Kaonic atoms – studies of the strong interaction with strangeness

J. Marton on behalf SIDDHARTA/SIDDHARTA2
Stefan Meyer Institute, Vienna

MESON, Cracow, May 2014
SIDDHARTA collaboration

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
MPE, Garching, Germany
PNSensors, Munich, Germany
RIKEN, Japan
Univ. Tokyo, Japan
Victoria Univ., Canada

EU Fundings: JRA10 – FP6 - I3HP
Network WP9 – LEANNIS – FP7- I3HP2
Austrian Science Fund

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Content

• Exotic atoms as probes for fundamental interactions
• Results of KH, K$^{3,4}$He experiments
• Open issues: K$^{-}$D measurement, high resolution experiments
• Experimental challenges (yield, background)
• Target and Instrumentation
• Summary and Outlook
What is a exotic (kaonic) atom?

"normal" hydrogen     "exotic" (kaonic) hydrogen

\[ n \approx \sqrt{\frac{m_{\text{red}}}{m_e}} \cdot n_e \]

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Exotic atoms

- Studies of fundamental interactions and symmetries with exotic atomic bound systems

Hadronic atoms are sensitive probes for the strong interaction at lowest energy (direct study of strong interaction at threshold)

- Lamb-shift muonic hydrogen → Proton radius
- Low-energy -QCD Chiral Symmetry Breaking
- Measurement of Particle masses Pion / Kaon Mass
- Electromagnetic Processes μCF, e.m. Cascade
- Fundamental Symmetries Matter-Antimatter
- Quantum-Electrodynamics
- Weak Interaction Muon Capture

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Cascade in hadronic atoms (KH,KD)

\[ n = \begin{cases} 4 & \text{s} \\ 3 & \text{p} \\ 2 & \text{d} \\ 1 & \text{f} \end{cases} \]

\[ \Gamma_{1s} \]

\[ K_\alpha \sim 6.3 \text{ keV} \]

\[ \varepsilon_{1s} = E_{2p-1s} \text{(meas.)} - E_{2p-1s} \text{(e.m.)} \]

observable hadronic shift and broadening

Probing strong interaction at threshold

shift and width of states \( n > 1 \) are negligible

due to the strong interaction kaon-proton the \( 1s \) level is shifted and broadened

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Kaonic hydrogen and deuterium

- Principal interaction = electromagnetic.

- Strong interaction manifests in hadronic shift and width of the 1s state → **energy displacement** from the electromagnetic value of the 1s state and **broadening** due to $K^-$ absorption.

![Energy levels diagram](image)

$$\varepsilon_{1s} = E_{1s}^{\text{meas.}} - E_{1s}^{\text{e.m.}(\text{calc.})}$$

$$E_{1s}^{\text{e.m.}(\text{calc.})} = E_{KG} + E_{VP} + E_{FS}$$

- Calculated solving the Klein-Gordon (KG) equation and taking into account vacuum polarization (VP) and final size (FS) effect (accuracy ~1eV).

- Strong interaction effect on 2p state is weak (meV) and experimentally undetermined, nevertheless has **severe consequences for the x-ray yield.**

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Experiments on kaonic hydrogen

Older experiments used liquid targets which have the disadvantage of lower yields (Stark effect)

KpX, PRL1997  
KEK (K beam)  
Gas target  
Si(Li) detectors

DEAR, PRL2005  
DAFNE (e⁺ e⁻ collider)  
Gas target  
CCD detectors

SIDDHARTA, PLB 2011  
DAFNE (e⁺ e⁻ collider)  
Gas target  
SDD detectors

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Kaonic atoms at DAΦNE/Frascati
SIDDHARTA data overview
Beam pipe in $e^+e^-$ intersection of SIDDHARTA

SIDDHARTA used the KLOE intersection of DAFNE

Luminosity increased with new system providing a large crossing angle (crab waist system)

Kaon detectors sitting below and above the intersection

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SIDDHARTA SDD Array

144 SDDs = 144 cm² active area
Background suppression in SIDDHARTA

Efficient background suppression by using the kaon - x-ray correlation
Comparison kaonic $^3$He and $^4$He

$\Delta E_{2p} = -2 \pm 2(\text{sta}) \pm 4(\text{sys})$ eV

$\Delta E_{2p} = +5 \pm 3(\text{sta}) \pm 4(\text{sys})$ eV

K-4He (3d-2p)

K-3He (3d-2p)

PLB697(2011)199

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## Kaonic helium results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Shift [eV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>KEK E570</td>
<td>+2±2±2</td>
<td>PLB653(2007)387</td>
</tr>
<tr>
<td>SIDDHARTA (He4 with 55Fe)</td>
<td>+0±6±2</td>
<td>PLB681(2009)310</td>
</tr>
<tr>
<td>SIDDHARTA (He4)</td>
<td>+5±3±4</td>
<td>arXiv:1010.4631,</td>
</tr>
<tr>
<td>SIDDHARTA (He3)</td>
<td>-2±2±4</td>
<td>PLB697(2011)199</td>
</tr>
</tbody>
</table>

- calibration under control within several eV

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Yields in kaonic helium atoms

- Study of the x-ray pattern in kaonic helium atoms (transitions to the 2p state)
- First determination of the absolute yields
- Indications of weak molecular Stark mixing
- Data are calling for improved cascade calculations

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**L-series X-ray yields of kaonic $^3$He targets**

The SIDDHARTA Collaboration

<table>
<thead>
<tr>
<th>Transition</th>
<th>$^3$He (0.96 g/l)</th>
<th>$^4$He (1.65 g/l)</th>
<th>$^4$He (2.15 g/l)</th>
<th>$^4$He (Liquid) [1]</th>
<th>$^4$He (Liquid) [3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L\alpha$</td>
<td>25.0$^{+6.7}_{-5.8}$</td>
<td>23.1$^{+6.0}_{-4.2}$</td>
<td>17.2$^{+2.6}_{-0.5}$</td>
<td>9.2 ± 2.4</td>
<td>8.9 ± 4.5</td>
</tr>
<tr>
<td>$L\beta$</td>
<td>3.6$^{+1.3}_{-0.7}$</td>
<td>4.2 ± 1.1</td>
<td>3.1$^{+1.6}_{-0.6}$</td>
<td>5.2 ± 1.3</td>
<td>2.3 ± 1.2</td>
</tr>
<tr>
<td>$L\gamma$</td>
<td>1.3$^{+0.5}_{-0.4}$</td>
<td>1.3 ± 0.6</td>
<td>0.7$^{+0.3}_{-0.0}$</td>
<td>2.4 ± 0.7</td>
<td>1.6 ± 0.8</td>
</tr>
<tr>
<td>$L_{high}$</td>
<td>5.2 ± 2.1</td>
<td>6.9$^{+2.0}_{-1.9}$</td>
<td>4.1$^{+1.1}_{-2.1}$</td>
<td>-</td>
<td>0.4 ± 0.3*</td>
</tr>
</tbody>
</table>

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K^-p result SIDDHARTA

\( \epsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst}) \, \text{eV} \)

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

Physics Letters B704 (2011) 113

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Kaonic atoms with deuterium gas (SIDDHARTA) fit for shift about 500 eV, width about 1000 eV, $K\alpha / K_{\text{complex}} = 0.4$

First exploratory $Kd$ x-ray experiment
Yield of K-series in KD

Preliminary study of kaonic deuterium X-rays by the SIDDHARTA experiment at DAΦNE

M. Bazzi a, G. Beer b, C. Berucci c,a, L. Bombelli d, A.M. Bragadireanu a,e, M. Cargnelli c,a, C. Cerceau (Petrescu) a, A. d’Uffizi a, C. Fiorini d, T. Frizzi d, F. Ghio f, C. Guaraldo a, R. Hayano g, M. Iliescu a, T. Ishiwatari c, M. Iwasaki h, P. Kienle c,i, P. Levi Sandri a, A. Longoni d, J. Marton c, S. Okada h, D. Pietreau a,e, T. Ponta c, A. Romero Vidal i, E. Sbardella a, A. Scordo a, H. Shi g, D.L. Sirghi a,e, F. Sirghi a,e, H. Tatsuno a, A. Tudorache e, V. Tudorache e, O. Vazquez Doce i, E. Widmann c, J. Zmeskal c

Upper limits (90 C.L.) for the x-ray yield (SIDDHARTA)

\[ Y(K_{\text{tot}}) < 0.0143 \]
\[ Y(K_{\alpha}) < 0.0039 \]
Results of SIDDHARTA

**Kaonic Hydrogen:** 400 pb$^{-1}$, most precise measurement, Physics Letters B704 (2011) 113

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


- **Kaonic helium 3:** 10 pb$^{-1}$, first measurement, published in Phys. Lett. B 697 (2011) 199

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Sources of experimental information on $K_{\text{bar}}N$ interaction

- K-p scattering data
  for threshold data extrapolation necessary

- Threshold branching ratios

- Kaonic atom data

Threshold branching ratios

$$\frac{\Gamma(K^-p \rightarrow \pi^+\Sigma^-)}{\Gamma(K^-p \rightarrow \pi^-\Sigma^+)}$$

$$\frac{\Gamma(K^-p \rightarrow \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \rightarrow \text{all inelastic channels})}$$

$$\frac{\Gamma(K^-p \rightarrow \pi^0\Lambda)}{\Gamma(K^-p \rightarrow \text{neutral states})}$$

- Kaonic hydrogen
- Kaonic Deuterium

1s state shift
1s state width

$\rightarrow$ x-ray spectroscopy

Constraints from precise kaonic hydrogen measurements $\rightarrow$ sub-threshold extrapolations of the KbarN amplitude with strongly reduced uncertainties

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Fig. 4. Real part (left) and imaginary part (right) of the $K^- p \rightarrow K^- p$ forward scattering amplitude obtained from the NLO calculation and extrapolated to the subthreshold region. The empirical real and imaginary parts of the $K^- p$ scattering length deduced from the recent kaonic hydrogen measurement (SIDDHARTA [15]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.
Predictions

Real and imaginary part of the $K^-n \rightarrow K^-n$ forward scattering amplitude in the sub-threshold region

Imaginary part of the $I=0$ KbarN and $\Sigma\pi$ amplitudes Error bands due to constraints by SIDDHARTA
Motivation for new experiments

- SIDDHARTA – K-p strong interaction observables
- SIDDHARTA – First exploratory experiment on K^-D

But: No data on hadronic shift and width of 1s state of kaonic deuterium
  → still to be measured

- Study of K-n interaction: Isospin-dependent scattering lengths from KH and KD → K^-p interaction at low energy is well understood, but the case of K^-d represents the most important missing information

- High resolution studies of kaonic atoms (e.g. K-He, heavier kaonic atoms)

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Expected shift and width

<table>
<thead>
<tr>
<th>$a_d$ [fm]</th>
<th>$\varepsilon_{1s}$ [eV]</th>
<th>$\Gamma_{1s}$ [eV]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.58 + i 1.37</td>
<td>- 887</td>
<td>757</td>
<td>Mizutani 2013 [4]</td>
</tr>
<tr>
<td>-1.48 + i 1.22</td>
<td>- 787</td>
<td>1011</td>
<td>Shevchenko 2012 [5]</td>
</tr>
<tr>
<td>-1.46 + i 1.08</td>
<td>- 779</td>
<td>650</td>
<td>Meißner 2011 [1]</td>
</tr>
<tr>
<td>-1.42 + i 1.09</td>
<td>- 769</td>
<td>674</td>
<td>Gal 2007 [6]</td>
</tr>
<tr>
<td>-1.66 + i 1.28</td>
<td>- 884</td>
<td>665</td>
<td>Meißner 2006 [7]</td>
</tr>
</tbody>
</table>

Modified Deser formula next-to-leading order in isospin breaking (Meißner, Raha, Rusetsky 2004 [3])
($\mu_c$ reduced mass of Kd, $\alpha$ finestructure constant )

\[
\varepsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu_c^2 a_d (1 - 2\alpha \mu_c (\ln \alpha - 1)) a_d
\]  

(1)


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Isospin scattering lengths

• The isospin scattering lengths $a_0$ and $a_1$ for $I=0,1$ cannot be determined from $\epsilon_{1s}$ and $\Gamma_{1s}$ from kaonic hydrogen.

• The (modified) Deser-type formula
  
  $\epsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^3 \mu_c^2 a_p \left(1 - 2\alpha \mu_c (\ln \alpha - 1)a_p\right)$

  $a_p = \frac{1}{2}(a_0 + a_1)$

• Kaonic deuterium provides the lacking information
  
  $a_n = a_1$

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

  $Q = \frac{m_N + m_K}{2m_N + m_K}$

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Goal

- Measurement of the shift $\epsilon_{1s}$ and width (broadening) $\Gamma_{1s}$ of the ground state 1s
- Since only the 1s state is measurably affected by strong interaction $\rightarrow$ measured K line energies compared to calculated e.m transition energies yield $\epsilon_{1s}$ and $\Gamma_{1s}$

\[
\epsilon = E_{np \rightarrow 1s} \text{(exp)} - E_{np \rightarrow 1s} \text{(e.m.)}
\]

<table>
<thead>
<tr>
<th>Transition</th>
<th>e.m. energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KD (2-1)</td>
<td>7.808</td>
</tr>
<tr>
<td>KD (3-1)</td>
<td>9.255</td>
</tr>
<tr>
<td>KD (4-1)</td>
<td>9.765</td>
</tr>
<tr>
<td>KD (5-1)</td>
<td>9.994</td>
</tr>
<tr>
<td>KD (6-1)</td>
<td>10.119</td>
</tr>
<tr>
<td>KD (\infty)</td>
<td>10.41</td>
</tr>
</tbody>
</table>

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## Comparison KH-KD

<table>
<thead>
<tr>
<th></th>
<th>Kaonic hydrogen</th>
<th>Kaonic deuterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield (Kα) estimates</td>
<td>3%</td>
<td>0.3% (depending on 2p state width)</td>
</tr>
<tr>
<td>Energy (Kα) e.m.</td>
<td>6.5 keV</td>
<td>7.8 keV</td>
</tr>
<tr>
<td>Shift (1s)</td>
<td>-283±36(stat)±6(syst)</td>
<td>-800 ? (estimate)</td>
</tr>
<tr>
<td>Width (1s)</td>
<td>541±89(stat)±22(syst)</td>
<td>800 ? (estimate)</td>
</tr>
</tbody>
</table>

### Diagrams

- **KH**
  - Data from KEK-PS E228, SIDDHARTA
  - Shift $\varepsilon_{1s}$ vs Width $\Gamma_{1s}$

- **KD**
  - Data from DEAR
  - Shift $\varepsilon_{1s}$ vs Width $\Gamma_{1s}$

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X-ray yields in K-D


KD experiments employing new instrumentation
From SIDDHARTA to SIDDHARTA2

Changes

- Factor 2 in density of deuterium gas
- Kaon trigger geometry and arrangement
- Discrimination $K^+/K^-$ by lifetime detector
- Active shielding of apparatus
- Higher timing resolution of SDDs by cooling

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Lightweight cryogenic target (used for KH)

- working T 22 K
- working P 1.5 bar

- Alu-grid
- Side wall: Kapton 50 µm
- Kaon entrance
- Window: Kapton 75 µm
Plans for SIDDHARTA2 at DAFNE

- new target design
- new SDD arrangement
- vacuum chamber
- more cooling power
- improved trigger scheme
- shielding and anti-coincidence (veto)

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New x-ray detectors

• JFET integrated on the SDD
  - lowest total anode capacitance
  - limited JFET performances
  - sophisticated SDD+JFET technology

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

Used in Siddharta

Proposed for kaonic deuterium measurement

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New SDDs for x-ray detection
(FBK and Politecnico Milano)

Excellent active to total area 85%
→ Large solid angle

Very good energy resolution

Very good timing at low T
SDD Characterization

• Extremely important for precision x-ray spectroscopy

  – Stability
    • Long term monitoring gain and offset
    • Stability under small temperature variations
    • Gain stability at different x-ray rates
  – Linearity
  – SDD time response at various temperatures
  – SDD operation at low temperatures
  – Radiation hardness

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Kaonic deuterium with SIDDHARTA2 at DAFNE

Monte Carlo Simulation for KD in SIDDHARTA2:
Shift: -805 eV
Width: 750 eV
Yield (Kα)=0.001
Luminosity: 800 pb-1

Presision from MC
Shift: 70 eV
Width 150 eV


We expect to measure shift and width of kaonic deuterium with a similar relative precision like kaonic hydrogen

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Option: kaonic deuterium @ J-PARC

Proposal for J-PARC 50 GeV Proton Synchrotron

Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium at J-PARC

submitted on April 13, 2014

Proposal for J-PARC K1.8BR spectrometer, for E15, E17

J-PARC K1.8BR spectrometer, for E15, E17

Proposal for J-PARC Submitted and presented 2014
SIDDHARTA2 @DAFNE

DAFNE – ideal for kaonic atoms
Kaon source (Φ decay in K⁻K⁺)
Low-energy kaons (127 MeV/c) ideal for stopping
No tracking

With 10 pb⁻¹ per day
1.5 10⁷ K⁻ per day isotropically
2% per kaon pair stopping in gas
144 SDDs from SIDDHARTA

Kaonic deuterium @J-PARC?

Kaon beam
Kaons at higher momentum (660-1000 MeV/c)
needs degrader
Tracking

With 30 kW beam power
430 10⁷ K⁻ per day
0.03% per kaon pair stopping in gas (660 MeV/c)
340 SDDs
Cryogenic target and SDDs

target cell: \( l = 160 \text{ mm}, \ d = 65 \text{ mm} \)
target pressure max.: \( 0.35 \text{ MPa} \)
target temperature: \( 23 – 30 \text{ K} \)
SDD active area: \( 246 \text{ cm}^2 \)
density: \( 5\% \text{ LHD} \)
\( (29\text{K}/0.35 \text{ MPa}) \)
Setup at J-PARC K1.8BR

CDH...cylindrical detector hodoscope
CDC...cylindrical drift chamber

T0......beam line counter
T1......beam line counter
BLC....beam line chamber

Solenoid
CDH
CDC
main degrader
SDD and deuterium target

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Monte Carlo results Kd@J-PARC

signal to background ~ 1:4
precision: shift ~56 eV, width ~139 eV

signal: shift - 800 eV
width 750 eV
density: 5% (LHD)
detector area: 246 cm²

Kα yield: 0.1 %
yield ratio as in Kβ

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Outlook: New precision studies with new technologies

- Kaonic helium $2p$ state shift/width
- 2 level studies in kaonic atoms
New experiments - microcalorimeter

Study of 2 transitions in the same kaonic atom for separating one-nucleon 1N) from multi-nucleon (mN) processes using micro-calorimeters

rms radii of potentials are characteristic features:

<table>
<thead>
<tr>
<th></th>
<th>( r_m )</th>
<th>Re(full)</th>
<th>Re(1N)</th>
<th>Re(mN)</th>
<th>Im(full)</th>
<th>Im(1N)</th>
<th>Im(mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>3.72</td>
<td>3.34</td>
<td>3.82</td>
<td>2.86</td>
<td>3.73</td>
<td>4.46</td>
<td>3.12</td>
</tr>
<tr>
<td>Pb</td>
<td>5.56</td>
<td>5.21</td>
<td>5.71</td>
<td>4.78</td>
<td>5.46</td>
<td>6.23</td>
<td>5.00</td>
</tr>
</tbody>
</table>

(values in fm).

Radius difference 1N-mN real terms=0.95 fm.

Radius difference 1N-mN imag. terms=1.2-1.3 fm.

Further applications of microcalorimeters for precision x-ray studies:

- K-He-3,4 2p-shift/width
- Charged kaon mass

Feasibility of new experiments

Microcalorimeter detectors based on Transition Energy Sensors (TES) achieved 53 eV resolution for 100 keV X-rays for an array of 5cm².

Resolution stays constant in the linear region (up to 400 keV).

To model less favorable conditions we adopted also increase of energy spread with \( \sqrt{E_X} \).


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Summary

• SIDDHARTA – important results on light kaonic atoms

• Impact for $K_{\text{bar}}N$ theory (see talk by W. Weise at this conference)

• SIDDHARTA – first exploratory experiment on $Kd$

• SIDDHARTA2 with improved apparatus aiming at a first extraction of 1s state shift and width in kaonic deuterium

• SIDDHARTA2 at DAFNE/J-PARC

• Close collaboration of experimentalists and theoreticians extremely important $\rightarrow$ LEANNIS (HadronPhysics3 in EU FP7)
Thank you

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