ASTRA: Advances and open problems in low-energy nuclear and hadronic STRAngelessness physics

From SIDDHARTA to SIDDHARTA-2

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INFN-LNF

on behalf of SIDDHARTA/SIDDHARTA-2 collaborations

23 – 27 October 2017
Trento, Italy
SIDDHARTA Collaboration

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SIDDHARTA data taking campaign: ended in November 2009

K-He4 data without Fe source

DAΦNE shutdown in Summer

New alignment of setup → Improve S/N ratio

K-He3 data (~4days)

SIDDHARTA performed kaonic atoms transitions measurements on the upgraded DAΦNE collider
The scientific aim

SIDDHARTA measures the X-ray transitions occurring in the cascade processes of kaonic atoms.

Fundamental study of strong interaction between anti-K & nucleus at low energy limit.
The scientific aim

the determination of the isospin dependent KN scattering lengths through a ~ precision measurement of the shift and of the width of the Kα line of kaonic hydrogen and the first measurement of kaonic deuterium
Kaonic Hydrogen atoms

Strong Interaction causes:
- Energy shift $\varepsilon$ of the last energy levels form their purely electromagnetic values AND
- Level width $\Gamma$ finite lifetime of the state corresponding to an increase in the observed level width

$\varepsilon = E_{2p \rightarrow 1s}^{\text{exp}} - E_{2p \rightarrow 1s}^{\text{e.m.}}$

$E(\text{e.m.}) \approx \frac{1}{2} \mu c^2 (Z\alpha)^2 \cdot \left[ \frac{1}{n_i^2} - \frac{1}{n_f^2} \right]$
In the framework of the SIDDHARTA experiment we have performed:

- the measurements related with the Kaonic helium transition to the 2p level (L-lines)
  - for first time in a gaseous target for $^4$He
  - for the first time ever for $^3$He
- Other low-Z kaonic atom transitions (kaonic kapton)
- Yields measurements (kaonic atoms cascade processes)
**SIDDHARTA results:**


- **Kaonic deuterium**: 100 pb$^{-1}$, as an exploratory first measurement ever, Nucl. Phys. A907 (2013) 69; Ph D


- **Kaonic helium 3** – 10 pb$^{-1}$, first measurement in the world, published in Phys. Lett. B 697 (2011) 199; Ph D


**SIDDHARTA – important TRAINING for young researchers**
**SIDDHARTA results: KH (2009)**

\[ \varepsilon_{1S} = -283 \pm 36\text{(stat)} \pm 6\text{(syst)} \text{ eV} \]

\[ \Gamma_{1S} = 541 \pm 89\text{(stat)} \pm 22\text{(syst)} \text{ eV} \]

Gas target (22 K, 2.5 bar)
144 SDD used as X-ray detector
Good energy resolution (140eV @ 6 keV)
Timing capability (huge background)

Drastically improved S/B ratio
SIDDHARTA results: KH (2009)

\[
\begin{align*}
\epsilon_{1s} &= -283 \pm 36 \text{(stat)} \pm 6 \text{(syst)} \text{ eV} \\
\Gamma_{1s} &= 541 \pm 89 \text{(stat)} \pm 22 \text{(syst)} \text{ eV}
\end{align*}
\]
SIDDHARTA results: KH (2009)

most reliable and precise measurement ever

→ new constraints on theories

$\varepsilon_{1s} = -283 \pm 36{\text{(stat)}} \pm 6{\text{(syst)}}$ eV

$\Gamma_{1s} = 541 \pm 89{\text{(stat)}}$ eV $\pm 22{\text{(syst)}}$ eV
SIDDHARTA results: $K^{-4}\text{He}$

Energy of $K^4\text{He} \ L_\alpha (3d \rightarrow 2p)$ line: $E_{\text{exp}} = 6463.6 \pm 5.8 \text{ eV}$

$E_{\text{e.m.}} = 6463.5 \pm 0.2 \text{ eV}$

$\Delta E = E_{\text{exp}} - E_{\text{e.m.}} = 0 \pm 6\text{(stat)} \pm 2\text{(syst)} \text{ eV}$

PLB 681 (2009) 310
Summary of the K-\(^4\)He shifts

for first time in a gaseous target for \(^4\)He
Target material: Kapton Polymide ($C_{22}H_{10}N_2O_5$)

World First! for the first time for $^3$He

SIDDHARTA results: $K^-^3$He

- $E_{\text{exp}} = 6223.0 \pm 2.4 \text{(stat)} \pm 3.5 \text{(syst.)} \text{ eV}$
- $E_{\text{e.m.}} = 6224.6 \text{ eV}$
- $\epsilon = \Delta E_{2p} = E_{\text{exp}} - E_{\text{e.m.}} = -2 \pm 2 \text{(stat)} \pm 4 \text{(syst)}$
K-p puzzle arose!

1970
- C.E. Wiegand (1971)

1980
- J.D. Davies (1979)
- M. Izycki (1980)
- P.M. Bird (1983)
- C.J. Batty (1979)
- S. Baird (1983)

1990

2000

2010

K-He puzzle arose!
K-p
1970
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S. Baird (1983)
1990
Significant improvement!
KpX @ KEK (1997)
DEAR @ DAΦNE (2005)
SIDDHARTA @ DAΦNE (2011)
2000
E570 @ KEK (2007)
SIDDHARTA (4He) @ DAΦNE (2009)
SIDDHARTA (3He) @ DAΦNE (2011)
2010
the measurement of the kaonic deuterium
the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions

SIDDHARTA-2 collaboration
starting from 2019 at DAFNE accelerator
SIIDHARTA-2
Silicon Drift Detector for Hadronic Atom Research by Timing Applications

- LNF - INFN, Frascati, Italy
- SMI - ÖAW, Vienna, Austria
- IFIN – HH, Bucharest, Romania
- Politecnico, Milano, Italy
- TUM, Munchen, Germany, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada
- Univ. Zagreb, Croatia
- Helmhotlz Inst. Mainz, Germany
- The Jagiellonian University, Poland
To perform precision measurements of kaonic atoms X-ray transitions

- unique information about QCD in the non-perturbative regime in the strangeness sector not obtainable otherwise

Starting with the precision measurement of shift and width of kaonic hydrogen

- NOW first measurement of kaonic deuterium

To extract the antikaon-nucleon isospin dependent scattering lengths

- chiral symmetry breaking (mass problem), EOS for neutron stars
Deser-type relation (including the isospin-breaking corrections) connects shift $\varepsilon_{1s}$ and width $\Gamma_{1s}$ to the real and imaginary part of $a_{K-p}$:

$$\varepsilon_{1s} + \frac{i}{2} \Gamma_{1s} = 2\alpha^3 \mu^2 a_{K-p} \left[ 1 - 2\alpha \mu (\ln \alpha - 1) a_{K-p} + \ldots \right]$$

A similar formula holds for $a_{K-d}$:

$$\varepsilon_{1s} + \frac{i}{2} \Gamma_{1s} = 2\alpha^3 \mu^2 a_{K-d} \left[ 1 - 2\alpha \mu (\ln \alpha - 1) a_{K-d} + \ldots \right]$$

The connection between the scattering lengths $a_{K-p}$ and $a_{K-d}$ and the s-wave KN isospin dependent (I=0,1) isoscalar $a_0$ and isovector $a_1$ scattering length:

$$a_{K-p} = \frac{1}{2} [a_0 + a_1]$$

$$a_{K-n} = a_1$$

$$a_{K-d} = \frac{4[m_N + m_K]}{[2m_N + m_K]} Q + C$$

$$Q = \frac{1}{2} [a_{K-p} + a_{K-n}] = \frac{1}{4} [a_0 + 3a_1]$$

$C$, includes all higher-order contributions, namely all other physics associated with the K-d three-body interaction.
The low energy kaon nucleon interaction is still a largely unexplored experimental field.

The measurement of the strong interaction shift and width is the unique method to precisely determine the kaon-nucleus strong interaction at low-energy limit.

Measuring the KN scattering lengths with the precision of a few percent will drastically change the present status of low-energy KN phenomenology and also provide a clear assessment of the SU(3) chiral effective Lagrangian approach to low energy hadron interactions.

"The most important experiment to be carried out in low energy K-meson physics today is the definitive determination of the energy level shifts in K-p and K-d atoms, because of their direct connection with the physics of the KN interaction and their complete independence of all other kind of measurements which bear on this interaction."

R.H. Dalitz
SIDDHARTA-2, consists in a series of improvements with respect to the SIDDHARTA setup aiming to dramatically:

- increase the S/B ratio and also the signal rate:
  - by gaining in solid angle
  - taking advantage of new SDDs
  and
  - of the reduction of the background:
  - by improving the SDDs timing
  - implementing of an additional veto system.

SIDDHARTA-2 is a development both on the detector side and on target side.
SIDDHARTA Kd exploratory measurement

First exploratory measurement for Kd

\[ Y(K_{\text{tot}}) = 0.0077 \pm 0.0051 \]

Kd K\(\alpha\) yield \[ Y(K_{\alpha}) = 0.0019 \pm 0.0012 \]

Yield of a factor about 10 smaller than the KH yield, estimated to be 1 to 2 % for K\(\alpha\).

an enhancement by one order of magnitude of the signal-to-background ratio is required for SIDDHARTA-2.
The SIDDHARTA-2 setup

- new target cell
- new vacuum chamber
- new cooling system
- new kaon monitor/trigger
- two veto systems
- K⁺ induced backg. veto
- new shielding structure
- new SDD detectors
A new vacuum chamber: to allow adding additional cooling power:
- SDD detectors (a faster answer of SDDs)
- target cooling system (increases the density of the gas-target->the numbers of stopped kaons.

✅ ready and tested
The SIDDHARTA kaon monitor:
scintillator pair, placed above and below the
IP, taking advantage that the \(\phi\)-meson is
decaying almost back-to-back to a \(K^+K^-\)
pair (49.2\%). The \(K^+\) and \(K^-\) are identified
in coincidence in each of the two detectors.

The basic change in the trigger configuration:

- a new shape for the upper scintillator of
  the kaon monitor
- its placement just below the kaon
  entrance window, above the shielding.

With this new position (which was not
possible in SIDDHARTA) only those kaons,
which are reaching directly the entrance
flange of the vacuum chamber will be
selected.

Compared with the “old” geometry, a reduction
of the hadronic and e.m. background is expected.
A thick scintillator (2 cm) will be placed below the lower scintillator of the kaon monitor system to disentangle the K⁺ and K⁻ mesons, based on the timing of the signals related to them.

The additional scintillator ("kaon-stop detector") - detects positively charges kaons by their decay into muons and allows selecting exclusively events in which the K⁺ does not enter the target cell.
Veto system:
- **veto-1**: outer barrel of scintillators, acting as a gas stopping detector (veto counter using the time information, to separate the events: relative long time that a kaon needs to stop in gas compared to the short time which is needed to a negative kaon to get absorbed in a solid (the entrance window of the target or the vacuum chamber)
- **veto-2**: an inner ring of scintillator tiles (SciTiles) placed as close as possible behind the SDDs for charge particle tracking
New SDD detectors

SIDDHARTA:
• JFET integrated on SDD
• lowest total anode capacitance
• limited JFET performance
• sophisticated SDD+JFET Technology

SIDDHARTA-2
• external CUBE preamplifier (MOSFET input transistor)
• larger total anode capacitance
• better than FET performances
• standard SDD technology

2x4 SDD array - single unit

SDD characteristics:
• area/cell = 64 mm²
• total area = 512 mm²
• T = -100°C
• drift time < 500 ns
The 4 x2 SDD array around the target cell

A further main feature is the large active to total area of about 75% (compared to 20% for the SIDDHARTA SDDs).

The new advanced production technology will allow: an efficient detector packing density, covering a solid angle for stopped kaons in a gaseous target cell of $\sim 2\pi$.

48 monolithic SDD arrays will be around the target with a total area of about 246 cm$^2$
**SIDDHARTA—2 final apparatus**

- Veto-1 counter
- Kaon monitor upper scintillator
- Veto-2 counter
- Target cell
- SDDs
- SDD-electronic
- Interaction region
- Kaon monitor lower scintillator
- Kaonstopper: K⁺-K⁻ discrimination
For more details regarding the SIDDHARTA-2 setup

See talk of F. Sirghi on 27/10/2017
The Monte Carlo simulations

Simulation in the framework of GEANT4
The yield of K-d: one order of magnitude below the K-p yield
Machine conditions – similar with SIDDHARTA 2009
The following main improvements are included in the final GEANT 4 simulation for the SIDDHARTA-2 experiment at DAΦNE, LNF-INFN:

- Changed geometry and gas-density: closer distance between IP and target cell, doubled gas density (3%), distance centre to SDDs
- Trigger system: upper kaon monitor (smaller than entrance window) DIRECTLY in front of target
- Added kaon live time detector for K+ discrimination: identification of the K+ by ($\tau_K = 12.8$ ns)
- Veto-1 and veto-2 system
- SDDs operation at lower temperature to improve timing resolution ($\sim 400$ ns)

$S/B = 1/100$ in SIDDHARTA $\Rightarrow$ $S/B = 1/3$ in SIDDHARTA-2
Geant4 simulated K^-d X-ray spectrum for 800 pb^{-1}

**achievable precision:**
- shift: 30 eV
- width: 75 eV

**signal:** shift - 800 eV
- width 800 eV
- density: 3% (LHD)
- detector area: 246 cm^2
- K\alpha yield: 0.1 %
- yield ratio as in K^-p
- S/B ~ 1 : 3

- charged particle veto
- asynchronous BG
DAFNE represents an (THE) 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 as SIDDHARTA has demonstrated.
SIDDHARTA-2 setup ready to be installed on DAΦNE in Summer 2018 and start, for at least one year, the data acquisition.
• Kaon mass precision measurement at the level of < 7 keV (kaon mass puzzle)

• Measuring, with higher precision, the X-ray transitions for Kaonic $^4\text{He}$ and Kaonic $^3\text{He}$ to the 2p level and the first tentative to the 1s level

• Other light kaonic atoms (light and heavy) (ex: K-O, K-C, etc)

• Heavier kaonic atoms (light and heavy) (ex: Si, Pb, etc)

• Investigate the possibility of the measurement of other types of hadronic atoms (sigmonic hidrogen?)
New SIDDHARTA-2 cooling design

**Target cooling:**
1 Leybold – 16 W @ 20 K  
new target cell  
cooling via ultra pure aluminum bars

**SDD cooling:**
4 CryoTiger – 60 W @ 120 K  
Liquid argon cooling lines:  
SDD cooling to 90 – 110 K

✓ cryo coolers available/tested
New SIDDHARTA-2 target prototype
The veto-1 system

Due to the:
- relative long time that a kaon needs to stop in gas compared to the
- short time which is needed to a negative kaon to get absorbed in a solid (the entrance window of the target or the vacuum chamber)
one can realize a veto counter by using this time information, given by an external scintillators array to separate these two types of events.

To achieve a good timing resolution, (independent of the “hit” position, 600 ps FWHM) the scintillator has to be read out on both side. Because the available space is limited due to shielding material, the photomultiplier tubes have to be on the same side (a special light-guide mirror design was used.
The veto-2 system

Veto-2 system is made of plastic scintillator pads read by SiPMs, arranged closely behind the SDDs to discriminate against charge particles hitting the SDDs.

It is planned to use tiles made out of small organic scintillators with sizes of 45 x 30 x 5 mm$^3$, attached to two Silicon Photo-Multipliers (SiPM) with a sensitive area of 4 x 4 mm$^2$, each. The main reasons for choosing organic scintillators are their fast response.
SIDDHARTA-2 setup improvements

• The new target geometry (130 mm diameter and 90 mm height) with the SDDs placed 5 mm from the target → larger solid angle and takes advantage of the flatter distribution of the stopped kaons.

• The new configuration → reduces the number of kaons reaching the target wall and producing background.

• The whole setup was compacted in vertical, to minimize the distance between the interaction point and the entrance window (from 190 to 150 mm) → to increase the acceptance.