Search for $\bar{p}$-^{16}O Bound States in $\overline{\text{P}}$ANDA

Simulation with GiBUU

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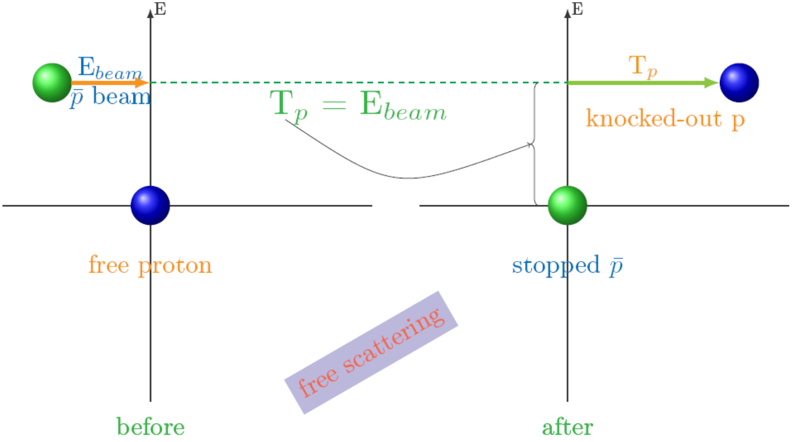
4. RIKEN, Japan

10.09.2012

Outline

$\bar{\text{p}}$-nucleus interaction



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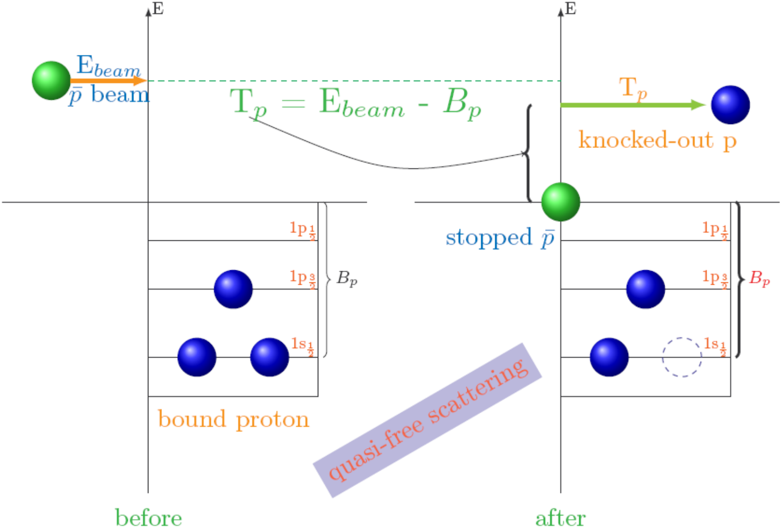

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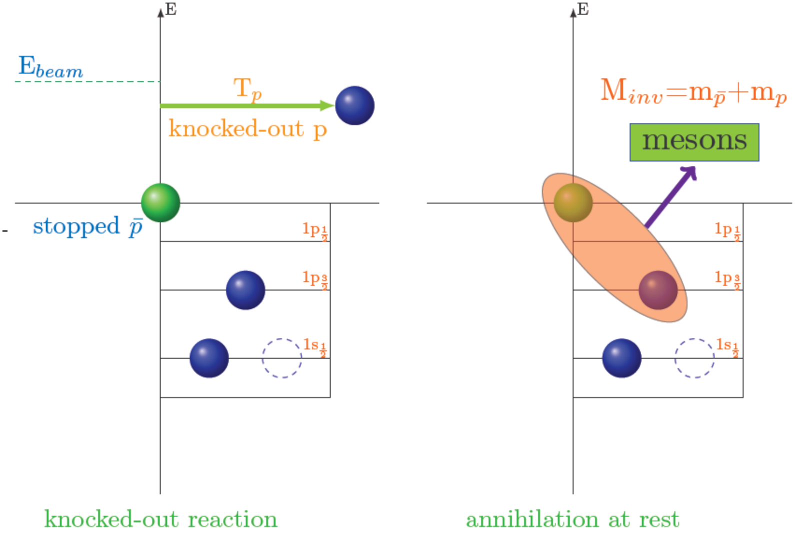

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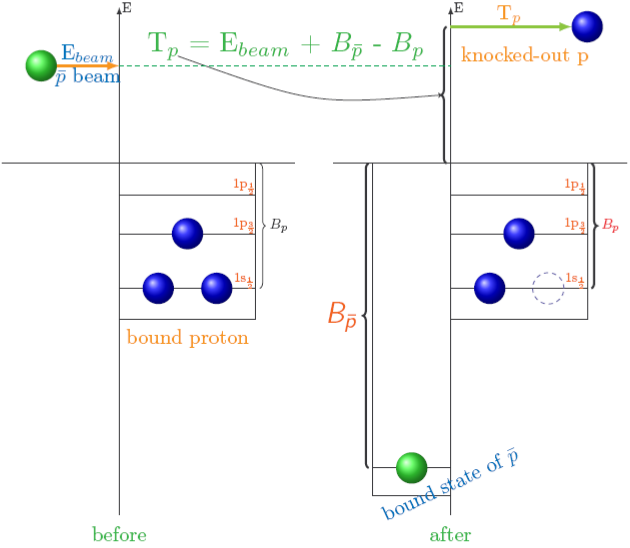

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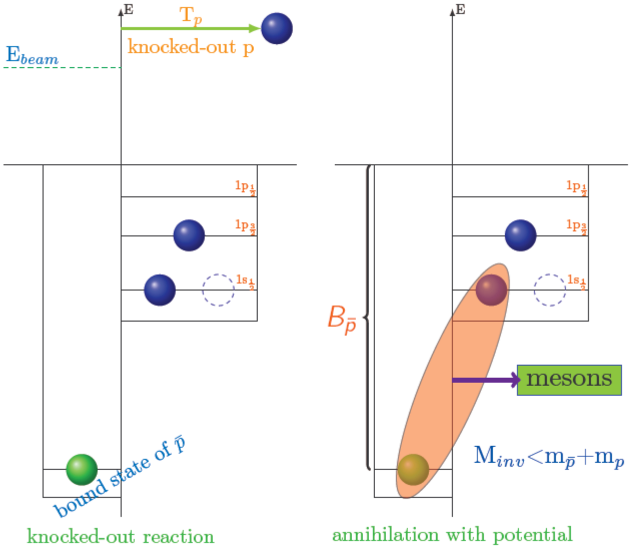
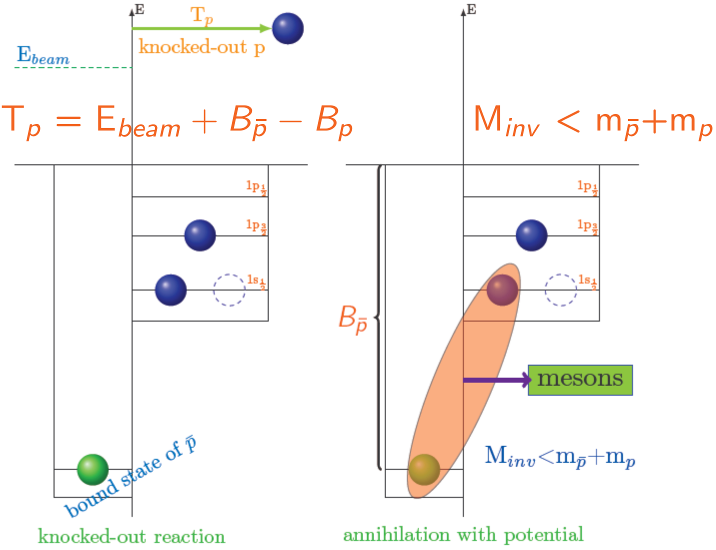
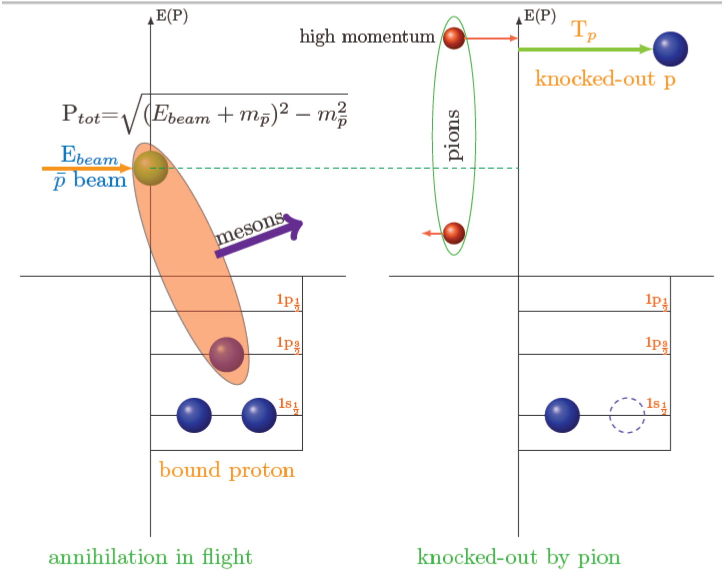


$\bar{p}$-nucleus interaction

$$T_p = E_{beam} + B_{\bar{p}} - B_p \qquad M_{inv} < m_{\bar{p}} + m_p$$



p̄-nucleus interaction

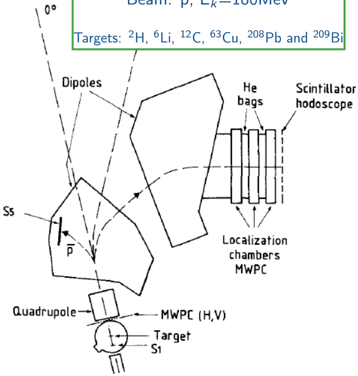


$(\bar{p},p)$ knock-out experiment

LEAR experiment in 1980s @CERN

Beam: $\bar{p}$, E_k=180MeV

Targets: ^{2}H, ^{6}Li, ^{12}C, ^{63}Cu, ^{208}Pb and ^{209}Bi



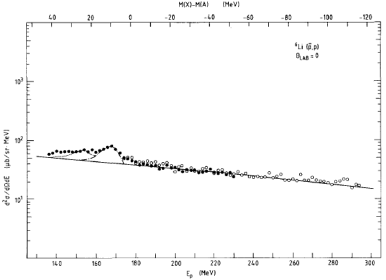


Fig. 2. Double differential cross sections for the ^{6}Li$(\bar{p},p)$X reaction at $E_{\bar{p}}=177.9$ MeV. The full line corresponds to an average temperature $T=101$ MeV. The dash-dotted line is the result of a quasi-free scattering calculation corresponding to an effective proton number $N_{eff}=0.15$. The dotted line represents the contribution of the quasi-free scattering on 1s-shell protons with an effective proton number 0.09.

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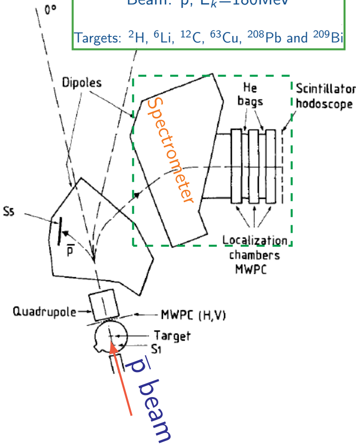

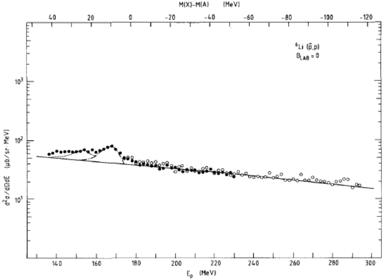

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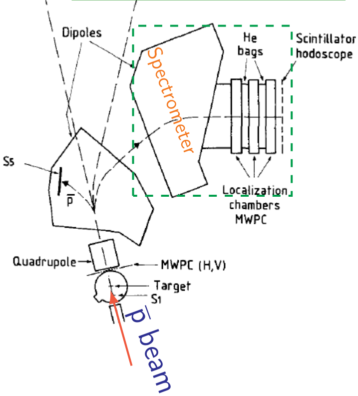
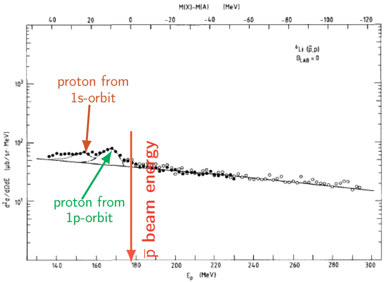


^{6}Li ($\bar{\text{p}}$,p) $^{5}_{\bar{p}}$He



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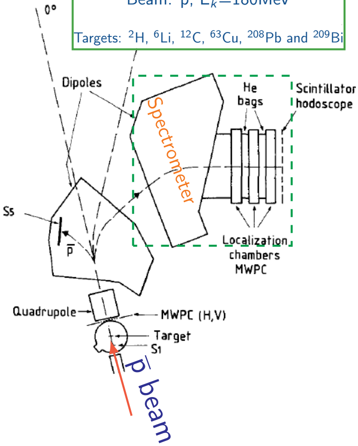

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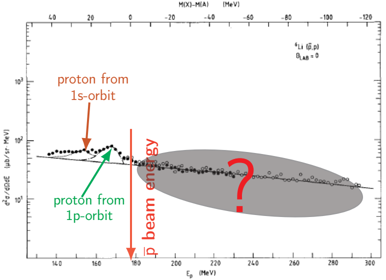

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Event Generator: GiBUU — Gießen-Boltzmann-Uehling-Uhlenbeck

- Institut für Theoretische Physik, JLU Gießen
  Prof. U. Mosel, Dr. A. B. Larionov, *et al*.
- Framework for elementary reations on nuclei

The GiBUU project

The **GiBUU project** is aiming to provide an unified transport framework in the MeV and GeV energy regimes for

- **elementary reactions on nuclei**, as e.g.
  - **electron** + A,
  - **photon** + A,
  - **neutrino** + A ,
  - **hadron** + A (especially **pion** + A and **proton** + A)
- and for **heavy-ion collisions**.

$$\bar{p} + A \longrightarrow \text{hadrons}$$

For those reactions, the flow of particles is modelled within a Boltzmann-Uehling-Uhlenbeck (BUU) framework. The relevant degrees of freedom are **mesons** and **baryons**, which propagate in mean fields and scatter according to cross sections which are tuned to the energy range of 10 MeV to more than 10 GeV. In the higher energy regimes the concept of **pre-hadronic** interactions is implemented in order to realize *color transparancy* and *formation time* effects. For a general overview of the model, please refer to our recent review paper:

Transport-theoretical Description of Nuclear Reactions
O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A. B. Larionov, T. Leitner, J. Weil, U. Mosel
Phys. Rept. 512 (2012) 1-124 Inspire arXiv:1106.1344

Paramters of $\bar{\text{p}}$-nucleus interation in GiBUU

Parameters for $\bar{\text{p}}$-nucleus interaction:

E_{beam} (GeV)	$\sigma^{\bar{p}p}_{ann}$ (mb)	$\sigma^{\bar{p}p}_{el}$ (mb)	**Target**	**Note**
0.18	84.7	80.9	^{6}Li	.. comparing the background with LEAR experiment
1.5	40.0	32.2	^{16}O	.. searching for $^{15}_{\bar{p}}$**N & $^{15}_{\bar{p}}$O bound states**

$\bar{\text{p}}$ potential in GiBUU:
ξ =0.2 — 0.3 $\rightarrow$ Re(V_{opt}) = -220 — -150 MeV

$\bar{p}$-^{6}Li collision simulation — Same conditions as LEAR experiment

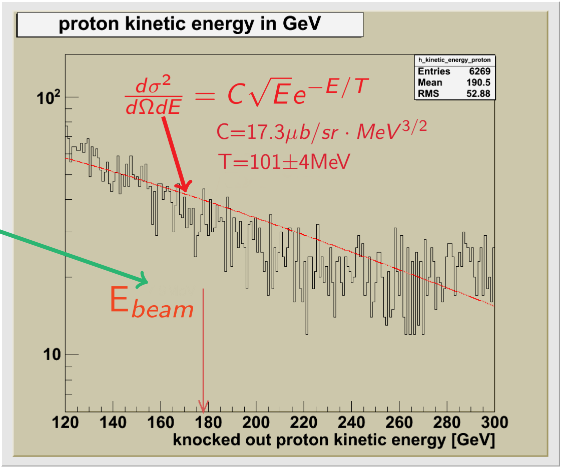
The continuous background of knocked-out protons

$\bar{p}$ beam:

E_{beam}=177.9MeV

Target:

^{6}Li



$\bar{p}$-^{16}O collision simulation

$\bar{p}$ beam: E_{beam}=1.5GeV; Target: ^{16}O

Signature:

First, knocked-out reaction → Only one knocked-out proton or neutron

$\bar{p}$ stopping

Second, annihilation at rest

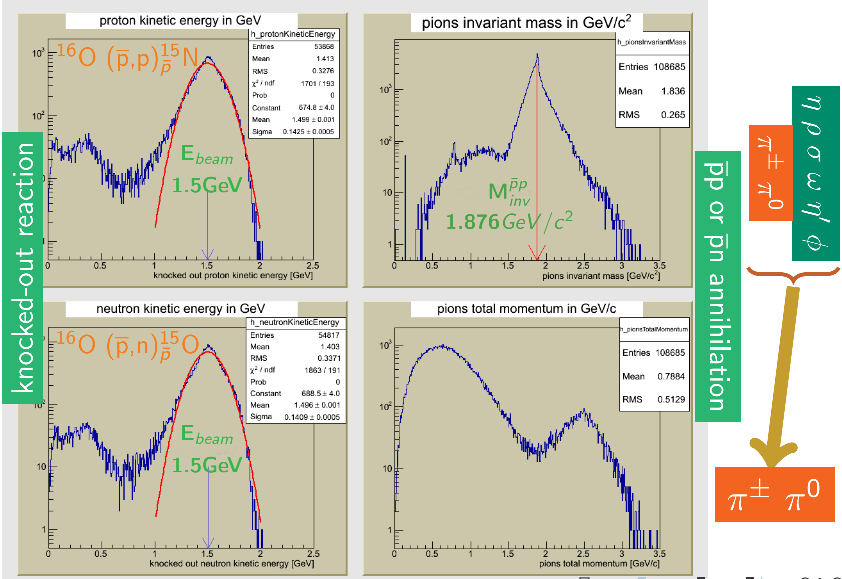
- $\pi^{\pm}, \pi^0$
- η, ρ, σ ω, η'
- ϕ
- $K^{\pm}, K^0$
- $K^{*\pm}, K^{*0}$

→ $\pi^{\pm}, \pi^0$

→ $K^{\pm}, K^0$ (πs)

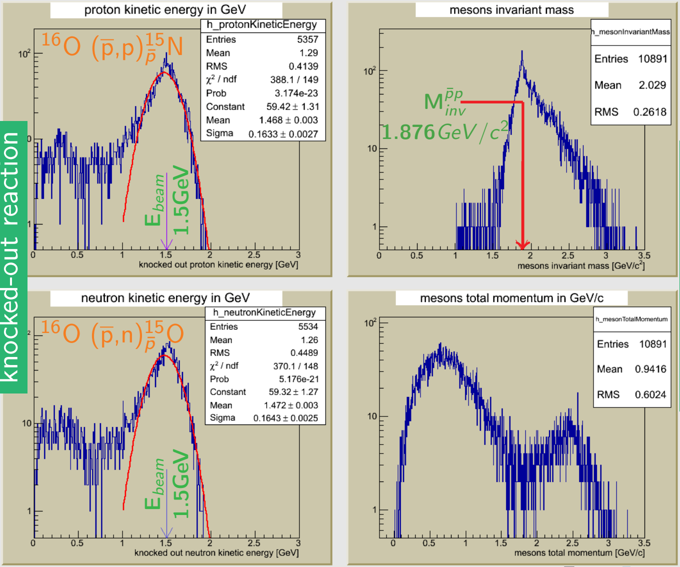
Background: knocked-out nucleons by high-momentum pions

The events with only pions in final state



The events with Kaons(and pions) in final state

knocked-out reaction



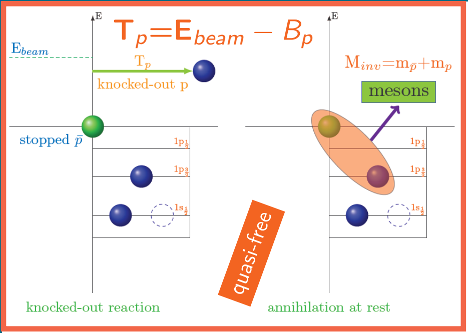
$\bar{p}p$ or $\bar{p}n$ annihilation

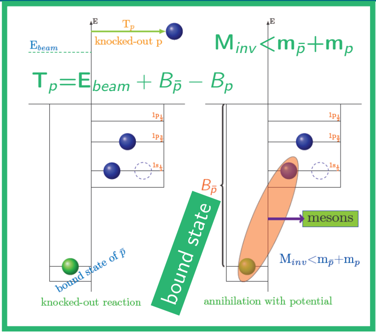
$K^{\pm} K^{0}$

$K^{*\pm} K^{*0} \phi$

$K^{\pm} K^{0}$ (πs)

The cutting conditions setting



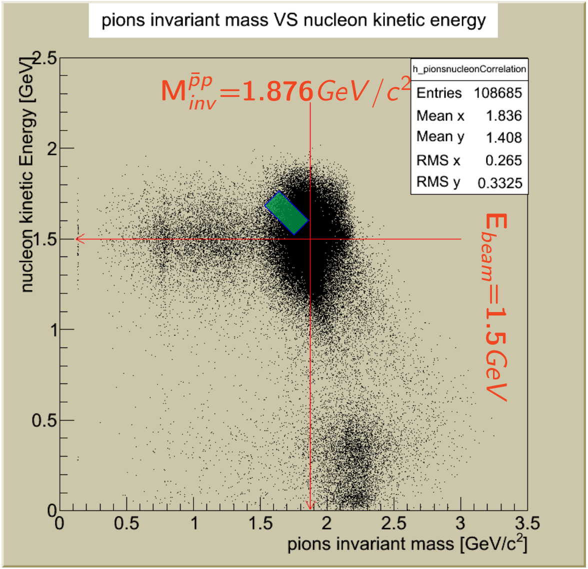


If B_p=30MeV and $B_{\bar{p}}$=150MeV($\epsilon \sim 37 MeV$):

	$T_p(GeV)$	$M_{inv}(GeV/c^2)$
quasi-free	1.47	$\sim$ 1.86
bound state	1.62	1.85 $\sim$ 1.70

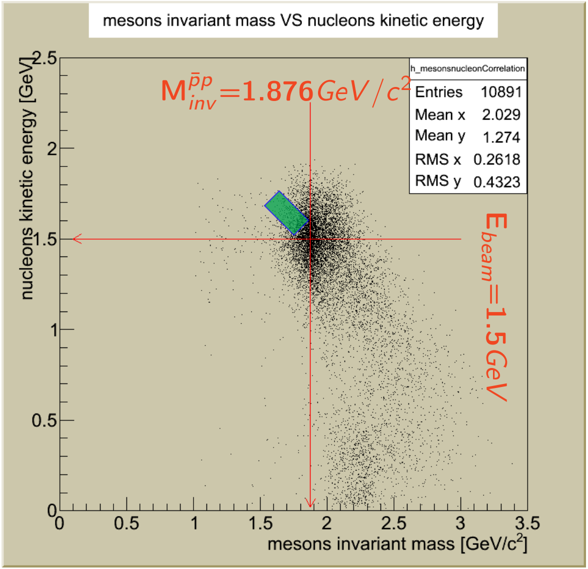
The correlation of knocked-out nucleon and decayed mesons

The events with pions in final state

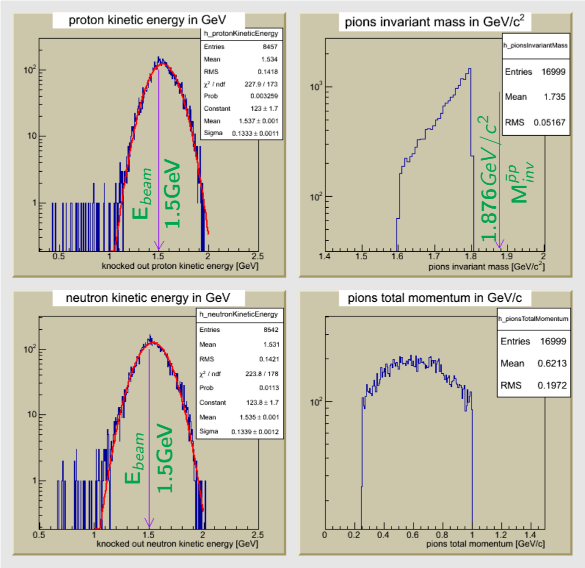


The correlation of knocked-out nucleon and decayed mesons

The events with kaons in final state



Search for bound state events

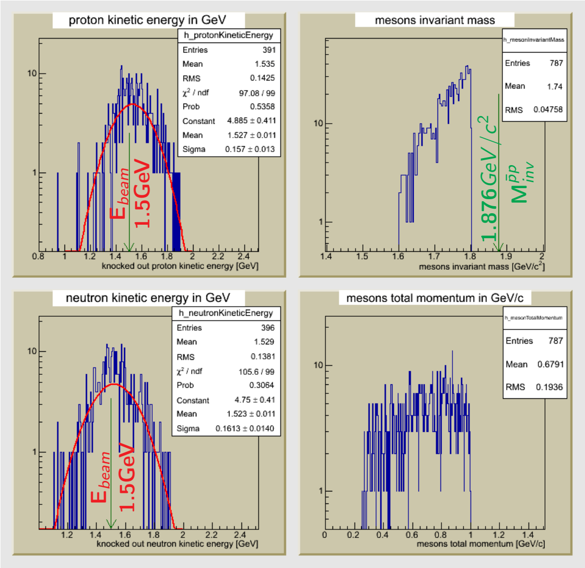


cutting conditions

$1.6 \leq M_{inv}^{mesons} \leq 1.8$

$0.25 \leq P_{tot}^{mesons} \leq 1.0$

Search for bound state events



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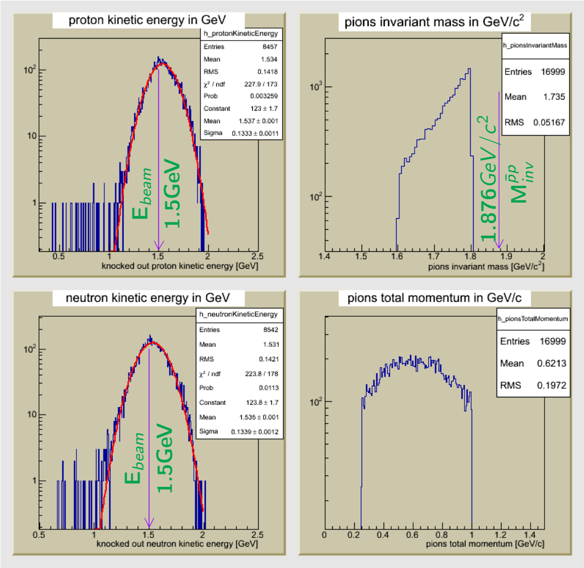

cutting conditions

$1.6 \leq M_{inv}^{mesons} \leq 1.8$

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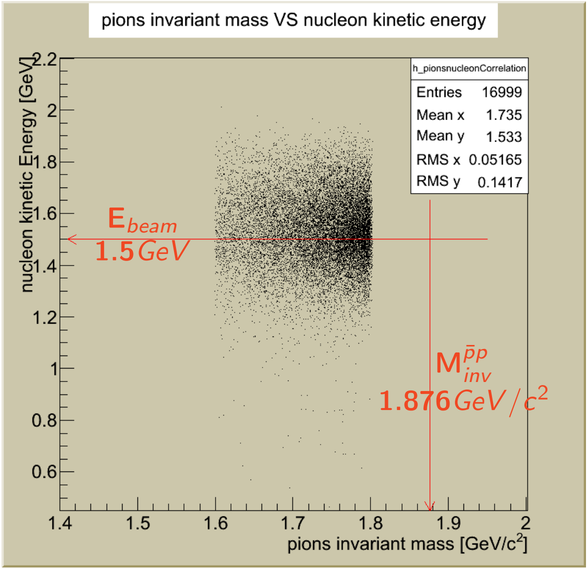
Mean value of the kinetic energy of knocked-out nucleon spectrum

~ 1.53 GeV

The correlation of knocked-out nucleon and decayed mesons



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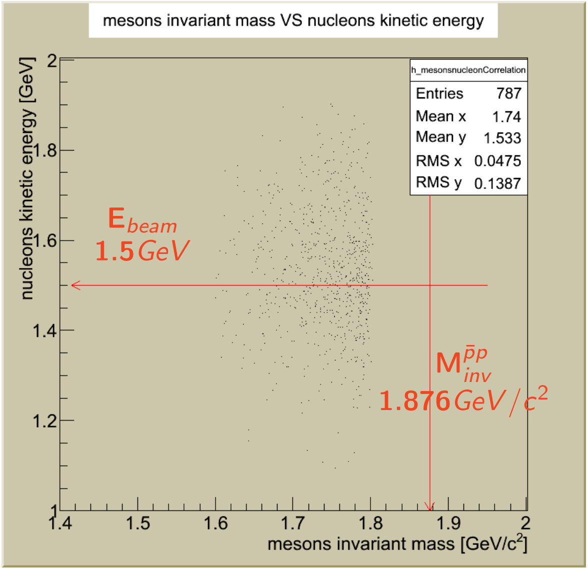


The conclusions of $\bar{p}^{16}O$ simulation

- 9×10^8 $\bar{p}$-^{16}O collision events had been simulated
- Suppression of the continuous knocked-out nucleon background by event selection of data analysis
- Up to now, no bound state event has been found
- The quasi-free scattering reaction cannot been rejected

List of References:

- E. Aslanides et al., Nucl. Phys. A 470, p.445 (1987)
- O. Buss et al., Phys. Rep. 512 (2012) 1-124
- C. Amsler, Rev. Mod. Phys. 70, 1293–1339 (1998)
- Y. Ma, talk of "Antiproton Nuclear Collision at PANDA"
- T. Leitner et al., Acta Phys. Pol. B,Vol.40 N9 (2009) 2571
- GiBUU Project, Institut für Theoretische Physik, JLU Gießen

Thank You for Your Attention!

Why no bound states structure observed?

Search for $\bar{p}$-^{16}O Bound States in $\overline{\text{P}}$ANDA

D.Lin Y.Ma F.Maas

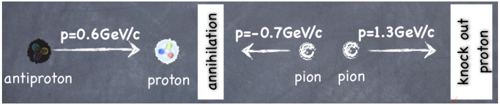
- Kinetic energy of knocked-out proton:

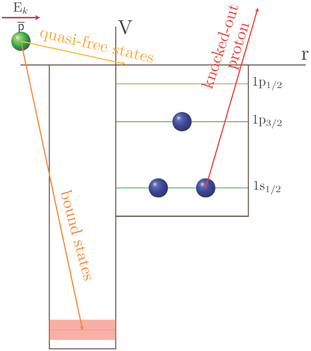
  $T_p = E_{beam} + B_{\bar{p}} - B_p$

- Low beam energy

- Strong background

$$\frac{d^2\sigma}{d\Omega dE} = C\sqrt{E}e^{-E/T}$$





^{6}Li protons

$\bar{p}$-^{16}O collision simulation

Events selection

only nucleons and mesons in event

- For nucleons:
  - Only one knocked-out nucleon
  - Without other scattering except knocked-out reaction
- For mesons: $\bar{p}p$ or $\bar{p}n$ annihilation
  - Only pions in final state:
    1. Directly to πs
    2. To η ρ σ ω η' ϕ to πs
  - Kaons OR Kaons and pions in final state:
    1. Directly to Ks (+ πs)
    2. To K*s ϕ to Ks+πs

$\bar{p}$-nuclear collision simulation with GiBUU

Output data structure from GiBUU

particle ID&charge — parents ID — position (x,y,z) — momentum (p_x,p_y,p_z)

1	0	37	0	0	0.938	1	22.700	-19.206	5.979	0.205	-0.189	0.056	951	19
-1	0	1159159	1	-1	0.938	1	0.849	-6.822	84.775	0.021	-0.233	2.257	951	19
1	1	37	0	0	0.938	1	17.485	24.554	-6.891	0.167	0.206	-0.048	952	19
1	0	37	0	0	0.938	1	-1.495	6.852	-6.576	0.054	0.108	0.090	952	19
1	1	37	0	0	0.938	1	13.230	-24.473	6.864	0.117	-0.247	0.072	952	19
1	0	37	0	0	0.938	1	6.957	-15.335	22.646	0.039	-0.380	0.280	952	19
1	1	37	0	0	0.938	1	-46.391	17.748	-13.506	-0.511	0.188	-0.165	952	19
1	1	37	0	0	0.938	1	18.707	-32.110	-12.055	0.174	-0.356	-0.085	952	19
101	0	1161528	103	0	0.138	1	12.105	-71.356	-15.531	0.111	-0.436	-0.073	952	19
1	1	37	0	0	0.938	1	12.645	17.096	10.720	0.115	0.096	0.087	952	19
1	0	37	0	0	0.938	1	26.447	-32.964	-15.097	0.264	-0.371	-0.154	952	19
1	0	37	0	0	0.938	1	-45.723	-16.568	3.307	-0.592	-0.212	0.022	952	19
1	0	37	0	0	0.938	1	41.655	-33.162	21.746	0.550	-0.439	0.294	952	19
1	0	37	0	0	0.938	1	8.039	6.803	5.444	-0.032	0.044	-0.024	952	19
1	1	37	0	0	0.938	1	19.627	-9.880	-22.527	0.174	-0.109	-0.211	952	19
1	0	37	0	0	0.938	1	-23.193	4.969	12.149	-0.244	0.042	0.034	952	19
1	1	1156293	1	-1	0.938	1	4.817	-1.671	85.798	0.133	-0.060	2.288	952	19
1	0	37	0	0	0.938	1	22.181	13.839	-14.753	0.217	0.124	-0.133	952	19
101	-1	1161528	1	-1	0.138	1	-54.952	24.827	44.689	-0.203	0.099	0.199	952	19
101	1	1161528	1	-1	0.138	1	-18.099	47.498	20.542	-0.028	0.109	0.056	952	19
101	-1	1161528	1	-1	0.138	1	5.740	65.098	10.616	0.038	0.203	0.044	952	19
101	1	1161528	103	0	0.138	1	-60.224	17.232	-55.460	-0.408	0.125	-0.393	952	19
1	1	37	0	0	0.938	1	17.197	11.546	-3.880	0.100	0.110	-0.091	953	19
1	0	37	0	0	0.938	1	13.775	-30.747	-9.313	0.067	-0.341	-0.020	953	19
1	1	1158628	2	0	0.938	1	-35.348	-18.626	41.149	-0.474	-0.253	0.551	953	19

knocked-out proton

BUU Equation

Boltzmann-Uehling-Uhlenbeck equation:

$$(\partial_t + \nabla_p H \cdot \nabla_r - \nabla_r H \cdot \nabla_p) f_i(r,p,t) = I_{coll}[f_i, f_N, f_\pi, f_\Delta, \cdots]$$

$$H = \sqrt{[M + U(r,p)]^2 + p^2}$$

This model is based on the BUU equation which describes the space-time evolution of a many-particle system in a mean-field potential.
where f_i(r,p,t) is the phase space density, H is the relativistic Hamiltonian of a particle of mass M in a scalar potential U, and I_{coll} is the collision term which accounts for changes in the phase space density due to elastic and inelastic collisions between the particles, and also due to particle decays into other hadrons.

- The cross section of $\bar{p}$-nuleus interaction:

$\bar{p}p$ annihilation cross section

$$\sigma_{\text{ann}}^{\bar{p}p} = \begin{cases} 51.52 p_{\text{lab}}^{-0.85} + 0.034 p_{\text{lab}}^{-2.94} & \text{for} \quad p_{\text{lab}} < 0.51 \\ 88.8 p_{\text{lab}}^{-0.4} - 24.2 & \text{for} \quad 0.51 < p_{\text{lab}} < 6.34 \\ 38 p_{\text{lab}}^{-0.5} + 24 p_{\text{lab}}^{-1.1} & \text{for} \quad 6.34 < p_{\text{lab}} \end{cases}$$

$\bar{p}p$ elastic scattering cross section

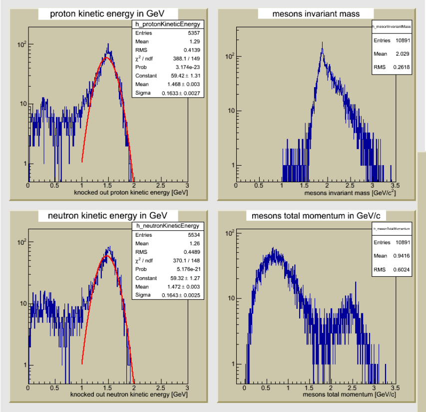
$$\sigma_{\text{el}}^{\bar{p}p} = 40 p_{\text{lab}}^{-0.56} + 5.8 \exp[-(p_{\text{lab}} - 1.85)^2]$$

σ in mb and p_{lab} in GeV/c

if p_{lab}=2.25GeV/c, then:

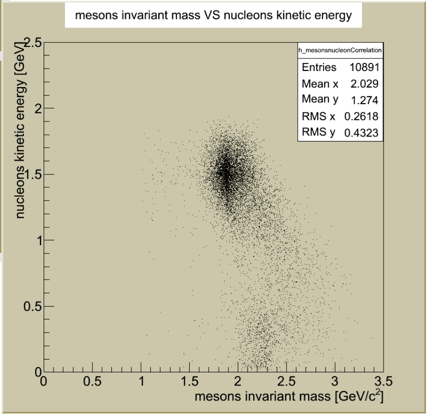
$\sigma_{ann}^{\bar{p}p} = 40.0$mb and $\sigma_{el}^{\bar{p}p} = 32.2$mb

The events with Kaons (and pions) in final state



knocked-out reaction

$^{16}\text{O}\ (\bar{\text{p}},\text{p})^{15}_{\bar{p}}\text{N}$ $\quad$ $^{16}\text{O}\ (\bar{\text{p}},\text{n})^{15}_{\bar{p}}\text{O}$



$\bar{\text{p}}\text{p}$ or $\bar{\text{p}}\text{n}$ annihilation at rest

$\text{K}^{\pm}\ \text{K}^{0}$ $\quad$ $\text{K}^{*}\ \phi$ $\xrightarrow{\text{to}}$ $\text{K}^{\pm}\ \text{K}^{0}\ (\pi)$

The $\bar{p}$ potential calculation

- Kinetic energy of knocked-out nucleon
  $T_p = T_{\bar{p}} + B_{\bar{p}} - B_p$ (Fermi Energy: $\epsilon \sim 37 MeV$)
- $\bar{p}$p or $\bar{p}$n annihilation at rest
  - Without potential
    $$M_{inv} = \sqrt{E_{total}^2 - P_{total}^2} = \sqrt{(M_0 + M_0)^2 - P_{\bar{p}}^2}$$
    $$= \sqrt{(0.938 + 0.938)^2 - (0)^2} = 1.876 [GeV/c^2]$$
  - With potential(V=-150MeV)
    $$E_{total} = E'_{total} = \delta E_k + M_0 + M_0 + V$$
    $$(\delta E_k = -V = 150 MeV)$$
    $$M'_{inv} = \sqrt{E'^2_{total} - P'^2_{total}}$$
    $$= \sqrt{(2M_0)^2 - (0.551)^2} = 1.793 [GeV/c^2]$$

Search for bound state events

- The continuous background of knocked-out nucleons
- Quasi-free(QF) scattering VS bound-state(BS) formation

$$\left(\frac{\sigma^2}{d\Omega dE}\right)_{QF} / \left(\frac{\sigma^2}{d\Omega dE}\right)_{BS} \sim 10^3$$