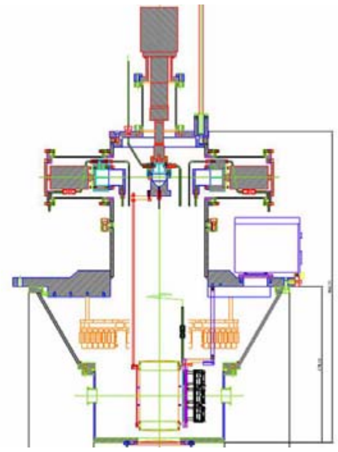


SIDDHARTA-2 Proposal

The upgrade of the SIDDHARTA apparatus for

an enriched scientific case

Exploring the (very) low-energy QCD in the strangeness sector by means of exotic atoms

14 June 2010

But are we sure of our observational facts? Scientific men are rather fond of saying pontifically that one ought to be quite sure of one's observational facts before embarking on theory. Fortunately those who give this advice do not practice what they preach. Observation and theory get on best when they are mixed together, both helping one another in the pursuit of truth. It is a good rule not to put overmuch confidence in a theory until it has been confirmed by observation. I hope I shall not shock the experimental physicists too much if I add that it is also a good rule not to put overmuch confidence in the observational results that are put forward until they have been confirmed by theory.

Sir Arthur Stanley Eddington

The SIDDHARTA-2 Collaboration:

Stefan Meyer Institute fur subatomare Physik, Vienna, Austria
P. Bühler, M. Cargnelli, O. Hartmann, T. Ishiwatari, J. Marton, K. Suzuki, E. Widmann, J. Zmeskal

Univ. Victoria, Victoria B.C., Canada
G. Beer

Univ. Zagreb, Croatia
D. Bosnar, I. Friscic, P. Zugec, M. Makek

INFN, Laboratori Nazionali di Frascati, Frascati, Roma, Italy
M. Bazzi, A. Clozza, C. Curceanu, A. d'Uffizi, C. Guaraldo, M. Iliescu, P. Levi Sandri, S. Okada, D. Pietreanu, K. Piscicchia, A. Rizzo, A. Romero Vidal, E. Sbardella, A. Scordo, D. Sirghi(*), F. Sirghi(*), O. Vazquez Doce

(*) as well from IFIN-HH Bucharest, Romania

INFN Sezione Roma1 and Ist. Superiore di Sanita', Roma, Italy
F. Ghio

Politecnico Milano and INFN Milano, Sez. Elettronica, Milano, Italy
L. Bombelli, C. Fiorini, A. Longoni

Univ. Tokyo, Japan
R. Hayano, HeXi Shi, H. Tatsuno

RIKEN, Japan
K. Itahashi, M. Iwasaki, H. Ohnishi, H. Outa

Excellence Cluster, TUM, Munchen, Germany
M. Berger, F. Cusanno, E. Epple, L. Fabbietti, P. Kienle, R. Lalik, K. Lapidus, R. Munzer, J. Siebenson

IFIN-HH, Bucharest, Romania
M. Bragadireanu

CONTENTS

Chapter 1 – INTRODUCTION

The SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) experiment was ending its data taking campaign in November 2009, after having performed kaonic atoms transitions measurements on the upgraded DAΦNE collider.

SIDDHARTA's original aim was to perform kaonic hydrogen and deuterium measurements of X rays emitted in transitions to their respective ground-levels in order to derive the shift and widths of these levels with respect to the purely QED calculated values, induced by the presence of the strong interaction between kaon and nuclei.

As we'll present in Chapter 2, this aim was only partially fulfilled, in spite of big efforts from DAΦNE and SIDDHARTA groups. Kaonic hydrogen transitions were measured with a precision better than ever, but the kaonic deuterium measurement remained practically un-performed. Other important measurements, kaonic helium 3 and 4 were performed – the KHe3 one being the first measurement ever.

The fact that the kaonic deuterium measurement could not be performed with the intended precision (for reasons which will be discussed in Chapter 2) pushed the SIDDHARTA Collaboration to pursue its realization and find solutions (logistic and technical) for its realization. While doing so, the SIDDHARTA Collaboration arrived not only to identify the technical solution allowing the measurement of the kaonic deuterium, but to propose other important measurements in the sector of exotic atoms – long time awaited by the low-energy strangeness QCD community. Moreover, the original SIDDHARTA Collaboration was enriched with new groups which joined the present proposal, achieving more strength and international value.

The present proposal is presenting the technical solution for the realization of SIDDHARTA-2, together with the enriched scientific case.

The proposal is structured in the following way: Chapter 2 is briefly presenting the SIDDHARTA results and limitations; Chapter 3 introduces SIDDHARTA-2's importance and opportunity, in terms of realization using DAΦNE; Chapter 4 presents the updated scientific case of SIDDHARTA-2, including many important measurements in the sector of kaonic atoms; Chapter 5 presents the upgraded SIDDHARTA-2 setup, where a technical solution is proposed for measurements in the 2-40 keV range, the main aim being the kaonic deuterium measurement's immediate realization; there are as well presented possible future upgrade-addings to the setup able to extend the measured energy domain to hundreds keV and MeV range – to realize measurements presented in Chapter 4 in a program which is previewing a few-years measurements campaign; the Collaboration, task sharing and the strategy are discussed in Chapter 6; the proposal ends with Chapter 7 – Conclusions.

Chapter 2 – SIDDHARTA – brief history, results and limitations

In the present Chapter we briefly present the SIDDHARTA's history – including obtained results (analyses still ongoing) and limitations. Such a presentation will turn useful when presenting the upgraded setup.

We start by reminding that the aim of the SIDDHARTA experiment was to perform precise measurements of kaonic hydrogen and kaonic deuterium X-ray transitions to the fundamental, 1s, level, such as to determine its shift and widths generated by the presence of the strong interaction in addition to the electromagnetic one. Only the combined measurement can allow the extraction of the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities for understanding aspects of low-energy QCD in the strangeness sector.

SIDDHARTA's main improvement with respect to the DEAR experiment running on DAFNE in early 2000s [1,2,3,4] was the use of fast X-ray detectors, the Silicon Drift Detectors (SDDs) [5] developed with the support of the EU FP6 Hadron Physics program (as JRA10 activity). Such detectors, having response time of about 1 μs (to be compared with seconds needed to the CCDs used in DEAR), could then be triggered in the SIDDHARTA experiment by using a couple of scintillators (the trigger system) placed below and above the beam pipe and triggering the SDDs in coincidence with the back-to-back generated kaons. In this way the biggest source of background could be suppressed coming from losses of the circulating beams. The remaining background is then either of hadronic origin (generated by kaons themselves directly or through their decay products) or residual accidentals from beam losses coming in the coincidence time window.

2.1 SIDDHARTA's results

SIDDHARTA apparatus was installed on the upgraded (crab cross and crab waist schemes were implemented on DAFNE in 2006-2007) DAΦNE [6,7] in late summer 2008, see Fig. 1 and Fig. 2, being the first experiment to take data on the new DAΦNE machine. After a period of machine and setup optimizations (including not only luminosity increase, but background reduction as well), SIDDHARTA started its data taking campaign in March 2009.

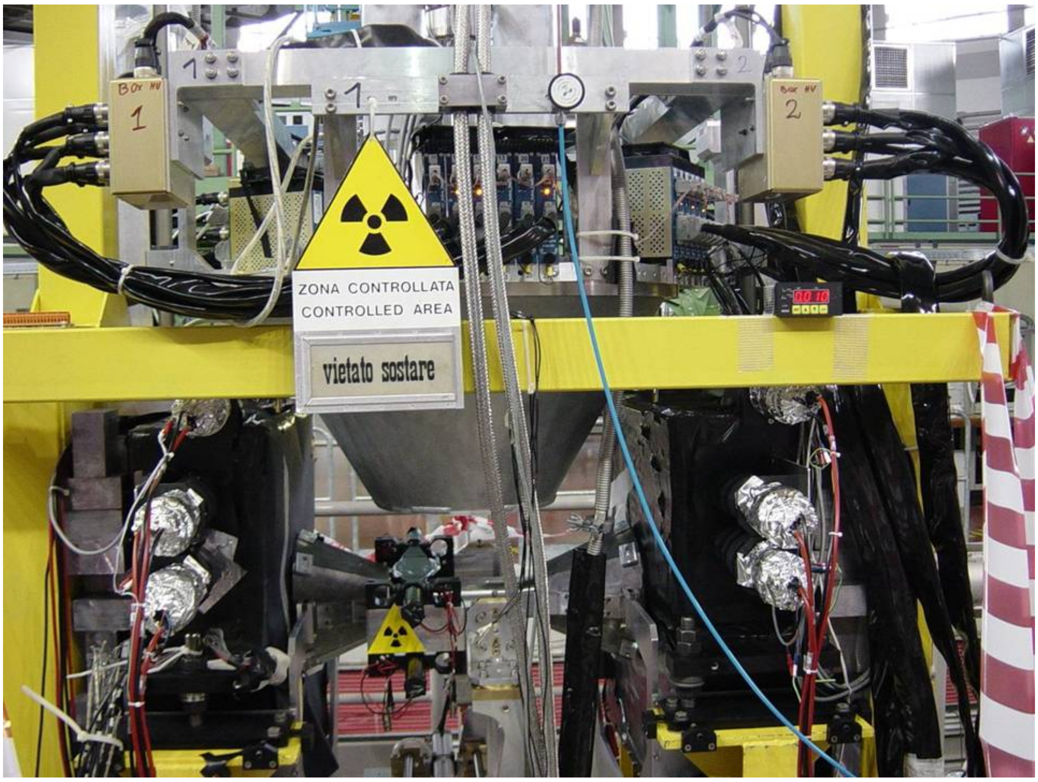


Fig. 1 The SIDDHARTA setup installed on the DAΦNE Accelerator

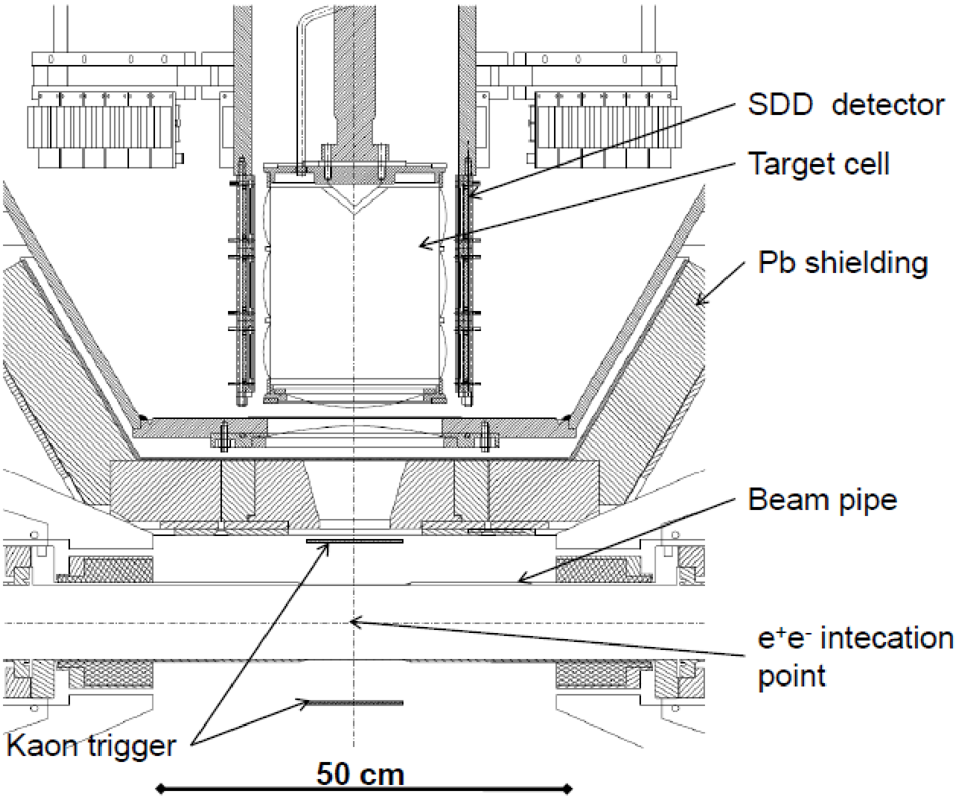


Fig. 2 Sketch of the SIDDHARTA setup; the target cell is surrounded by SDD detectors, placed within a vacuum chamber, surrounded by a lead shield.

The measurements performed by SIDDHARTA in 2009 were the following ones:

1) ***Kaonic helium4*** – originally used for setup optimization (especially the degrader tuning to follow the ϕ-boost, since the yield of kaonic helium transitions to the 2p level is much bigger than the KH one), proved to be a very competitive measurement; the results of partial statistics analyses were already published [8], see Fig. 3. Presently, the analyses are going on with the aim to include all accumulated statistics and to obtain an improved precision together with yield measurements, which are important for cascade calculations.

2) ***Kaonic* hydrogen X-ray** measurements to the 1s level – for a total integrated luminosity of about 400 pb^{-1} (the required luminosity by SIDDHARTA); presently the data analyses are undergoing (soon to be published) – we present in Fig. 4 a preliminary KH spectrum. The final results will clearly improve the DEAR ones.

3) ***Kaonic deuterium X-ray*** measurements to the 1s level – we were able to collect only about 100 pb^{-1} of integrated luminosity with respect to an original request of 600 pb^{-1}. The kaonic deuterium measurement was thus actually an exploratory measurement, being clear that for reasons basically of timing (KLOE installation) we could not perform the planned measurement. Data analyses are ongoing – showing a possible activity in the Kd region (about 2 σ); we will not present results here since further checks are necessary.

4) ***Kaonic helium3*** **–** this measurement, X-ray transitions to the 2p level, was performed for the first time ever by SIDDHARTA for a total integrated luminosity of about 18 pb^{-1}, in the last week of data taking. The importance of this measurement (to which the E17 experiment is dedicated at JPARC) is related to its relation to the possible existence of the so-called deeply-bound kaonic nuclei. The analyses showing a preliminary value of the shift compatible with zero within 10 eV are still ongoing (soon to be published) – we present in Fig. 5 a preliminary spectrum.

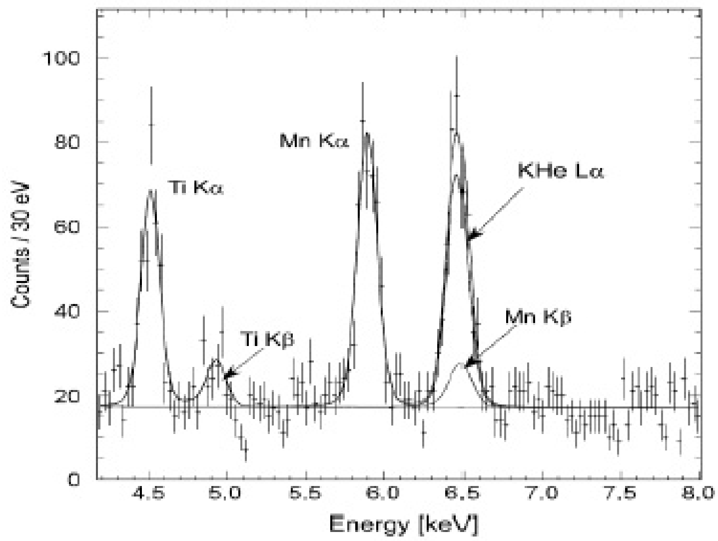


Fig. 3: Energy spectrum of the kaonic 4He X-rays. The kaonic 4He La line is seen at 6.4 KeV.

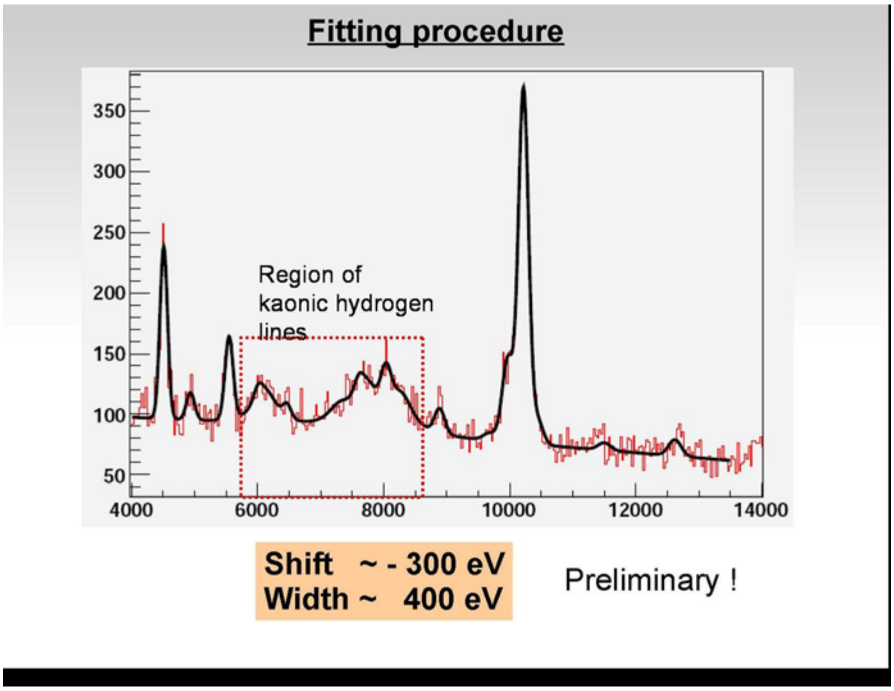


Fig. 4: Kaonic hydrogen preliminary spectrum

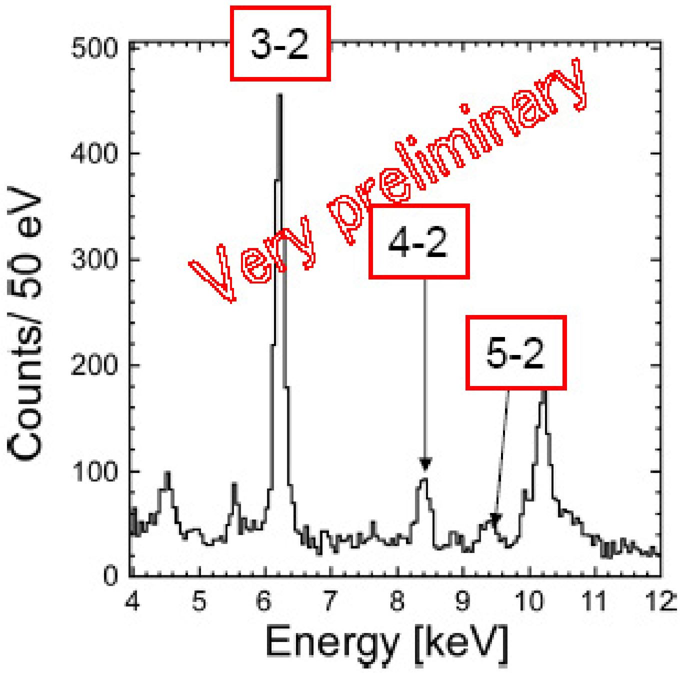


Fig. 5: Kaonic Helium3 preliminary spectrum where the transitions to the 2p level are clearly identified.

2.2 SIDDHARTA's limitations

The two main limitations during the SIDDHARTA run were the following ones:

a) The presence of a *still important background*, coming both from hadronic processes and from losses of circulating beams (accidentals). The S/B ratio during the KH run is evaluated as being around 1/5. The origin of still an important background is identified both as the trigger system which staying at a distance from the entrance window of the target (outside vacuum jacket, so higher solid angle viewed) is triggering on kaons which not necessarily enter inside the target and in the very limited space left for SIDDHARTA setup to optimize the external shielding (due to the presence of the DAΦNE luminosity monitor just at about 80 cm from the interaction point, IP).

b) The presence of *X-ray satellite transitions* coming from kaonic atoms created by kaons stopped in the materials present in the setup, in particular in the target wall

– for example from kaonic Oxygen and kaonic Carbon X-rays, disturbing the energy region of Kp and Kd X-rays.

There were other limitations too, which we mention below:

c) The *impossibility to run the setup during injections* – due to the latch-up of the first stage of the electronics (the input JFET) integrated directly on the detector, induced by the very high background during injections. The recovery time from this latch-up needs the reset of a detector voltage and this procedure lasts seconds. This effect was not actually previewed in the design of the biasing and readout electronics since when the electronics of SIDDHARTA was designed we expected much smaller background during injections, which might very well have been the case if more time would have been at disposal to optimize the machine

d) *Cooling power limitation* – with a more powerful cooling it would have been possible to get higher target density and lower SDDs working temperature (gaining in resolution). The cooling power was limited by the use of the best cooling technology present in 2003, when SIDDHARTA was designed and started to be built and ordered

e) **The obvious limitation of integrated luminosity** – we were unable to get the requested and assigned luminosity of 600 pb^{-1} for the Kd measurement, since we had to dismount the setup for the KLOE run (in spite of our repeated requests to prolong the duration of the run till the completion of the measurement and in spite of the support from our referees both in SC of LNF and from INFN).

In early 2010 a new scenario opened, favourable to the continuation of SIDDHARTA with an improved setup version, not only curing the above limitations, but implementing new features, allowing presenting an enriched scientific case, with a reinforced Collaboration. All these items are presented in the following Chapters.

Chapter 3 – SIDDHARTA-2 opportunity

Once the data taking of SIDDHARTA was over, in November 2009, the preparation of DAΦNE started for the roll-in and data taking of KLOE2. The KLOE2 experiment will run most probably for the next 3(4) years and it is unlikely (just not to say impossible) to imagine a roll-in and out of KLOE to allow SIDDHARTA to get some more data in the same Interaction Region. Having this in mind, the SIDDHARTA Collaboration addressed officially the DAΦNE team and DAΦNE's responsible, Dr. Pantaleo Raimondi, with the request to examine the feasibility of a SIDDHARTA run in the Interaction Region of DEAR/FINUDA, presently impossible to access due to separate beam pipes for the two circulating beams.

The request was seriously examined by the DAΦNE team and an official positive answer given, showing that the preparation of the second Interaction Region on DAΦNE where SIDDHARTA could run in beam-sharing mode with KLOE2 is feasible, with limited costs, and could be done on a time scale compatible with the stop of KLOE for insertion of the Inner Tracker after step-zero (see in Annex 1 the letter of request and the answer of Pantaleo), Fig. 6.

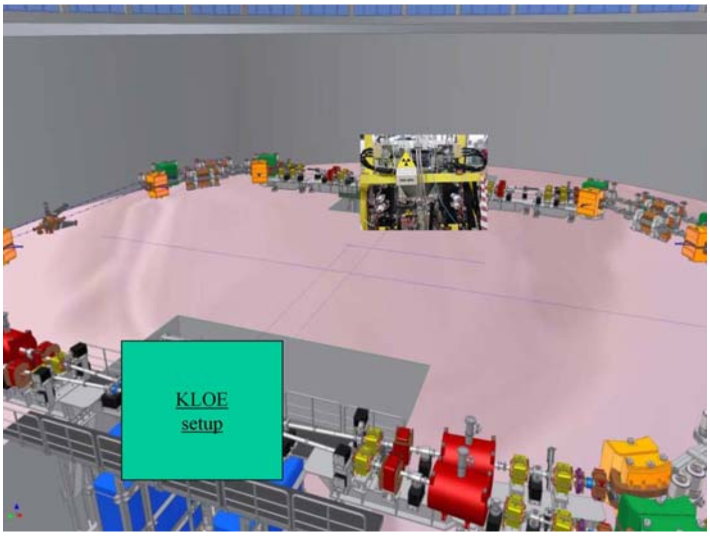


Fig. 6: The possible SIDDHARTA2 setup in the ex-DEAR/FINUDA Interaction Region of DAΦNE

At this point, without a conflicting situation with KLOE2, the SIDDHARTA Collaboration started to prepare the upgraded setup proposal, in which all limitations presented in Chapter 2 were considered. Moreover, an upgraded scientific case was considered, with support and motivations coming from the LEANNIS Network in the framework of the EU HadronPhysics2 FP7 project, in which SIDDHARTA is an important actor.

The Task 2 of LEANNIS is dedicated to SIDDHARTA – data analyses and interpretation – and in the framework of this Network work was going on seeing theoreticians and experimentalists working together not only for interpretation of results, but for directing the future experiment, SIDDHARTA2, as well.

In the last LEANNIS meeting, held in LNF-INFN in the days 8 and 9 April 2010, the SIDDHARTA2 physics case was discussed in detail, and many possible measurements proposed. What was actually a reality was a revival of the field – with a consideration of many measurements which could be foreseen in SIDDHARTA2 (eventually not necessary in a first measurement campaign, but in subsequent measurements, when new components could be added to the setup – as will be discussed in the next Chapters). It was checked that actually SIDDHARTA2 could become the future facility where to perform not only the fundamental and necessary kaonic deuterium measurement (overriding aim), but other measurements very important as well.

The files of the talks presented in the LEANNIS Frascati meeting are collected on the web-site:

http://www.oeaw.ac.at/smi/research/topics/strong-interaction/leannis/meetings/meeting-april-2010/

under a password WHICH IS obtainable to members external of LEANNIS under request.

In the next Chapter we present the SIDDHARTA2 enriched scientific case, resulted from the SIDDHARTA2 proponents, discussed and optimized with members of LEANNIS group, to whom we are very grateful.

Chapter 4 – SIDDHARTA2 (enriched) scientific case

Once the opportunity to perform an upgraded version of the SIDDHARTA experiment at the DAΦNE collider opened, we examined the various important measurements in the sector of exotic atom research and arrived to propose a rich scientific case, containing many measurements of light and heavy atoms. What we have in mind, as will become more clear in Chapters 5, where the upgraded setup and its possible future implementations will be shown, is a modular strategy, allowing to start with measurements feasible with modifications of the present setup doable in an one-year time scale, and then to continue, on a 5-years time scale by implementing the setup in order to go to higher energies and higher energy resolution.

4.1 Kaonic deuterium

The main aim of SIDDHARTA2 is to perform the kaonic deuterium measurement remained practically undone by SIDDHARTA.

The kaonic deuterium measurement of the X-ray transitions to the 1s level will allow to extract, together with the kaonic hydrogen results, the isospin-dependent antikaon-nucleon scattering lengths, fundamental for understanding the low-energy QCD in the strangeness sector. The measurement will be feasible with the modification discussed in chapter 5.

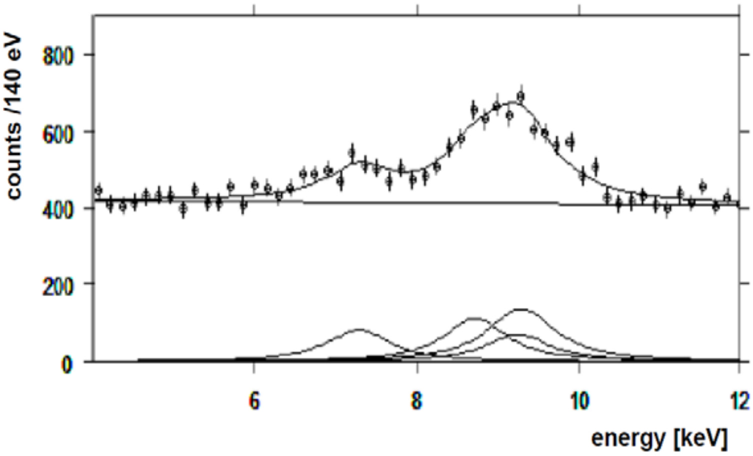


Fig. 7: MC simulation of the expected K^-d spectrum for the SIDDHARTA-2 upgrade taking the SIDDHARTA measurement into account. For an integrated luminosity of 600 pb^{-1} the shift could be extracted with about 10%.

4.2 Kaonic helium transitions to the 1s level

Fundamental, but very difficult, measurements in the sector of strangeness low-energy QCD are the X-ray transitions in the kaonic helium 3 and 4 to the 1s level, never even tempted. SIDDHARTA measured the transitions to the 2p level, basically unaffected by the strong interaction and presenting high yields using gaseous cryogenic targets. The transitions to 1s level, in the energy range of 30 keV, look very interesting and would represent a continuation of Kp and Kd measurements. The yield of such transitions will be prohibitive small – but in SIDDHARTA-2, with the improvements we plan to do (specially the additional installation of Si-PIN diodes), we could either arrive at a measurement or at establishing a competitive limit on the yield – which would bring important information as well (see as well Annex2).

4.3 Additional experiments – with minor modifications

4.3.1 Other kaonic atoms transitions

The bulk of data on kaonic atoms transitions are dating back to 30-40 years ago, being performed at extracted beams. Such data are often incomplete, not precise (see Fig. 8) or puzzling. One of the puzzles, referred to as “kaonic atoms puzzle” refers to an apparent conflict between phenomenological optical potentials obtained from fits to kaonic atoms data and the corresponding potentials constructed from more fundamental approaches [see Eli Friedman´s talk at the MESON2010 Conference]. The best-fit phenomenological potentials have the real part typical depths around 180 MeV at nuclear-matter densities, while the t-ρ potentials are less than half. Moreover, the corresponding depths of chiral-motivated potentials are even lower (30-40 MeV). Extrapolating the deep potential to 3-4 times the normal nuclear density, deeply bound kaonic nuclei might exist, as well as the condensation of K^- mesons; which is not the case for the shallow potentials. The carefully re-analyses of the world´s data on kaonic atoms, out of which the potential is derived, could not solve the puzzle. Theoreticians working on the field (see Friedman´s talk at the MESON2010 Conference) suggested that a re-measurement of some kaonic atoms on a small-well-selected number of targets could help in solving this puzzle. Among these targets are some light targets – the

Carbon, Nickel and Silicon ones, which could be done in SIDDHARTA-2. For these types of measurements we will use a pure Ge detector (energy range 4- 100 keV), placed at the free space below the beam pipe and using solid targets done in those materials.

The measurements of upper levels kaonic atoms could be useful in the extraction of the elastic antikaon-nucleon scattering amplitude in the Λ(1405) region too. As shown in Annex 2, where S. Wycech is proposing to SIDDHARTA-2, as discussed in the LEANNIS meeting, a series of measurements, for He4, Beryllium, Oxygen, Ca, Sn and Pb targets. In SIDDHARTA-2 we could do those measurements in the keV range either by filling the target with desired gas (He, O2) or using a solid target done in the desired material.

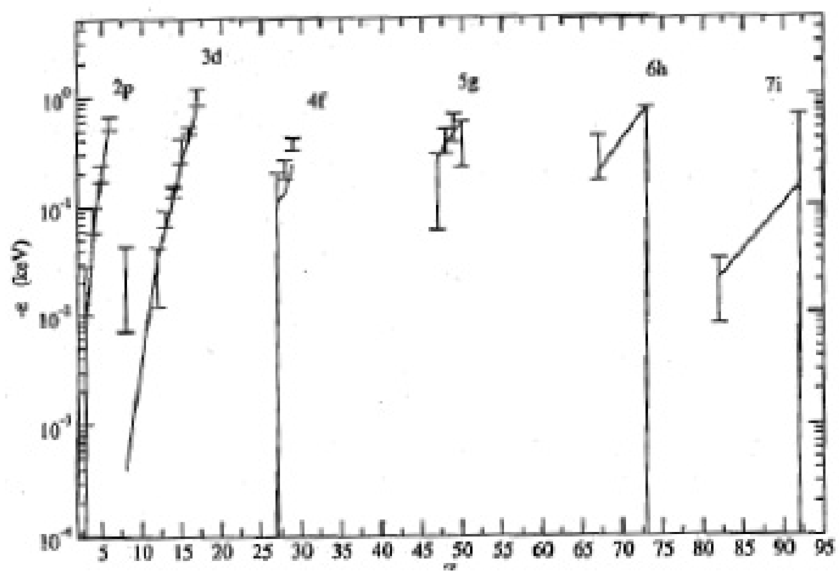


Fig. 8: Existing kaonic atoms data

4.3.2 Heavy kaonic atoms transitions

In spite of the fact that, at least in a first phase of SIDDHARTA-2, the use of SDDs will not allow the measurements in the range above 30 keV, we plan a modular strategy which could allow such type of measurements to be performed in the region left unused by SIDDHARTA-2 – below the beam-pipe. For these reason we present such type of measurements together with their importance.

The heavy kaonic atoms (in particular Si, Sn, Ca and Pb) transitions in the range of hundreds of keV are important for many reasons. Among these reasons we refer to Annex2 – where measurements on Ca, Sn and Pb (on various isotopes) are proposed in order to study K^- -

neutron interaction. Such measurements could as well contribute in solving the so-called kaonic atoms puzzle – briefly discussed previously.

4.3.3 Sigmonic atoms

The kaons stopping in the various materials/targets are generating out of the nuclear interaction with a certain (rather high) probability a Σ^- particle. Usually such particles, with very short lifetimes, will decay before they could to be stopped. SIDDHARTA2 is however evaluating the possibility to perform Sigmonic hydrogen and deuterium measurements by using higher (w.r.t. SIDDHARTA) density gaseous targets (by using more powerful cooling system – see Chapter 5).

The sigmonic hydrogen and deuterium measurements would allow the extraction of the Sigma- p scattering length from hydrogen, and then combining it with Sigma- n from deuterium will help to understand/ the current YN potentials and to confront it to the present values. The question whether Sigma- feels attraction or repulsion in nuclear or neutron matter is very important for understanding the onset of strangeness in neutron stars and thereby how soft the equation of state is. One of the first discussions of this problem is found in Balberg & Gal, NPA 625 (1997) 435.

4.4. Additional experiments – with new detector components

These types of experiments will need additional detectors, which could be installed in a second phase of the experiment, without disturbing the ongoing experimental programme.

We shall present possible technical solutions in Chapter 5.

4.4.1 Kaonic helium transitions to the 2p level

SIDDHARTA had performed measurements of K^-He-3 and -4 to the 2p level with statistic and systematic errors of few eV by using a very small amount of integrated luminosity (about 20pb^{-1} for each measurement). It could be of interest in SIDDHARTA-2 to repeat these measurements with an ambitious goal to arrive at less than 100 meV precision in shift and width. This will be only possible using a crystal spectrometer together with the CCD detector system of DEAR. Such measurements would help to fix once for all the value of shift and width and to disentangle between the optical potential solution (predicting basically no measurable effects) and some predictions related to deeply-bound kaonic nuclear states (where there is space for measurable eV shift and widths).

4.4.2 The charged kaon mass

The present value reported in PDG for the charged kaon mass is suspected by possible systematic errors, since it is a weighted value of two incompatible measurements (reason for which a Scale factor had to be applied) – see fig. 9

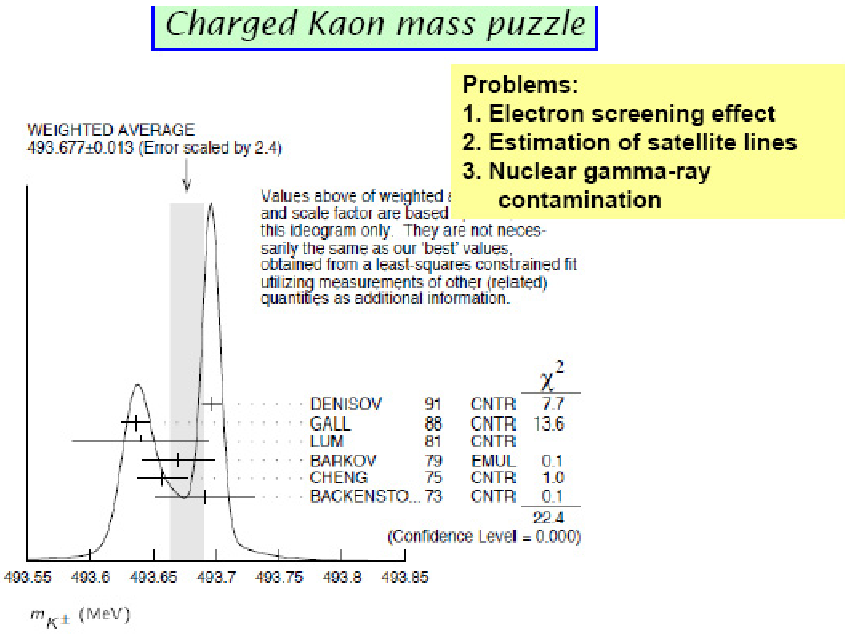


Fig. 9: The charged kaon mass situation

The two measurements were both measurements of kaonic atoms: kaonic lead transitions in one case [9] and kaonic carbon in the other [10]. The GALL [9] KPb (9->8) is the one measurement out of the average of all other data and was (is) suspected by some bias. But since there was no reason to discard it, in the end was kept in the averaged value, making the error blowing up to the 13 keV and introducing a possible systematics in the present value of charged kaon mass.

The kaon mass is extremely important, not only because it generated a puzzle, but because it has strong implications in nuclear, particle and fundamental physics; an improved or corrected measurement of the charged kaon mass can:

- change V_{us} of semi-leptonic K^+ decays (considering equality of K^+ and K^- masses)
- affect the decay $K^+ \to \pi^+ \nu\nu$ BR and other parameters
- contribute to CPT violation check by comparing K^+ and K^- masses
- impact on any particle decay having a K^+ in the final state (as for example $K^0 \to K^+ e\nu$)

Related to the importance of Kaon Mass determination we present in the ANNEX 3 – an email of Prof. R. Seki related to this item.

Therefore, the ideal measurement for charged kaon mass, potentially improving the PDG one by an order of magnitude, however would be (as proposed time ago by DEAR, [1]) the kaonic nitrogen measurement performed with a crystal spectrometer (since an energy resolution of few eV can be reached) which, however, needs a dedicated setup (and will become object of interest in the framework of SIDDHARTA-2 program at a later stage). With this type of measurement no theoretical input will be necessary to explain the experimental results (as message from Prof. Seki).

4.4.3 Radiative kaon capture by proton - measurements in the MeV range

Electromagnetic cascades in kaonic hydrogen and helium atoms indicate the intensity of the last $2P \to 1S$ transitions to be in the 1-10 % range. It is commonly assumed that most of mesons reach high nS or nP states and are absorbed by the nucleus. It is probable that in dilute gas a fraction of 0:001 of the mesons may undergo radiative processes:

$K^- p \rightarrow \gamma \, \Lambda(1405)$

or its nuclear analogues. This might offer a chance to study the shape and position of these states. Such a measurement was proposed by Prof. S. Wycech to SIDDHARTA2, in the framework of the LEANNIS Collaboration, see ANNEX 4.

In order to perform such type of measurement one needs detectors able to go in the MeV range. We shall present a possible technical solution in Chapter 5.

Chapter 5 – The SIDDHARTA-2 setup

The SIDDHARTA-2 setup necessarily starts from the existent SIDDHARTA apparatus, at which, however, important improvements/changes are previewed in order to overcome the limitations presented in Chapter 2.

With the improvements/changes presented in the coming Sections for SIDDHARTA-2 we expect the following gain factors:

- an increase of the signal/pb^{-1} of about a factor 2 (chapter 5.1.1 and 5.1.2)
- a S/B improvement about at least a factor of 10 (chapter 5.1.3 and 5.1.4)

In the following paragraphs the planned modifications and changes are discussed in detail.

5.1. First phase

The main changes to be performed for the first phase of SIDDHARTA-2 are mechanical improvements on the vacuum chamber in order to add additional cooling power to the SDD cooling system and replace the target refrigerator to a more powerful one. In addition the kaon trigger could be optimised and two types of active shielding components will further improve the S/B ratio. Due to more available space at the new interaction region a more sophisticated grated shielding structure (lead-copper-aluminium-plastic) around the SDD detectors will be constructed.

5.1.1 New vacuum jacket, target cell and SDD rearrangement

A part of the vacuum chamber has to be rebuilt to ensure optimal space for the planned additional detector systems and for the improved calibration systems with X-ray sources (like Fe-55) and X-ray tube. In addition ports for an upgrade of the cooling system will be foreseen.

A new target cell will be built with less material budget and selected wall materials (Be or Hostaphan) and reinforcement material (Al or Ti) to avoid unwanted fluorescence X-rays or kaonic X-ray lines from stopped kaons in the target material. The new target dimensions are 140 x 180 mm (first one being the diameter and the second one the height) – see Fig. 10.

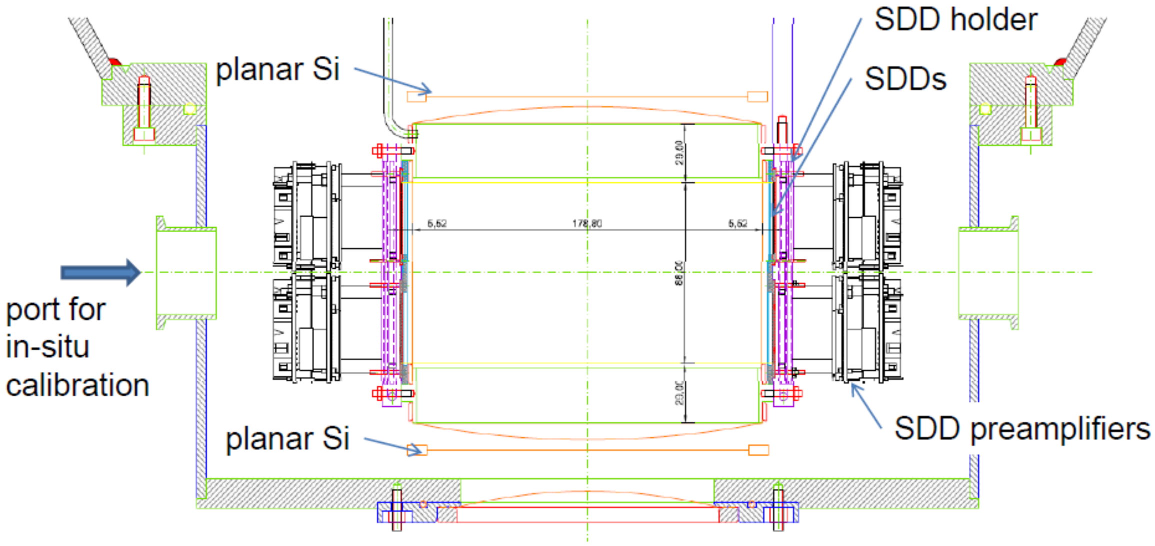


Fig. 10: The new vacuum jacket, target cell and SDD/Si-PIN arrangement for SIDDHARTA-2; side view.

The new target cell will be coupled with a more powerful cryogenic system, which will allow us to run with higher gas densities. A density of up to 5% (of liquid deuterium density) is planned, which will increase the kaon stops inside the target, but this high density is still acceptable in order not to lose too much kaonic X-rays due to the Stark-mixing.

The SDDs will be rearranged as close as possible around the target (taking care of the temperature difference between target ~ 20 K and detector ~ 120 K) such as to optimize the acceptance. The new SDD arrangement is shown in Fig. 10.

Monte Carlo simulations have shown that a gain in the signal per produced kaon of a factor about 2 is achievable using SDDs (144 cm^2) with an increase of the target density to about 3% (of LHD).

5.1.2 New cryogenic system

The SIDDHARTA cooling system was based on a 3 Joule-Thomson refrigerators (CryoTiger) for SDD cooling and a closed cycle helium refrigerator (APD) for cooling the target gas. But, it was shown that their cooling power was close to the limit. Therefore, SIDDHARTA-2 will be equipped with additional CryoTiger systems, in total 4 CryoTigers will be used and also a more powerful refrigerator for cooling the target cell, with almost twice the cooling power of 19 W at 20 K. A different technical solution is foreseen now to cool the target cell, which is about 0.5 m away from the cold end of the refrigerator system, namely a closed liquid hydrogen cooling loop is planned which allows us to reduce drastically the material budget in the upper part of the target cell (reduction of material which might produce bremsstrahlung).

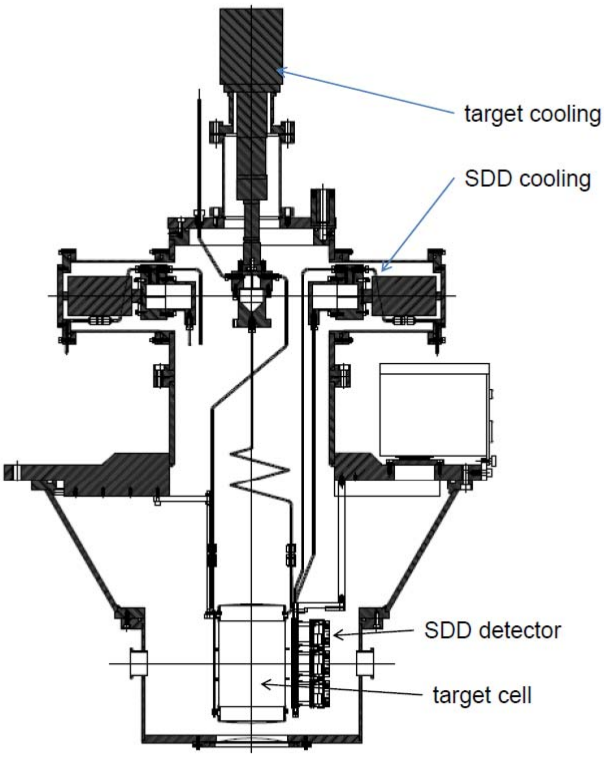


Fig. 11: The SIDDHARTA2 setup – showing the new liquid hydrogen and liquid argon closed cooling systems to be used for target and SDDs; strongly reducing the material budget on top of the target cell.

For cooling SDDs (and in future additional Si-PIN diodes) a similar system as used for the target cooling is planned making use of liquid argon as the coolant. This time the cooling power will be delivered by the 4 CryoTigers, as shown in Fig. 11.

This new system will not be limited in cooling power and will allow on one hand to increase the density of the target gas and on the other to improve the cooling of the SDDs with a gain in the timing resolution of a factor about 2, which is essential for further improving the background conditions.

5.1.3 New trigger, anticoincidence and active shielding system

In order to gain in S/B ratio one has to trigger only on the kaons entering the target volume. This fact was realized in SIDDHARTA only partially, since the trigger system (scintillators read by PMs) were outside the vacuum jacket – about 12 cm away from the target entrance window. Therefore, although the size of the kaon trigger was optimized, a certain number of kaons were not entering the target volume, but were absorbed on the side walls before and produced background events. For SIDDHARTA-2 we plan firstly to move the upper scintillator panel of the kaon monitor as close as possible to the entrance window of the vacuum chamber, secondly to install an anti-coincidence detector at the exit of the target chamber and thirdly to place in front of the target entrance window a segmented planar silicon detector to get additional spatial information as close as possible in front of the target cell, as shown in Fig. 12.

An important feature to minimise hadronic background events, which are produced due to the kaon absorption by the nucleus, will be a detector system made of scintillating strips read out with SiPM behind the SDD detector system. Events which are seen in coincidence between SDDs and the scintillating strips will be rejected (shown in Fig. 12).

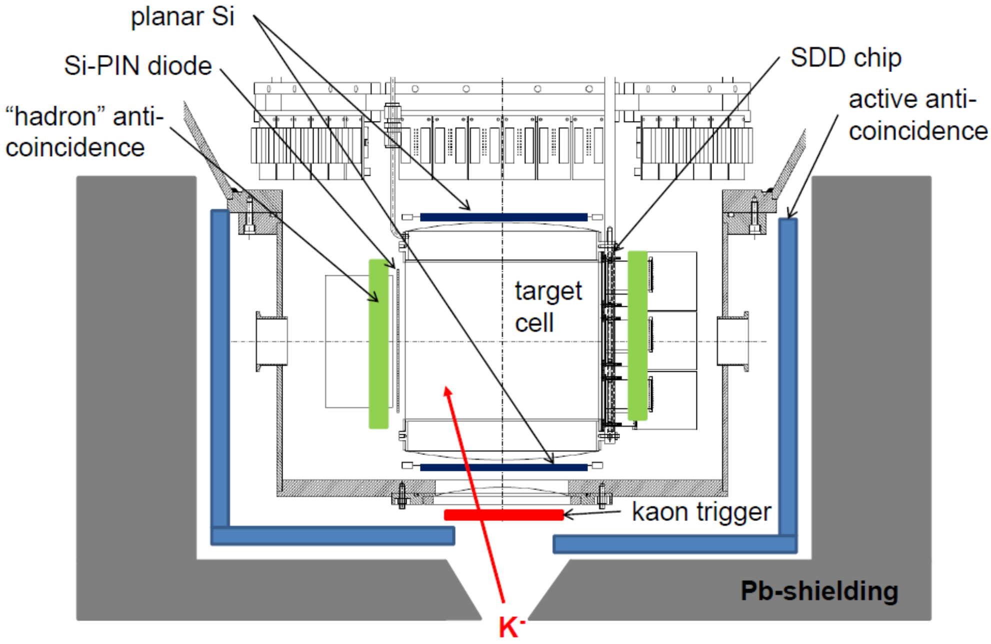


Fig. 12: The plastic scintillator (red) of the new kaon trigger system in SIDDHARTA-2 (only the upper scintillator) is shown just in front of the target window. An additional veto system will be placed around the vacuum chamber (plastic scintillator, blue). Below and on the top of the target cell position sensitive Si-detectors (dark-blue) are mounted to gain additional position information of the entering kaon with the lower one and to reject kaons which will not stop in the upper one. Finally, additional scintillators strip (green) are mounted behind the SDDs/Si-PINs to reject charged particles coming from the kaon absorption in the target gas. In addition to the SDDs Si-PIN diodes are foreseen as X-ray detectors with faster response.

Moreover, an additional veto (anticoincidence) system will be positioned around the target cell in order to reject those events which still pass to the lead shielding around the target. The technical solution we have in mind is based on an R&D done for AMADEUS in the framework of the JRA EU WP28 of the HadronPhysics2 project– and uses SiPM reading out strips of scintillators.

The new trigger system and anti-coincidence should bring an increase of the signal-to-background ratio by about a factor of 4.

5.1.4 Optimized shielding

In the framework of SIDDHARTA, due to the very limited space, it was not possible to optimize the shielding (as was eventually done in DEAR). We plan for SIDDHARTA-2 to prepare an optimized shielding, following the lesson learned in the framework of DEAR (layers of various decreasing Z-materials all around the setup).

5.2 Important upgrades

After successful R&D and test measurements we have additional ways to improve quite drastically the SIDDHARTA-2 setup, which will be addressed in the following paragraphs.

5.2.1 New readout electronics

In order to solve the latch-up problem during injections, new readout electronics is necessary. The Politecnico Milano group has already gained experience in this type of new, fast recovering electronics, and is able to built a new version of the readout chip implementing a fast (1 microsecond) recovery cycle procedure. This solution would allow SIDDHARTA to take data during injection (remaining vetoed only for the small period of time when effectively injection occurs (so having about 80% duty-cycle during injection – with the today's injection schemes; this figure might change if fast kickers will be implemented).

The overall duty-cycle of SIDDHARTA2 then might become as high as 90% (to be compared with the 50% at best in SIDDHARTA)

5.2.2 Additional X-ray detectors

To increase the detection efficiency for kaonic X-rays as well as to improve the signal-to-background ratio an additional X-ray detector system is planned. Si-PIN diodes, having a total active area of about 200 cm^2, with 32 channels arranged on one chip (20mm x 80 mm) are planned to be built. The goal is to retain a still relatively good energy resolution about 250 eV (compared to SDDs about 140 eV), but to achieve a much better time resolution in the order of a few ns (compared to the SDDs about 800 ns or below 500 ns at lower temperature). Of course, the good timing will help to further suppress the accidental background. A picture of a prototype cell is shown in Fig. 13.

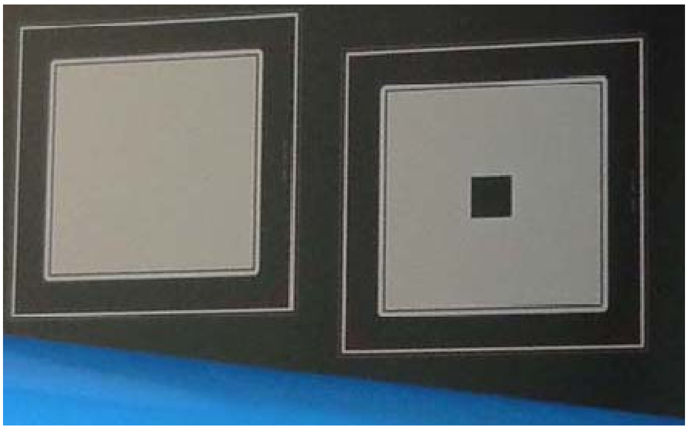
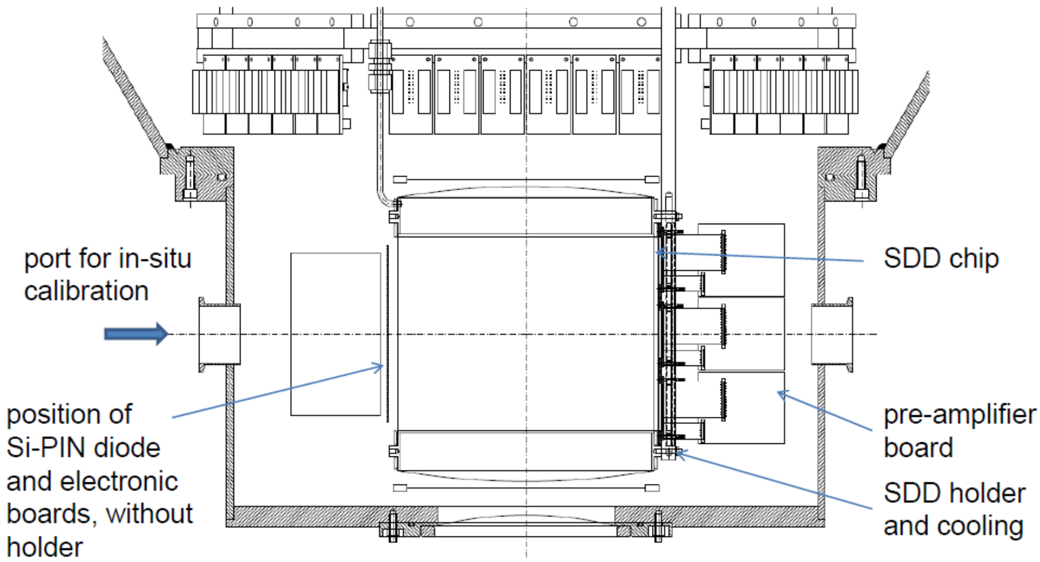


Fig. 13: Picture of two prototype Si-PIN diode cells with a size of 6mm x 6 mm

Figure 14 will show a combined arrangement with SDDs and Si-PIN diodes improving due to a better active to total area ratio compared to SDDs and therefore to a more compact design around the target cell, the solid angle by a factor of 3.



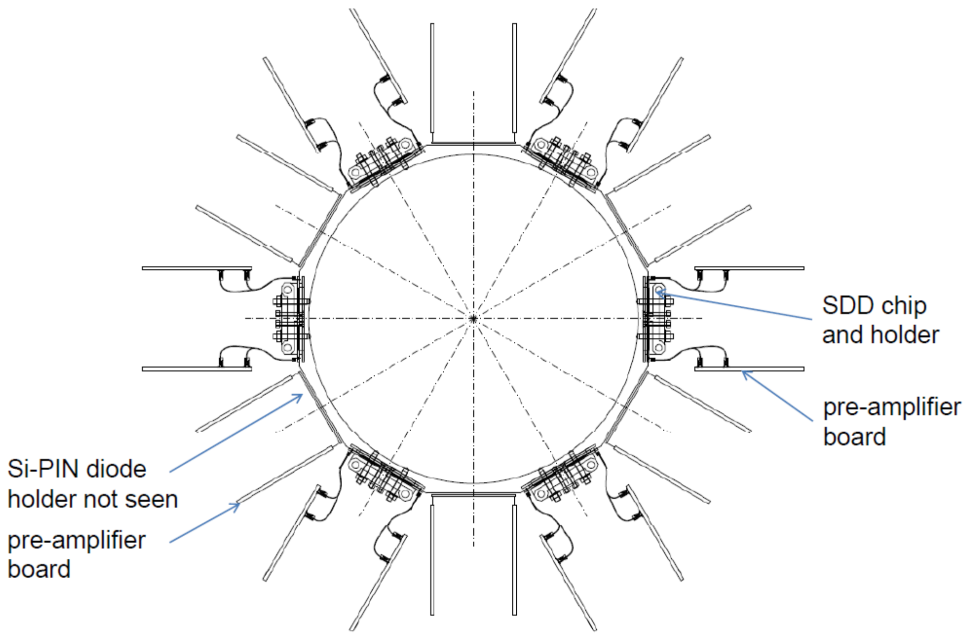


Fig. 14: Schematic of the SIDDHARTA-2 setup with a combined arrangement of SDDs and Si-PINs in SIDDHARTA-2 (sid- view and top-view). Due to a new design of the Si-PIN we will achieve a factor of 3 larger active to total area than with SDDs.

5.3 Second phase - further possible implementations

As was shown in Chapter 4, the SIDDHARTA2 scientific programme is considering measurements of X and γ ray transitions in energy ranges not accessible to the SDD detectors. We want to give an idea of how these measurements could be implemented in the future – considering a few-steps strategy – even if none of this solution is technically considered in detail. So the coming sections are to be considered as indicative, still giving an idea of what could realistically be done.

5.3.1 Measurements in hundred of keV range

In order to perform measurements in the hundred keV range on solid targets we think about implementing a dedicated setup in the space left free below the beam pipe. Possible detectors which could be used are: HPGe (an N-type Coaxial HPGe Detectors from ORTEC in the energy range from about 3 keV to about 10 MeV is ready to be used as well as a semi-planar

Ge detector in the energy range from about 3 keV to 1 MeV) or e.g. newly developed CdZnTe detectors will be considered in addition.

At least two detectors are already available and test measurements will be performed as soon as possible to gain information of the background situation at DAΦNE.

5.3.2 *Measurements in the MeV range*

Since the measurement in the MeV range is very special and asks for a hydrogen gaseous target, a possible solution might be to place detectors just outside the SIDDHARTA-2 setup and measure the γ rays coming from the target. Such a solution is presented in Fig. 15.

We are presently considering the idea of using BaF2 detectors and are in contact with the Milano group to gain more information.

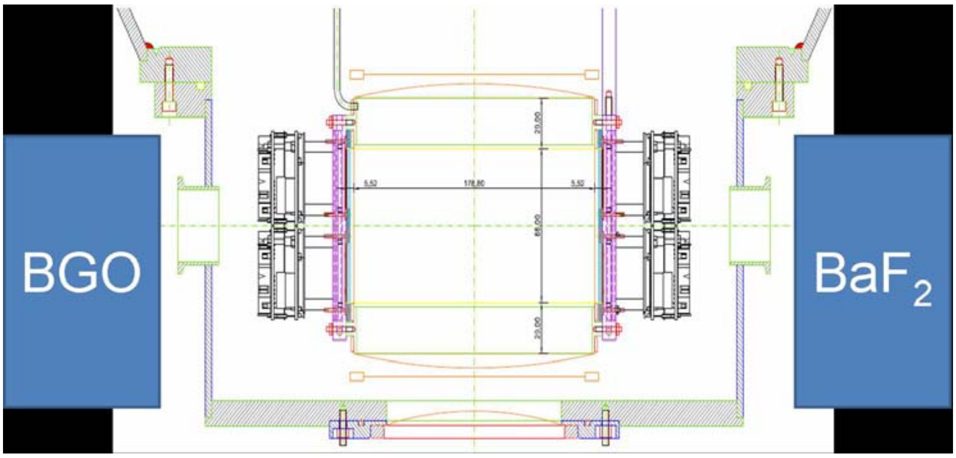


Fig. 15. Possible placement of gamma rays detectors around the target cell (outside the vacuum jacket)

5.3.3 *High energy resolution measurements – crystal spectrometer*

For the measurement of the 2p level shift and width in helium, but even more important for the precise determination of the charged kaon mass a crystal spectrometer is one of the best solutions. An energy resolution below 100 meV is achievable, with the drawback of low efficiency (acceptance). A crystal spectrometer was used at PSI to determine the charged pion mass and also in hadron physics experiments in the determination of shift and width of the 1s state of pionic hydrogen in the order of meV. Evaluation to optimize the efficiency of such an apparatus by realising the stringent requirements to achieve meV precision is under investigation. See ref. [1] for technical details – in the case of kaon mass precision measurement.

Chapter 6 – Collaboration, tasks and strategy

6.1 SIDDHARTA2 Collaboration and tasks

The SIDDHARTA2 Collaboration is built starting from the core of the SIDDHARTA Collaboration, namely the following participating Institutes with their respective tasks in the framework of the collaboration:

- SMI, Vienna, Austria; mechanics, cryogenics, Monte Carlo and data analyses; detectors for high-energy; Si-PINs
- Univ. Victoria, Canada; Monte Carlo and data analyses
- LNF-INFN, Frascati, Italy; electronics, trigger, mechanics, cryogenics, Monte Carlo and data analyses
- Politecnico Milano, Italy; electronics
- RIKEN, Japan; trigger, data analyses; detectors for high-energy
- Univ. Tokyo, Japan; Monte Carlo, data analyses
- IFIN-HH Bucharest, Romania; trigger and Slow Control

to which the following Institutions will be added:

- TUM, Munchen, Germany; electronics, trigger; detectors for high-energy, Si-PIN
- Univ. Zagreb, Croatia; data analyses and Slow Controls

In addition, this proposal will be strengthened due to the Collaboration with LEANNIS (in the framework of FP7), where experimentalists and theoreticians all over the world are working together in the field of low-energy kaon-nucleon/nuclei interaction and low-energy QCD.

SIDDHARTA-2 represents one of the strongest efforts to cope with this type of physics having world-recognized members in all sector (technical and scientific).

6.2 *Strategy*

The SIDDHARTA-2 strategy is a modular strategy extended for duration of at least 5 years:

- install the SIDDHARTA2 Interaction Region and perform the modifications of the DAFNE collider in the SIDDHARTA2 IR (ex DEAR/FINUDA) in the stop after KLOE2-step zero (tentative time end of 2011)

- install the SIDDHARTA-2 setup in 2012 (phase 1: new mechanics and cryogenics, trigger system, active and passive shielding) and run for short periods in sharing mode with KLOE2 as occurred in DEAR-KLOE (adding as soon as possible the new electronics and Si-PIN detectors)

- going to operate the region under the beam pipe to perform measurements for high energy (hundreds of keV), as soon as a setup will be ready for this type of measurements

- going to perform measurements in the MeV range (see Sections 4.4.3 and 5.3.2) when detectors available

The strategy for the first measurement campaign is obviously the measurement of kaonic deuterium.

Based on the SIDDHARTA findings, the actual S/B rate for KH is at the level 1/5, meaning an S/B ratio for Kd at the level 1/50-1/100 (lower yield and larger width). With the factors gained from the setup improvement, the S/B for Kd is becoming 1/5-1/10, making a measurement in the range of a few 10 eV precision feasible for an integrated luminosity of about 600 pb^{-1} , which could then become the first good measurement of Kd ever performed.

The other campaign measurements will be dedicated to:

- kaonic helium measurements to 1s levels, and kaonic oxygen, needing estimated total integrated luminosities of the order of 500 pb^{-1}

- solid target measurements : Sn, Si, Ca, Ni targets, for estimated about 500 pb^{-1}

- MeV measurements for kaon absorption in hydrogen (re-measuring kaonic hydrogen as well)

- Measurements with a setup below the beam pipe could be done in parallel with the others measurements, as soon as a preliminary setup will be ready: among these measurements, for the reasons explained in Chapter 4, we shall give priority to the kaonic lead measurements.

- crystal spectrometer measurements need completely new setup – the strategy is under evaluation.

In Conclusion, the overall strategy of SIDDHARTA2 foresees a strategy of measurements with different periods of data taking, extending from 2012 till the end of KLOE2 data taking (continuing eventually in parallel with the AMADEUS data taking). This strategy can be then further extended, as function of the findings and of beam availability.

Chapter 7 – CONCLUSIONS

The SIDDHARTA2 proposal has the huge potential to be the **decisive experiment** in the sector of kaonic atoms measurements. Such measurements are **fundamental in understanding QCD behaviour in the low-energy strangeness sector**. The only existing competitor, JPARC, is going to perform Kaonic Helium 3 measurement to the 2p level in the near future, with the aim to arrive at a precision below 2 eV. SIDDHARTA-2 plans to go much further: to perform series of measurements in the keV range for kaonic atoms, s**tarting with the fundamental kaonic deuterium one,** using gaseous (so no Compton effects of resulting X-rays) targets and complement with solid targets. Eventually, SIDDHARTA-2 is going to extend the range of measurements for heavier targets, and will contribute so to the solution of old pending puzzles (see Chapter 4) or giving a new value for the charged kaon mass – with far reaching implications in sectors of particle and fundamental physics.

SIDDHARTA-2 is having ambitious goals, extended to many years time schedule, with a **modular strategy**.

The SIDDHARTA-2 setup implements the present SIDDHARTA setup with new features, being at frontier in all sectors (cryogenic, electronics and trigger). The collaboration has the competence and the capacity to do all what is presented in this proposal.

It is a broad international collaboration, having the main worldwide recognized representatives in the experimental sector of exotic atoms physics. The scientific programme is pursued in collaboration with the best theoreticians working in the field.

Moreover, SIDDHARTA-2 is going to take advantage of two of the HadronPhysics2 FP7 initiatives: the LEANNIS WP9 Network, and the SiPM WP28 Joint Research Activity. We plan as well to apply to the new HadronPhysics3 call (just coming these months) both for physics (continuation and upgrade of LEANNIS) and detectors.

DAΦNE represents (as always did) an EXCELLENT FACILITY in the sector of low-energy interaction studies of kaons with nuclear matter. It is actually the IDEAL facility for kaonic atoms studies and the SIDDHARTA-2 collaboration, with its broad international nature, is convinced that NOW AND HERE the measurements could be done (or else the future in this sector might remain open, with all its fundamental implications).

Acknowledgements

The SIDDHARTA2 Collaboration is very grateful to the DAΦNE staff for the continuous support and help not only in running DEAR and SIDDHARTA, but in having it made possible to pursue the adventure by proposing the SIDDHARTA2 measurements. It would have not been possible to arrive at this proposal without the support and imaginative effort from the DAΦNE staff. We thank as well all LNF structures and services – too many to be named – whose contribution was and we are sure, will continue to be fundamental.

We are as well grateful to the LNF-INFN Director, Prof. Mario Calvetti, for his support and continuous encouragement. We acknowledge the INFN support and help.

The SIDDHARTA SC-LNF referees (Profs. Weise and Linde), as all the SC Committee members and SC Chair (Prof. Cavalli Sforza), together with SIDDHARTA referees inside INFN (Dr. Sara Pirrone and Dr. Enrico Scomparin) and the Nuclear Physics group President in INFN, Prof. Angela Bracco, are thanked for their pushing us always to do better.

We acknowledge the support in the framework of EU FP6 and FP7 HadronPhysics and HadronPhysics2 projects.

Last but not least we thank to all our theoretician colleagues and friends, among which: Yoshinori Akaishi, Eli Friedman, Avraham Gal, Jiri Mares, Toshi Yamazaki, Ulf Meissner, Akaki Rusetsky, Ryoichi Seki, Wolfram Weise, Slawomir Wycech.

We thank Prof. Sergio Bertolucci for his support in DEAR and SIDDHARTA.

We thank as well to the following financing agencies: OEAW (SMI), IFIN-HH.

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ANNEX 1 - Letter from the SIDDHARTA Collaboration to DAFNE

Frascati, 19 November 2010

To Resp. Divisione Acceleratori
Dr. Pantaleo Raimondi

Direttore LNF-INFN
Prof. Mario Calvetti

Dear Pantaleo,

based on the success of the SIDDHARTA and DEAR experiments, and considering that DAΦNE was, is and is going to be the *only machine in the world* where the physics of exotic atoms with strangeness (kaonic, sigmonic) can be systematically studied, we kindly ask to you and to the accelerator division *to consider the idea of a second Interaction Point (in ex-FINUDA/DEAR region), where in the future the continuation of exotic atom research can be guaranteed by the installation and run of a SIDDHARTA2 (upgrade of SIDDHARTA) experiment.*

We ask you to consider both the *feasibility* (including *financial* item) and the *impact*, as well as a possible *run scenario* (taking into account that most likely SIDDHARTA2 would run in SIDDHARTA/DEAR – like conditions) and *time-scale*.

Such a possibility would not only constitute an appealing possibility for the field of low-energy strangeness QCD sector, but would keep alive and even reinforce the broad international community interested in this kind of physics.

Confident that you and the accelerator division will find new and exciting solutions along with your tradition, we send you our best regards together with our gratitude for the excellent work done up to now

Carlo Guaraldo,
Spokesperson of SIDDHARTA

Catalina Curceanu
INFN SIDDHARTA responsible

Johann Zmeskal
Technical SIDDHARTA coordinator

Official answer of DAFNE to SIDDHARTA request of considering feasibility of upgraded-SIDDHARTA in the ex-DEAR/FINUDA interaction Region

Frascati, December 17, 2009
prot. n. 0002779-09
To: Siddharta Collaboration
From: Accelerator Division
Object: New Siddharta Run

The Siddharta Collaboration kindly asked to examine the possibility of a new Siddharta Run in Dafne. We have studied the best scenario trying to optimize the: - Compatibility with the Kloe Experiment

- Flexibility in switching between Kloe and Siddharta
- Maximum reuse of the present hardware

The solution we consider consists in installing the present Siddharta Interaction Region in the Finuda (and Dear) IR, without the existing Permanent Magnet Final Doublets (PM-FD) that are reused for the Kloe IR. Such installation can be performed in the Dafne Shut-Down at the beginning of 2011 (roughly after 10months of Kloe data taking), when Kloe will be upgraded. In such way the installation will be completely transparent to the Kloe Experiment in terms of down-time and machine performances for Kloe, since the optic will be unchanged.

For the Siddharta Run we have to reinstall the Siddharta Detector and the PM-FD. The DA will purchase them since we do not want to touch the Kloe-IR. Siddharta will run with the Kloe Detector Off and probably with the Kloe-Solenoid On (to be analyzed) like the Dear Run. Overall Dafne performances for Siddharta should be similar to the present ones. At the end of the run the PM-FD will be removed and Kloe can resume operations without any other hardware modifications (no intervention on the vacuum chamber). The overall cost for the necessary hardware (mainly the PM-FD) will be about 350KEuro. The impact on the Kloe Experiment will be limited to the duration of the Siddharta Run when Kloe will not take data. Overall we can state that if the INFN would like to pursuit such scenario, there is a relatively straightforward solution.

Best Regards, Pantaleo Raimondi

ANNEX 2 – Proposal from S. Wycech to measure kaonic atoms

Extraction of elastic $\bar{\mathrm{K}}$-N scattering amplitudes in the $\Lambda(1405)$ region from upper levels in K^- atoms

S. Wycech

Motivation

Collisions of zero energy $\bar{\mathrm{K}}$ with bound nucleons are described by the scattering amplitude

$$a_{KN}(E = -E_S - E_{recoil}) \tag{1}$$

where the energy in $\bar{\mathrm{K}}\mathrm{N}$ center of mass is given by E_S - the separation energy and E_{recoil} - the recoil energy of the $\bar{K}N$ pair relative to the nucleus.

The energy dependence of Im $a(E)$ reflects the shape of $\Lambda(1405)$. It could by tested in "higher" levels of heavier atoms and in all levels in (H,He) atoms. These involve nucleons of *the same* (or almost the same) separation energies. The E_{recoil} is calculable.

The trend in the existing data is indicated in Table I -bold numbers. The dependence on real potential is calculable and changes little. The cases He, Be, C are close to the peak of $\Lambda(1405)$ $(E_S + E_{recoil} \approx 36, 30, 29)$ MeV.

The effect of peak region is also seen in global fits. Eli Friedman has Im $a = i0.37$fm for upper levels and Im $a = i0.94$ fm for lower widths and shifts, Re $a \approx 0.7$ fm in both cases [N.Ph.A579p518]. Such a difference happens because in lower levels K meson meets nucleons bound more strongly.

Suggestions

• To study $\Lambda(1405)$ measure X rays more precisely in nuclei of strongly bound protons

^{4}He - width

^{9}Be - repetition of the unprecise result

^{16}O , ^{18}O - large binding , extra neutrons , case difficult

• To study K- neutron interactions.

The atomic levels could give $a(neutron) \approx a(neutron)Swave + b(neutron)_{Pwave}2l(l+1)/<R_{capture}>^2$. The P wave contribution due to $\Sigma(1385)$ looks horrible but it is in fact a calculable constant in medium and large nuclei. Im $a(neutron)$ may be obtained from the deuteron but probably more precisely from neutron excess nuclei. The targets of interest are

^{2}H - known

1

^{208}Pb - there is an anomaly in Table I. It yields an excessively large Im $a(neutron)$, but the error is large.

^{112}Sn,^{116}Sn, ^{120}Sn, ^{124}Sn, - the differences could give $a(neutron)$

^{40}Ca .... ^{48}Ca, - similar series

TABLE I: Scattering lengths obtained from upper levels of kaonic atoms versus the proton separation energies E_S. Third column gives experimental level widths. Other columns present Im a extracted from the data under four assumptions : perturbation, optical model with Re $a = 0, -0.5, -0.7 fm$ respectively. These values correspond to central Re $V_{optical} = 0, \simeq -60, \simeq -90$ MeV respectively.

nucleus	E_S	$\Gamma[eV]$	Im $a[fm]$	Im $a[fm]$	Im $a[fm]$	Im $a[fm]$
			impulse	Re $a = 0$	Re $a = -0.5$	Re $a = -0.7$
^{4}He	20	-	-	-	-	-
^{9}Be	16.9	0.04(.02)	**1.39(0.70)**	-	-	-
^{12}C	15.9	0.98(.16)	**1.23(0.25)**	1.45	1.18	1.04
^{24}Mg	11.7	0.08(.03)	**0.40(0.15)**	-	-	-
^{28}Si	11.6	0.53(.06)	**0.52(0.06)**	-	-	-
^{32}S	8.6	3.10(.36)	**0.74(0.08)**	0.95	0.66	0.52
^{27}Al	8.3	0.30(.04)	**0.62(0.08)**	-	-	-
^{112}Sn	7.5	15.1(4.4)	**0.52(0.15)**	-	-	-
^{31}P	7.3	1.44(.41)	**0.64(0.18)**	0.79	0.52	0.35
^{37}Cl	6.4	5.7 (1.5)	**0.60(0.23)**	0.78	0.47	0.32
^{65}Cu	6.1	7.0(3.8)	**0.850(0.45)**	-	-	-
^{113}In	6.1	11.4(3.7)	**0.51(0.33)**	-	-	-
^{107}Ag	5.8	7.3(4.7)	**0.61(0.39)**	-	-	-
^{108}Cd	5.8	6.2(2.8)	**0.32(0.14)**	-	-	-
^{3}He	7	-	-	-	-	-
^{2}H	2	-	-	-	-	-
^{1}H	0	-	**0.31(0.12)**	-	-	-
^{208}Pb	8.0	4.1(2.0))	**1.24(0.60)**	-	-	-
^{238}U	7.6	15.1(4.4)	**1.36(0.39)**	-	-	-

ANNEX 3 - Message from Prof. Ryoichi. Seki related to the importance of charged kaon mass determination

I strongly recommend the precision kaon mass measurement of the SIDDHARTA-2 project with the highest priority.

My reasons are two-fold:

1) The current puzzle of the charged kaon mass is an experimental issue, independent of theoretical interpretations, and it can be resolved only by carrying out careful precision experiments and analyses. SIDDHARTA-2 is in a very good position for realizing this, equipped with the technology much more accurate than the previous one used two decades ago. I must emphasize that such experiments provide an IMMEDIATE, DIRECT merit to the group, as the precise mass determination itself is a discovery, addressing fundamental issues such as the PCT violation.

2) The resolution of the puzzle requires careful assessment of two systematic uncertainties because the mass determination consists of two steps: The first step is the experimental determination of atomic transition energies, and the second is the analysis for extracting the kaon mass from the energies determined. The first step is the critical, purely experimental one, in which the SIDDHARTA-2 setup would play the critical, decisive role. The second step is the theoretical one, using the established techniques of quantum chromodynamics (QED) and of atomic physics, but it must be done with a careful assessment of the systematic uncertainties associated with the analysis. They could contribute appreciably to the precision mass determination and should be treated equally with care. If needed, I could contribute to the SIDDHARTA-2 project on this second step.

The current puzzle is a result of the experiments carried out over more than three decades, and perhaps some historical elaboration of it would help clarifying the issue, especially related to the point 2) above.

In the 2008 edition [Phys. Lett. B667, 1 (2008)], Particle Data Group reports the current world average/fit of the kaon mass based on the six experiments (five kaonic-atomic and one emulsion). The mass is determined only with 32ppm, far cry from charged pions 0.25ppm. Even the phi(1020), the parental particle of the charged kaons at Frascati, is determined with 19.6ppm. As the accompanying note to the Particle Listing by T. G. Trippe clarifies, the current puzzle had been created by the disagreement between the most recent measurements with the small uncertainties of 22ppm and 14ppm claimed [GALL88 and DENISOV91, respectively]. The Trippe note focuses on the first step of the two experiments, but perhaps their second step should also be critically examined on its uncertainties.

The experiment before these experiments was that of a LBL-NBS collaboration [quoted as LUM81 in the PDG table, and published as PRD 23, 2522(1981)], in which I did the second step. Both steps including their uncertainty assessments are spelled out in detail in the publication. Using the best technology available at that time, we reported the total uncertainty of 109ppm, which is large, but with it the mass value was not in disagreement with the current PDG values. Note that prior to GALL88 and DENISOV91, all four (somewhat scattered) measured mass values had no appreciable disagreement.

Before closing, I would like to add a personal note: Our LUM81 uncertainty was large but was an outcome of careful assessment on both steps (Table II explains the assessment of the second step.) The leading experimentalist of LUM81, Prof. Clyde Wiegand, was responsible for the pioneering kaonic atom experiments carried out by the SegrÃ¨-Chamberlain group at LBL since late 50’s, as described in our review [Ann Rev. Nucl. Sci. 25, 241 (1975)]. After working closely with him over several years, with no hesitation I can state that Clyde, my teacher-friend-colleague was a very careful experimentalist. He was a long-term collaborator of Prof. E. SegrÃ¨ and participated in the LBL experiment of the anti-proton discovery.

Summarizing, I believe that the precision kaon mass measurement would be a good oppotunity for the SIDDHARTA group and should be carried out with the highest priority.

Best wishes,
Seki

ANNEX 4 – Proposal of Prof. S. Wycech to measure nuclear capture of kaons by proton with emission of a γ in the range of MeVs

On radiative K-Atom → K-Nucleus transitions.

S. Wycech
Andrzej Sołtan Institute for Nuclear Studies 00-681 Warsaw, Hoza 69, Poland *

(Dated: May 30, 2010)

Radiative transitions from K-mesic atoms to nuclear states of K mesons are discussed. The transition $K^- p \to \gamma\ \Lambda(1405)$ is of particular interest as it could supply information on the $\Lambda(1405)$ structure in the elastic $\overline{K}N$ channel. The rate for this and similar transitions in the deuteron are estimated. A theory for the line shapes is given.

I. INTRODUCTION

The search for deeply bound states of $\overline{K}$ attracts considerable experimental effort in several laboratories [1–3]. The methods used to produce such states involve collision processes with the in flight or stopped particles. These reactions offer several advantages but are characterized by large transfers of momentum. The interesting branching ratios are small, about 10^{-4}. It is shown below that studies of radiative *atom* → *nucleus* transitions may offer comparable or even more convenient ratios of 10^{-4} to 10^{-3}. These transitions will be called γ-ray emissions. Two categories of nuclear states are considered

• S- wave states such as $\Lambda(1405)$ and its analogues in nuclei. These, apparently deeply bound, states are formed by the same S - wave $\overline{K}$-N attraction which forms the $\Lambda(1405)$.

•• Nuclear states built by $\Sigma(1385)$. These are loosely bound with the $\Sigma(1385)$ attached weakly to the nuclear surfaces. The widths are similar to the width of $\Sigma(1385)$

During atomic cascades $\overline{K}$-mesons undergo several types of transitions: the Auger electron emission, the X-ray emission, collision induced transitions, γ-ray emissions and finally the nuclear capture. In this process many atomic states are occupied for a while. From some of these states the γ-ray transitions offer noticeable branching ratios. These are mostly P wave states. The main topic of this work is an estimate of the γ radiative rate relative to the nuclear absorption rate. The simplicity of such calculation is based on the fact that both the nuclear capture rates Γ_{abs} and the γ transition rate Γ_γ involve contraction of large atomic systems to a small nuclear system. As a consequence the ratio $\Gamma_\gamma / \Gamma_{abs}$ depends only weakly on the main quantum number of the atom. On the other hand, this ratio does depend on the structure - in particular on the radius and binding energy - of the nuclear state. For the states of interest in the light K-mesic atoms $\Gamma_\gamma / \Gamma_{abs}$ is shown to reach $\simeq 0.01$. In larger Z atoms these rates seem to drop to 0.001 or less. However, as the nature of K-nuclear states is uncertain, higher angular momentum states are likely and positive surprises are possible.

Electromagnetic cascades in the K^- hydrogen atoms indicate the intensity of the last $2P \to 1S$ transitions to be in the few % range. It is commonly assumed that most of mesons reach high n, S or n, P states and are absorbed by the nucleus. Below it is shown that in gas targets a fraction of 0.0001 to 0.001 of the lost mesons may undergo radiative processes $K^- p \to \gamma\ \Lambda(1405)$, or its nuclear analogues. This offers some chance to study the shape and position of these states.

In the case of hydrogen the transition in question is

$$(K^- p)_{atom} \to \gamma\ \Lambda(1405), \tag{1}$$

where $\Lambda(1405)$ is the "nuclear state" of interest. This state is apparently both the mechanism of $\overline{K}$ meson attraction to nuclei and a doorway state in the formation of deeply bound nuclear states of $\overline{K}$. Thus, it is of prime interest to learn the $\Lambda(1405)$ properties: energy, width and spectral distribution of this quasi-bound state. Strictly speaking the radiative process ends with subsequent decays of $\Lambda(1405)$ to the Σ hyperon and pi meson

$$(K^- p)_{atom} \to \gamma\ \Lambda(1405) \to \gamma\ (\Sigma\pi) \tag{2}$$

which determine the structure of $\Lambda(1405)$ via the shape of spectral lines. The advantage of reaction (2) is that it depends on the properties of $\Lambda(1405)$ in the elastic $\overline{K}N$ channel which is not easy to reach in collisions.

This paper has double purpose :

* wycech@fuw.edu.pl

• determination of the rate for the γ transitions from P and S-wave atomic states.
• determination of the γ line shapes
and the main interest is the hydrogen and deuterium. The third basic question concerns the occupation of these states in the atomic cascade process. It goes beyond the scope of this work, but there exists extensive literature on this subject.

Section II gives the results. All calculations are removed to appendices. These include radiation rates for electric photons (transitions from P-wave atomic states to S-wave nuclear states as well as magnetic photons (transitions $S \to S$ and $P \to P$). The shape of lines are calculated for broad as well as narrow resonances. The standard limits of dipole transitions are obtained to check these calculations against well known results.

II. RESULTS

In the first part of this section the calculated γ radiation rates are presented. These are compared to the absorption rates expected on the basis of $\overline{K}$-N phenomenology. The second part indicates the shape of the γ lines.

The main assumption here is that in the cascade process the K^- meson occupies some n, P states and to a sizable extent is absorbed from these states. That happens at low gas pressure, at least in some cascade models [14],[15]. Similar conclusions are obtained in antiprotonic hydrogen.

A. The γ radiation rates

The first estimate is made with the assumption that $\Lambda(1405)$ is a bound state of the $\overline{K}$ and nucleon. Its wave function is calculated in a simple model (appendix C). For atomic transition of electric type one finds (appendix A)

$$\Gamma_{electric} = \frac{4}{3}\alpha\, k \int d\mathbf{r}\, |\psi_f(r)\, [\, \frac{\exp(-i\mathbf{r}\mathbf{k}\frac{M_N}{M_N+M_K})\mathbf{p}_r}{M_K} + \frac{\exp(-i\mathbf{r}\mathbf{k}\frac{M_K}{M_N+M_K})\mathbf{p}_r}{M_N}]\, \psi_i(r)\, |^2. \tag{3}$$

In this equation $\mathbf{p}_r$ is an operator acting on the relative coordinate in the initial atomic wave function, $\alpha \approx 1/137$ is the fine structure constant ψ_i (ψ_f) is the atomic (nuclear) wave function and M_K, M_N are Kaon and Nucleon masses. The dipole $\Delta l = 1$ limit is not very bad in the atomic hydrogen and the $\Lambda(1405)$ case but fails already in the deuterium. Formula (3) reflects the fact that two particles radiate (Fried Martin factor).

The nuclear absorptions and γ transitions involve contractions of large atomic objects to small nuclear systems. Atomic radii of interest are characterized by $n \cdot B$ where B is the Bohr radius and n is the principal quantum number. In all cases of practical interest $n \cdot B \gg$ *nuclear radius* and one needs to know the atomic wave functions at the nuclear distances only . The radial parts close to the origin are given by

$$R_{n,l}(r) \simeq r^l\, N(n,l) \tag{4}$$

where $N(n,l)$ is a normalization factor. This formula allows to scale the rates with respect to n

$$\Gamma(n,l) = \Gamma(n_{min},l) \cdot [\frac{N(n,l)}{N(n_{min},l)}]^2 \tag{5}$$

where n_{min} is the minimal value of n allowed for a given angular momentum l. This rule works for both the nuclear capture and the γ transition widths. For the lightest elements we need two towers of states : one for $l = 0$ the other one for $l = 1$. It is from these states that the nuclear capture takes place. Thus

$$\Gamma(n, l = 0) = \Gamma(1, S) \cdot \frac{1}{n^3} \tag{6}$$

$$\Gamma(n, l = 1) = \Gamma(2, P) \cdot \frac{32}{3} \cdot \frac{(n-1)(n+1)}{n^5} \tag{7}$$

To obtain the rate one needs only the $2P$ level widths. The numerical values in hydrogen are given in table (I). The $\Gamma_{absorption}$ has been calculated from the $\overline{K}N\Sigma(1385)$ coupling [9]. The $\Gamma_{electric}$ includes also the $1/2$ factor due to the fact that K^-p state is a mixture of isospin 0 and isospin 1 states and $\Lambda(1405)$ has isospin 0. These rates have been calculated with formula (3). More subtle calculations involve the full line shape. Formulas given in appendix

TABLE I: Transition rates from the $2P$ states in K-mesic hydrogen.

$E_B[MeV]$	$\Gamma_{electric}$ $[meV]$	$\Gamma_{electric}/\Gamma_{absorption}$	$\Gamma_{absorption}$ [meV]
27	$1.5 \cdot 10^{-2}$	0.5%	3
12	$3.9 \cdot 10^{-2}$	1.3%	3

and equation (8)of this section indicate enhanced radiation of low energy photons. These enhance the total rate by about 50%.

Table (I) indicates that γ transitions may contribute about one percent of the capture rates in the nP states. Experimental K^- hydrogen data indicate the intensity of the last $2P \to 1S$ transitions to be in the few % range. It is commonly assumed that most of mesons reach high n, S or n, P states and are absorbed by the nucleus. In this way the occupation probability of n, P states is apparently quite large. Some cascade models [14],[15] estimate these at a few percent level at least in dilute gases. All together one could expect the emission of one γ ray per $10^3 - 10^4$ stopped mesons.

Deeply bound states in the KNN system are less certain. Experiments [3][2]indicate existence of a broad state bound by about 100 MeV. Model calculations suggests this state to be isospin $I = 1/2, I^3 = -1/2$ built upon a pair of nucleons with $I_{NN} = 1, I^3_{NN} = 1$, spin $S_{NN} = 0$. The main component "K^-pp" is used frequently as its signature. The isospin brother of this state with the quantum numbers $I_{NN} = 1, I^3_{NN} = 0$, $S_{NN} = 0$ may couple to the deuteron $I_{NN} = 0$,, $S_{NN} = 1$ state. This requires magnetic photon and involves nuclear spin flip transition. The rate is reduced by a factor 1/3 due to the isospin re-coupling but enhanced due to the large photon momentum. The result given in table (II) is obtained with a simple step wave function with the indicated radius mean squared. The rate is small in comparison to the absorption rate. In addition the chances to reach the atomic S states are small. This case seems non-practical.

There is a chance to form another KNN state built with $I_{NN} = 0$,, $S_{NN} = 1$ quantum numbers built with excitations of the $\Sigma(1385)$ state [11]. The formation of such a state is much more frequent. That is also the case even if this state exists only as a virtual state.

TABLE II: Kaonic deuterium transition rates. First line : the magnetic transition from the $1S$ atomic state in K-mesic deuterium atom to the deeply bound state. Second line - the electric transition from atomic $2P$ state to loosely bound $1S$ state built upon $\Sigma(1385)$

E_B [MeV]	$R_{m.s}$[fm]	Γ_γ [eV]	$\Gamma_\gamma/\Gamma_{absorption}$	$\Gamma_{absorption}$ [eV]
100	1.9	$9 \cdot 10^{-2}$	$9 \cdot 10^{-5}$	$1 \cdot 10^{3}$
47	7	$1.8 \cdot 10^{-4}$	$0.6 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$

B. The γ line shape

It is shown in appendix B that the shapes of γ lines in hydrogen for the basic P-wave atom $S \to P$-wave transitions are given by three factors. These are : (1) The absorptive part of the elastic K^-p scattering amplitude $T_{KN,KN}$ extrapolated to the $\Lambda(1405)$ region, (2) The contribution from the photon phase space and (3) The effects of K^-p propagation in the intermediate states. The last two factors strongly deform the Lorentzian shape expected for a quasi-bound state. The main formulas are given in the appendix, here a simplified one is presented, it neglects some recoil and off-shell effects. One has $\Gamma_{electric} = \int\ dk\ S(k)$ where the spectral density is given by

$$S(k) = Im\ T_{KN,KN}(E_{atom} - k)\frac{k}{[(k + B_{atom} + k^2(1/2\mu_{KN} + 1/2M_{KN})]^2} \cdot const. \quad (8)$$

In this expression, k is the photon energy, μ_{KN} and M_{KM} are the reduced and total masses of the KNsystem, B_{atom} is the atomic binding and $E_{atom} = M_K + M_N - B_{atom}$.

The quantity of interest is $Im\ T_{KN,KN}(E_{atom} - k)$ for energies extending below the KN threshold. The resonant peak is strongly deformed but the related factor given by eq.(8) may be calculated with a good accuracy. Experiments would resolve the position of $\Lambda(1405)$ and distinguish the two approaches: the phenomenological one [7],[8] from the chiral one [6],[5],[4]. The two binding energies in table (I) refer to these two cases.

Conclusions

The measurements of radiative transitions to nuclear states of $\overline{K}$ have a fair chance of experimental success. The expected branching may reach 0.001 in some cases. Similar radiative transition $K^-p \to \gamma\ \Sigma(1190)$ was measured with $1 * 10^{-3}$ branching [12] although in ref.[13] the photons from $K^-p \to \gamma\ \Sigma(1385)$ were not detected.

APPENDIX A: RADIATION RATES

This appendix describes the rate for radiative process

$$p\ \bar{K} \to \gamma\ \Lambda(1405). \tag{A1}$$

At first let us calculate the electric transition to $\Lambda(1405)$ understood as a bound state of p and $\bar{K}$, described by a normalized wave function ψ_f. As the radiation width is not given by the standard dipole formula the proper expression is discussed in some detail. The emission of magnetic photons is discussed next. These calculations offer a fair estimate for the rates but cannot predict the line shape. To do that one needs to describe also the decay of $\Lambda(1405)$. Such questions are tackled in the subsequent section, more precise calculations enhance the rates by about 50%.

1. The meson radiates

The meson coupling to radiation is given by Hamiltonian

$$H_E = e\frac{\overrightarrow{A}\,\overrightarrow{p} + \overrightarrow{p}\,\overrightarrow{A}}{2M_m}. \tag{A2}$$

where M_m is the meson mass. The photon vector potential $\overrightarrow{A}$ normalized to one photon per volume V equals

$$\overrightarrow{A}(\mathbf{r}) = \overrightarrow{\varepsilon}\sqrt{\frac{4\pi}{2kV}}\exp(-ikt)\exp(-i\mathbf{kr}) + \overrightarrow{\varepsilon}\sqrt{\frac{4\pi}{2kV}}\exp(-ikt)\exp(i\mathbf{kr}). \tag{A3}$$

In these equations $(\mathbf{k}, \overrightarrow{\varepsilon})$ are the photon momentum and polarization, the electric charge is given by $e^2 = \alpha \approx 1/137$
The initial wave function

$$\Psi_{atom} = \psi_i(\mathbf{r}_n - \mathbf{r}_m), \tag{A4}$$

and the final wave function is

$$\Psi_f = \exp(-i\mathbf{P}_f\mathbf{R})\psi_f(\mathbf{r}_n - \mathbf{r}_m) \tag{A5}$$

where $\mathbf{r}_n$ $(\mathbf{r}_m)$ denote the coordinates of the proton (meson). The C.M. coordinate $\mathbf{R} = \mathbf{r}_n\ \vartheta_n + \mathbf{r}_m\ \vartheta_m$ with $\vartheta_n = M_n/(M_n + M_m)$, $\vartheta_m = 1 - \vartheta_n$.
The relevant transition matrix consists of two terms

$$(\Psi_f|\overrightarrow{A}\,\overrightarrow{p} + \overrightarrow{A}\,\overrightarrow{p}|\Psi_i) = 2\,\overrightarrow{p}_i(\Psi_f|\overrightarrow{A}|\Psi_i) + (\Psi_f|[\overrightarrow{p}\,\overrightarrow{A}]|\Psi_i) \tag{A6}$$

where $\overrightarrow{p}$ denotes the corresponding momentum operator for the meson. The second term vanishes since $\overrightarrow{p}\,\overrightarrow{A} \sim \overrightarrow{k}\,\overrightarrow{\epsilon} = 0$. In more detail

$$(\Psi_f|H_E|\Psi_{atom}) = -e\sqrt{\frac{4\pi}{2kV}}\int d\mathbf{R}\exp(-i\mathbf{R}(\mathbf{k}+\mathbf{P}_f))\ \int d\mathbf{r}\psi_f(r)\exp(-i\mathbf{r}\mathbf{k}\vartheta_n)\frac{\overrightarrow{\varepsilon}\,\overrightarrow{p}_i}{M_m}\psi_i(r). \tag{A7}$$

where $\mathbf{r} = \mathbf{r}_n - \mathbf{r}_m$. The center of mass is factored out and

$$(\Psi_f|H_E|\Psi_{atom}) = -e\sqrt{\frac{4\pi}{2kV}}\ (2\pi)^3\delta(\mathbf{P}_f + \mathbf{k})\ \int d\mathbf{r}\psi_f(r)\exp(-i\mathbf{r}\mathbf{k}\vartheta_n)\frac{\overrightarrow{\varepsilon}\,\overrightarrow{p}_i}{M_m}\psi_i(r). \tag{A8}$$

The radiation probability is now obtained as

$$\Gamma = 2\pi\delta(B_f - B_i - \frac{P_f^2}{2M_f} - k)\ \Sigma_\epsilon\ |(\Psi_i|H_E|\Psi_f)|^2\frac{d\mathbf{k}d\mathbf{P}_f}{(2\pi)^3\ (2\pi)^3} \tag{A9}$$

where B_i is the initial atomic and B_f the final nuclear binding energy. Now,the integration over P_f is performed against the momentum conservation delta in Eq.(A8), another momentum conservation delta is reduced by the volume $V \simeq (2\pi)^3\delta(0)$. The average over the photon direction and the summation over photon polarization τ involves

$$\Sigma_\tau \ < \overline{\epsilon}_i^\tau \epsilon_j^\tau >= \delta_{ij}/3 \ \Sigma_\tau \ |\epsilon^\tau|^2 = 2/3\delta_{ij}. \tag{A10}$$

With the phase space element

$$\delta(\Delta - k)\frac{d\mathbf{k}}{(2\pi)^3} = \frac{4\pi\Delta^2}{(2\pi)^3}, \tag{A11}$$

one obtains

$$\Gamma = \frac{4}{3}\alpha \ k \mid \int d\mathbf{r} \ \exp(-i\mathbf{r}\mathbf{k}\vartheta_n) \ \psi_f(r)\frac{\mathbf{p}_m}{M_m} \ \psi_i(r)|^2. \tag{A12}$$

In the limits of small photon momentum $k \to 0$ and $\vartheta_n \to 1$ (heavy nucleus) equation (A12) reduces to the known dipole formula

$$\Gamma_{dipole} = \frac{4}{3}\alpha \ (B_f - B_i)^3 \mid \int \ d\mathbf{r} \ |\psi_f(r)\mathbf{r}\psi_i(r)|^2, \tag{A13}$$

but such limits are not justified in the transitions studied.

2. The nucleus radiates

For radiating proton an additional magnetic part of H_γ is needed and this coupling differs by the sign of e in Eq.(??)

$$H_\gamma = -e\frac{\overrightarrow{A}\overrightarrow{p} + \overrightarrow{p}\overrightarrow{A}}{2M_n} - e(1+\kappa_1)\frac{\overrightarrow{\sigma}(\overrightarrow{\partial} \times \overrightarrow{A})}{2M_n} = H_E + H_M \tag{A14}$$

where the anomalous part of the proton magnetic moment is denoted by $\kappa_1(proton) = 1.792.\kappa_1(neutron) = -2.191$ Since the meson and proton momenta are opposite both electric transitions act coherently. Repetition of the steps (A3-A13) yields the widths of electric transitions

$$\Gamma_{electric} = \frac{4}{3}\alpha \ k \ \int d\mathbf{r} \ \psi_f(r)[\frac{\exp(-i\mathbf{r}\mathbf{k}\vartheta_n)\mathbf{p}_r}{M_m} + Z\frac{\exp(-i\mathbf{r}\mathbf{k}\vartheta_m)\mathbf{p}_r}{M_n}\psi_i(r)|^2. \tag{A15}$$

In this equation $\mathbf{p}_r$ is an operator acting on the relative coordinate in the initial atomic wave function. For generality reasons the nuclear charge Z was introduced. In the dipole limit $k \to 0$ the term in square brackets reduces to the Fried-Martin factor[16].

APPENDIX B: THE LINE SHAPE

For a narrow unstable state the shape of atomic lines is expected to be Lorentzian. For a broad state, in particular for a broad states close to threshold, this is no longer true. This point is discussed below in the case of two-channel systems. The channels denoted by i, j consist of the initial KN and the decay $\Sigma\pi$ hyperon-pion channel. The reaction under consideration is

$$p \ \bar{K} \to \gamma \ (p\bar{K}) \ \to \gamma \ (\Sigma\pi) \tag{B1}$$

Interactions that take place after the photon is emitted are described by a 2×2 scattering matrix with elements $T_{KN,NK}, T_{KN,\Sigma\pi}, T_{\Sigma\pi,\Sigma\pi}$. These matrices are generated by some basic interactions, possibly by a potential 2×2 matrix $V_{i,j}$. For a general discussion of the line shape one needs T off-energy and off-momentum shell i.e. $T_{i,j}(q, E, q')$. This may be calculated in terms of potential models, but in the case of chiral theories only the energy off-shell extension $T_{i,j}(E)$ is known. For such a situation the zero range force limit is assumed. To find the line shapes such a limit is satisfactory, due to very short interaction ranges. For the sake of presentation, the Fourier transforms to space coordinates $T_{i,j}(u, E, u')$ will also be used. We have

$$T_{i,j}(q, E, q') = \int du \int du' \ \exp(i\mathbf{q}\mathbf{u})T_{i,j}(u, E, u')\exp(-i\mathbf{q}\mathbf{u}). \tag{B2}$$

These matrices are defined in a manner characteristic for potentials. The relation to scattering amplitudes $f_{i,j}(q,E,q')$ which have the dimension of length is

$$T_{i,j}(p,E,p') = \sqrt{\frac{4\pi}{2\mu_i}}\ f_{i,j}(q,E,q')\ \sqrt{\frac{4\pi}{2\mu_j}} \tag{B3}$$

where μ are reduced masses in the corresponding channels.

1. The electric photon

To present the method the simplest case of radiating meson is discussed first. The transition (B1) is described by the amplitude

$$F_{decay} = (\Psi_f|\ T_{\Sigma\pi,KN}\ G_{KN}\ H_E\ |\Psi_{atom}) \tag{B4}$$

where G_{KN} describes the propagation of the KN system after the photon emission and the transition part of scattering matrix $T_{\Sigma\pi,KN}$ is expected to be dominated by the $\Lambda(1405)$ resonant state. The relevant momenta are denoted by: $\mathbf{k}$-the photon momentum, $\mathbf{q}_f$- the $\Sigma\ \pi$ relative momentum, $\mathbf{P}_f$- the total momentum of KN (and $\Sigma\pi$) pair. To calculate F_{decay} one needs several integrations

$$F_{decay} = \int (\Psi_f(\mathbf{R},\mathbf{u}) T_{\Sigma\pi,KN}(u,u') G_{KN}(\mathbf{u}'-\mathbf{r}) H_E(\mathbf{R},\mathbf{r}) \Psi_{atom}(\mathbf{r}). \tag{B5}$$

to be performed over the repeated space coordinates. The final state wave function

$$\Psi_f = \exp(-i\mathbf{P}_f\mathbf{R})\exp(-i\mathbf{q}_f\mathbf{u}), \tag{B6}$$

allows the baryon-meson center of mass motion may be factored out. Thus

$$F_{decay} = e\sqrt{\frac{4\pi}{2kV}}\ (2\pi)^3\delta(\mathbf{P}_f+\mathbf{k})\ F_{cm}. \tag{B7}$$

and the transition inside the baryon-meson system is given by factor

$$F_{cm} = -\int d\mathbf{r} \int d\mathbf{u'} \int d\mathbf{u} \exp(-i\mathbf{u}'\mathbf{q}_f)\ T_{\Sigma\pi,KN}(u,E_{KN},u')\ G_{NK}(\mathbf{u}'-\mathbf{r})\exp(-i\mathbf{r}\mathbf{k}\vartheta)\frac{\overrightarrow{\varepsilon}\overrightarrow{p}}{M_K}\ \Psi_{atom}(\mathbf{r}). \tag{B8}$$

The initial energy of the atom is $E_i = M_p + M_K - B_{atom}$, where B_{atom} is the atomic binding. As the total momentum conservation given by eq.(B7) yields $\mathbf{P} = -\mathbf{k}$ the energy of intermediate KN pair in its center of mass is

$$E_{KN} = M_p + M_K - k^2/2M_{KN} - k \tag{B9}$$

where $k^2/2M_{KN}$ is the recoil energy of the atom. In the KN center of mass system the kinetic energy is negative

$$\varepsilon_{KN} = -B_{atom} - k^2/2M_{KN} - k. \tag{B10}$$

and the propagator

$$G_{NK}(\mathbf{u}'-\mathbf{r}) = \int \frac{d\mathbf{q}}{(2\pi)^3}\ \frac{\exp(i\mathbf{q}(\mathbf{u}'-\mathbf{r}))}{\varepsilon_{KN}-\varepsilon_{KN}(q)}, \tag{B11}$$

where $\varepsilon_{KN}(q) = q^2/2\mu KN$, is exponentially damped in space. The integrations over u, u' yield

$$F_{cm} = \int \frac{d\mathbf{q}}{(2\pi)^3}\frac{T_{\Sigma\pi,KN}(q_f,E^{CM},q)}{\varepsilon_{KN}(q)-\varepsilon_{KN}}\ \int d\mathbf{r}\exp(i(\mathbf{k}\vartheta-\mathbf{q})\mathbf{r})\ \frac{\overrightarrow{\varepsilon}\overrightarrow{p}}{M_K}\ \Psi_{atom}. \tag{B12}$$

The atomic states of prime interest are the P wave states. For an m-th component of such a state one has $\Psi_{atom}(\mathbf{r})^m = \mathbf{r}^m\ \varphi(r)$. For large atoms the radial function $\varphi(r)$ changes slowly and

$$\overrightarrow{\varepsilon}\overrightarrow{p}\ \Psi_{atom}(\mathbf{r})^m = \varepsilon^m\ \varphi(r)_{atom}\ (1+O(r/B)). \tag{B13}$$

For hydrogen the r/B terms are small. The second integration in equation (B12) yields essentially $(2\pi)^3\ \delta(\mathbf{k}\vartheta - \mathbf{q})$ since for photons of large energies $k > 1/B$ the long tailed $\varphi(r)_{atom}$ brings negligible momenta. One obtains

$$F^m_{cm} = \frac{T_{\Sigma\pi,KN}(q_f, E^{CM}, k\vartheta)}{B_{atom} + k^2/2M_{KN} + (k\vartheta)^2/2\mu_{KN} + k}\ \varepsilon^m\ \varphi(0) \tag{B14}$$

Two factors given in this equation are essential to understand the line shape. The one looked for is due to the singularity in the $T_{\Sigma\pi,KN}(E^{CM})$ which describes $\Lambda(1405)$. It generates a line of Lorentzian type. The second factor is due to the propagator of intermediate KN system i.e the denominator in eq.(B14). For small photon momenta it increases approaching the region known as "infrared catastrophe" which happens in the emission of low energy photons by systems of continuous energy spectrum. In our case the real catastrophe is not met as the increase in F_{cm} of eq.(B14) stops at $k \sim B_{atom}$ that is at few KeV. For $k < B_{atom}$ there exists another cutting factor due to the momentum distribution in the $\varphi(r)_{atom}$ which is neglected in eq.(B14). In the nuclear region of interest (large k) the propagator enhances the left shoulder of line.

The knowledge of F_{decay} allows one to find the full shape of atomic line. The rate of decay (B1) is given by

$$\Gamma_{decay} = 2\pi \int \delta(E_i(KN) - E_f(\Sigma\pi) - k)\ \Sigma_\epsilon\ |F_{decay}|^2 \frac{d\mathbf{k}\ d\mathbf{P}_f}{(2\pi)^6} \frac{d\mathbf{q}_f}{(2\pi)^3}. \tag{B15}$$

Within the integral over the final phase space one can single out that part which describes the $KN \to \Sigma\pi$ transition in the corresponding center of mass system. In the two channel system, below the KN threshold on has the optical theorem (unitarity relation)

$$\int \frac{d\mathbf{q}_f}{(2\pi)^3} T_{\Sigma\pi,KN}(q, E^{CM}, q_f)^* \delta(E_i(KN) - E_{\Sigma\pi}(q)) T_{\Sigma\pi,KN}(q_f, E^{CM}, q) = \ 2\ Im\ T_{KN,KN}(q, E^{CM}, q) \tag{B16}$$

which is valid on-shell i.e. for momenta related to energies. In this work very small corrections related to the off-momentum shell extensions will not be discussed. These are of the order $(kR_i)^2 < 10^{-2}$ where $R_i < 0.8$ fm is the interaction range in the meson baryon system.

The radiation probability is now obtained as

$$\Gamma_{decay} = \int S(k)\ dk \tag{B17}$$

with the spectral density given by

$$S(k) = k\ ImT_{KN,KN}(E^{CM}) \frac{C_{atom}}{(k + B_{atom} + k^2/2M_{KN} + (k\vartheta)^2/2\mu_{KN})^2}. \tag{B18}$$

The constant determined by the normalization of the atomic wave function is

$$C_{atom} = e^2 \frac{2}{\pi} (\frac{\varphi(0)}{M_K})^2 \tag{B19}$$

The shape of the electric transition line is determined by three factors : the shape of resonance, phase space for photon emission and the effects related to infrared catastrophe. The two last factors deform strongly the typical Lorentzian line shape. The residual part of this section finds

2. The limit of a very narrow state

In the case of strong dominance of the quasi-bound state, the transition matrix may be presented as an operator

$$\hat{T}_{KN,\Sigma\pi}(E) = \frac{V_{KN,KN} \mid \Phi >< \Phi \mid V_{KN,\Sigma\pi}}{E - E_{qbs} + i\Gamma_{qbs}/2} \tag{B20}$$

where E_{qbs} and Γ_{qbs} are the position and width of the quasi-bound state, $\mid \Phi >$ is the quasi-bound state wave function. The width is determined by the condition

$$\Gamma_{qbs} = \int \frac{d\mathbf{q}_f}{(2\pi)^3} \mid < \Phi \mid V_{KN,\Sigma\pi} | q_f > |^2 \delta(\varepsilon_{\Sigma\pi} - \varepsilon_{\Sigma\pi}(q_f)) \tag{B21}$$

In the limit of a very narrow state the decay channel is almost decoupled and has negligible effect on the structure of $\mid \Phi >$. Hence

$$G_{KN}(E_{qbs})V_{KN,KN} \mid \Phi >=\mid \Phi > \tag{B22}$$

This relation eliminates the free spectrum in the intermediate KN states and removes the enhanced emission of low energy photons. Introducing equations (B20) to (B22) into formula (B12) and using the integral

$$\int dk \frac{\Gamma}{(E-k)^2+\Gamma^2} = 2\pi \tag{B23}$$

one recovers equation (A12) for the radiative width.

3. Magnetic transitions

In the hydrogen case the magnetic transitions from atomic S states to $\Lambda(1405)$ seem negligible due to apparent lack of spin structure. In the case of Kaonic deuterium such transitions are possible since the spin state of deuteron $S_{NN}=1$ differs from the spin state different from the $S_{NN}=0$ spin state in the deeply bound "K^-pp" system. The electric photon coupling factor $-\vec{\varepsilon}\,\vec{p}_i/M$ is changed to

$$\vec{\varepsilon}\,\vec{p}_i/M \longrightarrow i\ [[(1+\kappa_1)_p\vec{\sigma}_p + (1+\kappa_1)_n\vec{\sigma}_n]\ \times \vec{k}]\,\vec{\epsilon}/2M \tag{B24}$$

It gives transitions from spin singlet to spin triplet states. The shape of magnetic line is also different . One has now

$$S_{magnetic}(k)\ \sim\ S(k)\ k^2. \tag{B25}$$

APPENDIX C: A SIMPLE WAVE FUNCTION FOR $\Lambda(1405)$

The separable model is used to describe formation of $\Lambda(1405)$ as a bound state of $\overline{K}N$ pair. The potential which depends on relative $N-\overline{K}$ coordinate is given in momentum space by

$$V(k,k') = \alpha v(k)v(k') \tag{C1}$$

where Yamaguchi form-factors $v(k) = \beta^2/(\beta^2+k^2)$. One free parameter α is chosen to reproduce the separation energy of two approaches : the phenomenological one and the chiral one. The range parameter β is adopted from more involved multiple channel descriptions. It ranges between 3.5 to 6 fm, here we use $3.8fm$[10] although for our purposes the actual value of $\beta$is not relevant. Standard calculations generate off-shell scattering amplitude

$$f_{KN} = \frac{v(k)v(k')}{\alpha^{-1}+G(E)}. \tag{C2}$$

With the non-relativistic form of the kinetic energy $E_{kin} = q^2/(2\mu_{KN})$ one obtains

$$G(E) = \int d\tau \frac{\mathbf{v(t)^2}}{2\pi^2(\tau^2-\mathbf{q}^2)} = \frac{\beta}{\mathbf{2(1-iq/\beta)^2}}. \tag{C3}$$

Below the threshold $1/\beta + G$ is forced to have a zero corresponding to the bound state. The imaginary momentum at this point is

$$p_B = (\frac{\alpha\beta^3}{2})^{1/2} - \beta = \sqrt{2M_rE_B} \tag{C4}$$

where E_B is the separation energy and M_r is the reduced mass for $\overline{K}N$ pair. The wave function is of the Hulthe'n form

$$\Psi_B = N\frac{\exp(-\alpha\ r)-\exp(-\beta\ r)}{r}, \quad N = \sqrt{\frac{2\alpha\beta(\alpha+\beta)}{4\pi(\beta-\alpha)^2}} \tag{C5}$$

TABLE III: Separable model parameters for the isospin 0 KN system.

$E_B[MeV]$	$\kappa[fm^{-1}]$	$\alpha[fm^{-1}]$	
27	3.8	0.669	phenomenological
12	3.8	0.446	chiral

Two results are collected in Table III.

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