΦNE2, for a yearly integrated luminosity of about 10 fb$^{-1}$, the total numbers of kaons generated in about 2 months (the same time interval of the KEK DAQ) will be $\sim 2 \times 10^9$, out of which about $1.4 \times 10^9$ can be stopped inside the target.

For a dedicated 4$\pi$ detector we assume the following figures of merit:
- acceptance for the detection of charged particles: 90%;
- detection efficiency for neutrons detector: 36%;
- solid angle for the neutron/proton detector: 90%.

From these numbers one gets:
stopped kaons efficient for detection of the reaction products \( \approx 10^8 \)

Consequently, the expected signals at DAΦNE2, in the case of a \(^4\text{He}\) target, would be:
- about 45000 in the \((K^-\, p)\) reaction for the \(S^0(3115)\) neutral tribaryon;
- about 12000 in the \((K^-\, n)\) reaction for the \(S^+(3140)\) charged tribaryon;
- about 7000 in the \((K^-\, n)\) reaction for the \(S^+(3115)\) charged tribaryon.

As far as the signal/background ratio (S/B) is concerned, the neutrons produced by low-energy negative pion absorption, will be strongly reduced at DAΦNE2, as previously shown. Moreover, the implementation of a \((K^-, K^+)\)-pair trigger and of an X-rays trigger from kaonic atoms decay, should improve S/B by more than a factor 2.

In conclusions, the data collected at DAΦNE2 might clarify a number of unsolved problems in the actual experimental evidences of \(\overline{K}\)-nuclear clusters.
- the confirmation of the very existence of \(\overline{K}\) nuclear clusters with a sound statistical significance;
- the effective positions of the peaks and, therefore, of binding energies;
- the precise determination of the natural widths;
- the formation rates;
- the quantum numbers.
Features of the experimental setup

Preliminary to the definition of the experimental setup, it is vitally important to identify methods to study the characteristic features of the kaonic bound nuclear systems: binding energy, level widths, angular momenta, isospin, sizes, densities, etc. This can be done by not only observing the production stage of the $\bar{K}$-clusters via missing mass spectroscopy, but also their decay products since their momentum correlations contain information on the internal structure of the exotic system. It is therefore necessary to use a $4\pi$ detector capable of detecting all particles created in both the formation and decay of the $\bar{K}$-clusters. This is similar to the FOPI detector at GSI Darmstadt, where the formation of $\bar{K}$-clusters in heavy-ion collisions and in a p-d reaction is studied. A major improvement beyond all currently existing detectors will be the addition of the capability to detect neutrons, which will, for the first time, allow the complete determination of all formation and decay channels.

Exotic nuclear states in light nuclei produced with $(K^-, N)$ reactions, at rest or in flight, the first ones mandatory when working at DA$\Phi$NE, will be observed by the energy distribution of the ejected protons and neutrons via the missing mass spectra of the $(K^-, p)$ and $(K^-, n)$ reactions. Outgoing protons (400÷500 MeV/c) will be measured in the $4\pi$ detector by a magnetic spectrometer equipped with plastic scintillators and drift chambers. The emitted neutrons (400÷500 MeV/c) will be detected by a surrounding array of neutron detectors located 2-3 meters from the target.

Using a $4\pi$ detector system surrounding the target, charged decay particles from kaonic nuclei can be identified event by event, and their 4-momenta can be determined. The exotic states are expected to predominantly decay into final states containing $\Lambda$ hyperons and protons, deuterons or larger systems of nucleons, if the binding energy is so large that decays into $\Sigma\pi$ are forbidden. The most important feature of a detector is therefore the reconstruction capability for $\Lambda$ hyperons from the invariant mass of their decay into $p + \pi^-$. This implies good
particle identification for these particles. Λ’s from the decay of light $\bar{K}$–nuclear clusters like $K^-\text{pp}$, $K^-\text{ppn}$, $K^-\text{pnn}$ will have maxima momenta of 500÷700 MeV/c. The same holds for the other decay products of the $\bar{K}$–nuclear clusters, like protons and deuterons. The decay of these high-momentum Λs produces protons of 500÷800 MeV/c momenta and pions of 200÷300 MeV/c momenta. A good momentum resolution for these particles is mandatory for a clean reconstruction of Λ’s.

From this data, frame-invariant Dalitz plots can be constructed, which are expected to reflect the size and density of the initial exotic state. Special attention must be paid to two-body correlations in a Dalitz plane, which may lead to a fake effect in an invariant mass spectrum $\Lambda + p$, which might be confused with the genuine mass of an exotic strange dibarion $K \bar{p} p \rightarrow p + \Lambda$ if all the three particles are not detected.

8 Experimental programme

Following the present exploratory experiments, studies with a dedicated experimental setup at DAΦNE2, tailored to characterize the structure of hadronic nuclei are planned. Such a programme is based on precision spectroscopy studies of a number of light kaonic nuclei, as function of their baryon number $A$ and isospin $T$, and then of heavier nuclear targets.

The first objective of such a structure programme is to determine the quantum numbers (spin, parity, isospin) of all states, including excited ones, in addition to their energies. A precise measurement of the energies of a $T=1$ multiplet would give its Coulomb energy difference (about 4 MeV) and thus information on the size of kaonic nuclei. The challenge of this programme is to reach the necessary accuracy in the determination of the mass differences of the multiplet.

The most interesting problem with respect to the identification of excited states of kaonic nuclei is the measurement of the spin-orbit interaction by detection of $p_{1/2}$.
– $p_{3/2}$ spin-orbit splitting which is predicted to be as large as 60 MeV for the small size of kaonic nuclei.

As all the states of kaonic nuclei are quasi-stationary, important information on their structure is contained in their total and partial decay widths. Until now, only an upper limit, $\Gamma < 21$ MeV, is known for a kaonic tribaryon state and no information on partial decay channels is available. The total and partial widths of decaying kaonic nuclei are determined by their wave functions and contain thus very basic structure information. For strongly bound systems, non-mesonic decay channels are the only open ones. They are of the type $NY \rightarrow p\Lambda$, $p\Sigma^0$ and $n\Sigma^+$. All decay channels can be identified if the detector has neutron detection capability as planned. The $p\Sigma^0$ channel can be indirectly detected using the $\Lambda$-decay information from the $\Sigma^0 \rightarrow \Lambda + \gamma$ decay. The $n\Sigma^+$ channel is identified by its $nn\pi^+$ branch.

In an upcoming paper by Ivanov et al. the non-pionic total decay width of $K^-pp$ is calculated to $\Gamma=13$ MeV and also the partial widths to the $\Sigma$ channels. By measuring these quantities, which are determined by squares of the transition amplitudes from the kaonic nuclei to the hadronic final states, basic structure information on the exotic states is obtained. For an accurate measurement of the total width of kaonic nuclei an energy resolution of 1 MeV or better is required.

An even more detailed structure information can be extracted from a Dalitz analysis of three-body decays of kaonic nuclei, as was pointed out recently by Kienle, Akaishi and Yamazaki in a paper submitted to Physics Letters B. The Dalitz analysis of 3-body decays such as $K^-np \rightarrow \Lambda+p+\pi^-$, $K^-ppp \rightarrow \Lambda+p+p$ or $K^-npp \rightarrow \Lambda+p+n$, displays the intensities of correlated partial invariant mass spectra in the Dalitz plane. This distribution reflects sensitively the momentum wave functions of decaying state and its angular momentum transfer. By measuring Dalitz plots of three-body decay channels one can study the size of kaonic nuclei and assign spin and parity to the decaying states.

The most fundamental system which we plan to study is the kaonic dibaryon states of $K^-pp$ and $K^-np$, which are favorable produced using a $^3$He gas target in $^3$He($K^-_{\text{stopped}}$, n/p) reactions. Their masses including their total widths will be
determined by neutron and proton energy measurements. Exclusive measurements of their decays allow to determine partial decay widths and also Dalitz plots in 3-body channel such as $K^-np\rightarrow\Lambda+p+\pi^-$. 

Similar measuring programs are intended for kaonic 3-baryon states populated in reactions using a $^4$He gas target. Furthermore we plan to extend these studies systematically over a broad range of nuclear targets starting from Li, B and Be nuclei. In addition to one-nucleon knock-out reaction two-nucleon outgoing reaction studies may be used to populate interesting states and to perform exclusive measurements of all reaction and decay products in the planned 4$\pi$ detector system.

Finally, there is a very intriguing opportunity for the future to study with the proposed detector nuclear systems bound by two antikaons. Such “double-strange nuclei” would be very exciting to produce and study in view of the prediction of Akaishi and Yamazaki that such states would have roughly twice the binding energy and density compared with kaonic nuclei bound by one antikaon. The binding energy is so large that it would bring them in the regime of kaon condensation and the density so high that some theories predict transition to the color superconducting phase.

In an upcoming paper by Weise, Kienle and Yamazaki it will be proposed to use the antiproton annihilation reaction on light nuclei to produce and study double-strange nuclei in reactions such as:

$$\bar{p}+^4\text{He}\rightarrow[K^-K^-pnn]+2K^+ \quad (8.1)$$

As the binding energy of the $2K^-$ mesons is expected to be very large, it is possible to induce the annihilation reaction with stopped antiprotons, thus small momentum transfer will favour the formation of double-kaonic nuclear systems. A detector planned to study single-kaonic nuclei, is ideal for a detailed investigation of double-kaonic states by antiproton annihilation. It can be built in a way that it meets all requirements to identify and measure the energy of two $K^-$ mesons in the final state and detect also the decay products. The ideal place to study these reactions would be the planned FLAIR facility at GSI Darmstadt, which is expected to become operational around 2013 (?).
The scientific programme of the \( \bar{K} \) nuclear clusters facility will be discussed in dedicated meetings and in the dedicated Workshop: “Exotic hadronic atoms, deeply bound nuclear states and antihydrogen: present results and future”, to be held at ECT* (Trento), on June 19-24, 2006.

9 Formation of an international collaboration

This (pre)Letter of Intent has been written by physicists of the international collaboration DEAR/SIDDHARTA, which are working on DA\( \Phi \)NE since 1996 and where they will be still engaged for the next three years. To the DEAR/SIDDHARTA collaboration belong 11 institutions from 8 different countries. The interest raised in the international community by kaonic atoms physics at DA\( \Phi \)NE involved, since the beginning, also scientists from outside Europe, as Japan, USA and Canada, which actively participated and are participating to the experiments at DA\( \Phi \)NE.

This means that the same phenomenon as in the case of DEAR/SIDDHARTA may occur again for the new Frascati initiative on kaonic nuclei. In this case, a “hard core” of an international collaboration does already exist.

Other considerations support the strong appealing of the new initiative and consequently a potentially large interested community. The planned \( 4\pi \) detector at DA\( \Phi \)NE2 would represent the only facility in the world where \( K^- \) induced reactions at rest are studied. Moreover, after the GSI merging into FAIR, Frascati would be the only laboratory in Europe to go along this line of research.

The fact to become the European counterpart with respect to the Japanese programmes at J-PARC reinforces the plan to apply to the Seventh Framework Programme of EU (FP7), to obtain a substantial economical support both for developments of detectors and for the upgrading of the actual machine.
It is worthy to recall that Frascati national laboratories are a recognized European Research Infrastructure of EU (in FP5 and in FP6) and therefore they benefit of the EU funds for Transnational Access. This means that European groups from eligible countries (actually 33) and scientists from extraeuropean countries, but belonging to groups of eligible countries, may apply for access to Frascati and work on DAΦNE fully reimbursed.

In conclusion, *a variety of arguments scientific, but not only*, suggest that a dedicated facility in Frascati to study deeply bound kaonic nuclear states – one of the hottest topics of hadron physics – *should receive a very favorable acceptance* from the world scientific community. The creation of a large international collaboration should naturally follow. *Work in this direction is in progress.*

10 Conclusions

The scientific case on which is founded the proposal formulated in this (pre) Letter of Intent – study of deeply bound kaonic nuclear states - deals with one of the most important, yet unsolved, problems in hadron physics: *how the hadron masses and hadron interactions change in the nuclear medium and what is the structure of cold dense hadronic matter.*

*Our aim was to illustrate the extreme importance of this sector of hadron physics, on which recently a great attention both from theoretical and experimental sides has been addressed.*

*Deeply bound kaonic nuclear clusters offer the ideal conditions* for investigating the way in which the spontaneous and explicit chiral symmetry breaking pattern of low-energy QCD changes in the nuclear environment. The cold high-density nuclear matter of kaonic clusters could also provide information on *kaon*
condensation and a transition from a hadronic phase to a quark-gluon phase, therefore on changes of vacuum properties of QCD and on quark condensate.

Looking at current and future experiments planned in the world, it turned out that, after the closure of KEK in December 2005, two facilities will be active in the field: J-PARC in Japan, and GSI (FOPI) in Europe. The first one will produce kaonic nuclear clusters with $K^-$-induced reactions in flight. GSI will follow, before being absorbed in the new complex of facilities FAIR, an alternative approach, represented by nucleus-nucleus and proton-nucleon collisions.

Here comes the major role that a dedicated setup on DAΦNE2 can play. The new facility can become the scientific pole to study $K^-$-induced processes at rest, which were indicated as the more direct way to investigate the $\bar{K}$ clusters in nuclear matter. No other laboratory, after KEK will be closed, will study $K^-$-induced processes at rest. This is a complementary approach with respect to the others, which can be indeed considered as part of a structured strategy to attack some of the major open problems of low-energy QCD.

As far as the experimental setup is concerned, it was preliminary stressed that it must be a dedicated one, so to have all the necessary degrees of freedom. We have identified the methods to study the characteristic features of the $\bar{K}$-nuclear clusters, which must consists not only in observing the production stage of a $\bar{K}$-nuclear cluster, but also in detecting the decay products. It is then compelling to use a $4\pi$ detector capable of detecting all particles created in both the formation and decay of $\bar{K}$-nuclear clusters.

The experimental programme consists of precision spectroscopy studies of a number of light kaonic nuclei, as a function of their baryonic number $A$ and isospin $T$, followed by measurements on heavier nuclei.
The measurements to be performed are:

- $^3\text{He}(K_{\text{stopped}}, p/n)$ reactions to study the strange dibaryons $K^- pp$ and $K^- pn$.
  
  Their masses, including their total widths, will be determined by neutron and proton spectra. Exclusive measurements of their decays will allow to determine partial decay widths.

- Similar programme of measurements are intended for a $^4\text{He}$ target.

- We plan to extend these studies systematically to a broad range of nuclear targets starting from $\text{Li}$, $\text{B}$ and $\text{Be}$ nuclei.

- In addition to one-nucleon knock-out reactions, two-nucleon outgoing reactions studies will be also performed to populate other exotic states.

- Three-body decays, to study sizes, densities, and angular momenta.

We believe that the impact on the world scientific community of such initiative in Frascati will be great. Signals in such sense have been already manifested. An interest similar to that manifested towards the kaonic atoms research line on DAΦNE may be expected for the kaonic nuclei.
Appendix
A: Other experiments in the strangeness sector

A1. Sigmonic atoms

The study of sigmonic atoms X-ray transitions could be, in principle, performed with the SIDDHARTA setup, in which $\Sigma^-$ is generated in the interaction of the negatively kaon with the nuclei. In order to be able to stop $\Sigma^-$, one needs, in this case, to use high density (liquid) targets.

A technical solution might be the replacement of the cylindrical target of SIDDHARTA with a cylindrical crown, filled with a liquid target [55].

A preliminary simulation was done for the case of sigmonic helium, where indications for the yield of transitions exist [56]. In this case, an integrated luminosity in the range of about $1000 \text{ pb}^{-1}$ is necessary, in order to obtain a precision of about $10 \text{ eV}$ for the $2p$ level parameters.

Strong interaction information from $\Sigma$- atoms is limited at present to only 23 poor quality data points from experiments at CERN [57], RAL [58] and BNL [59]. A phenomenological study of the density dependence of the $\Sigma$-nucleus optical potential $V_{\text{opt}}$ could not determine unambiguously $V_{\text{opt}}$ inside the nucleus due to the too poor quality of the atomic data [60]. Precise measurements are therefore awaited.

A2. Measurement of the charged kaon mass

The particle Data Group [61] assigned a precision to the charged kaon mass which is one order of magnitude worse with respect to that on the charged pion mass (26 p.p.m. for the kaon mass, 2.5 p.p.m. for the pion mass).
Further, the charged kaon mass:

\[ M_{K^+} = 493.677 \pm 0.013 \text{ MeV}, \]  

(A1)
is obtained by making a weighted average of six measurements. The weighted average of the six errors on the mass is 5 keV (10 p.p.m.), but a huge scale factor (S=2.4) was introduced on the error, to take into account a serious disagreement between the most recent and more precise results of Denisov [62] and Gall [63], which differ by 60 keV. Both two experiments were carried out by measuring X rays from kaonic atoms using solid targets.

The uncertainty on the kaon mass has severe implications on the determination of the \( K^- p \) (and \( K^- d \)) scattering lengths from the measurement at percent level of the \( K_\alpha \) line shift of kaonic hydrogen (and kaonic deuterium).

In summary, a precise determination of the charged kaon mass is badly needed, but only a new measurement can settle the disagreement between the present input data.

The method proposed by DEAR [64] to use a gaseous nitrogen target with a two-arm crystal spectrometer coupled with CCD detectors used as position sensitive X-ray detectors, can give a precision on the kaon mass below 10 keV. The feasibility of this measurement with the SIDDHARTA setup by using the escape peak technique is an option under study.
References

[56] E. Friedman, private communication.