NUCLEAR PHYSICS STUDIED WITH ANTIPROTONS

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for Guillaume Hupin and Jaume Carbonell : Orsay
with help of Alireza Dehghani : Orsay

MOTIVATION

PUMA at CERN : From
Alexandre Obertelli

Fig. 7: Itinerary of PUMA from ELENA to ISOLDE.

PUMA EXPERIMENT

PRODUCES ANTIPROTONS
COLLIDES WITH UNSTABLE NUCLEI
MAKES ANTIPROTONIC ATOMS

waits for X ray cascade, and nuclear capture

DETECTS π MESONS FROM ANNIHILATION
FINDS MESONIC CHARGE DISTRIBUTIONS

THIS COLLABORATION STUDIES

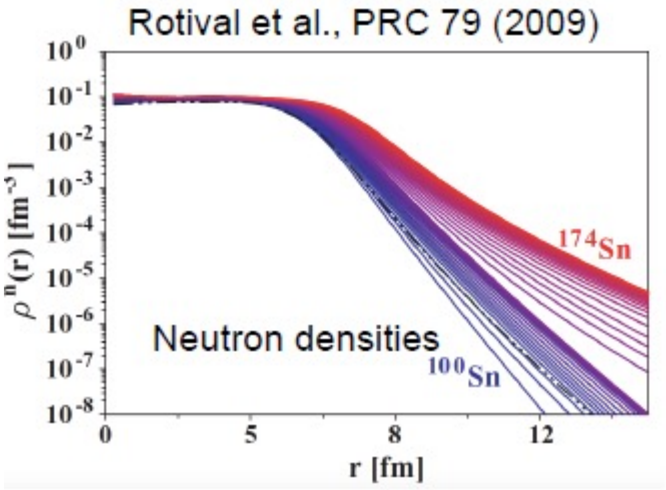
ATOMIC ORBITS OF NUCLEAR CAPTURE
RATIO σ (Pbar –n) / σ(Pbar – p)
➔ NEUTRON HALO (SKIN)

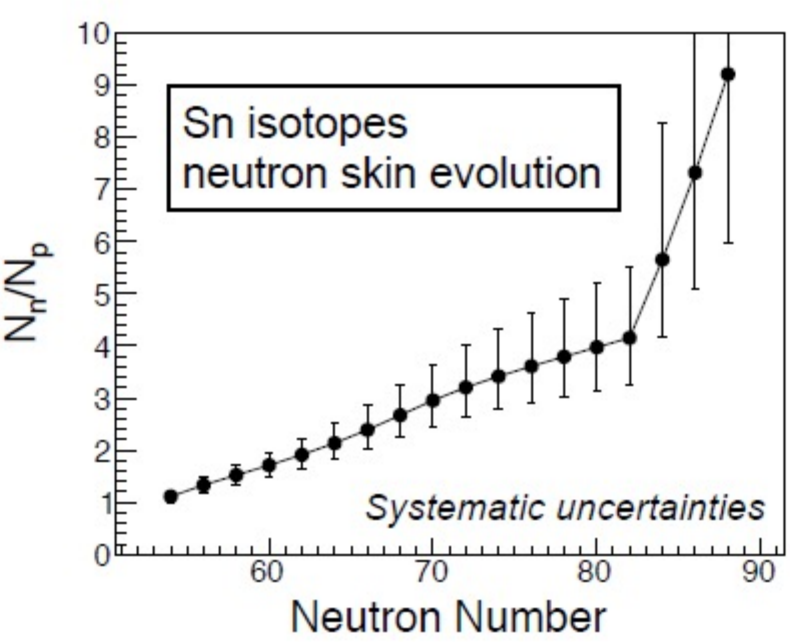
Expectations - an example

from A. Obertelli

n/p ratio expected at capture radius

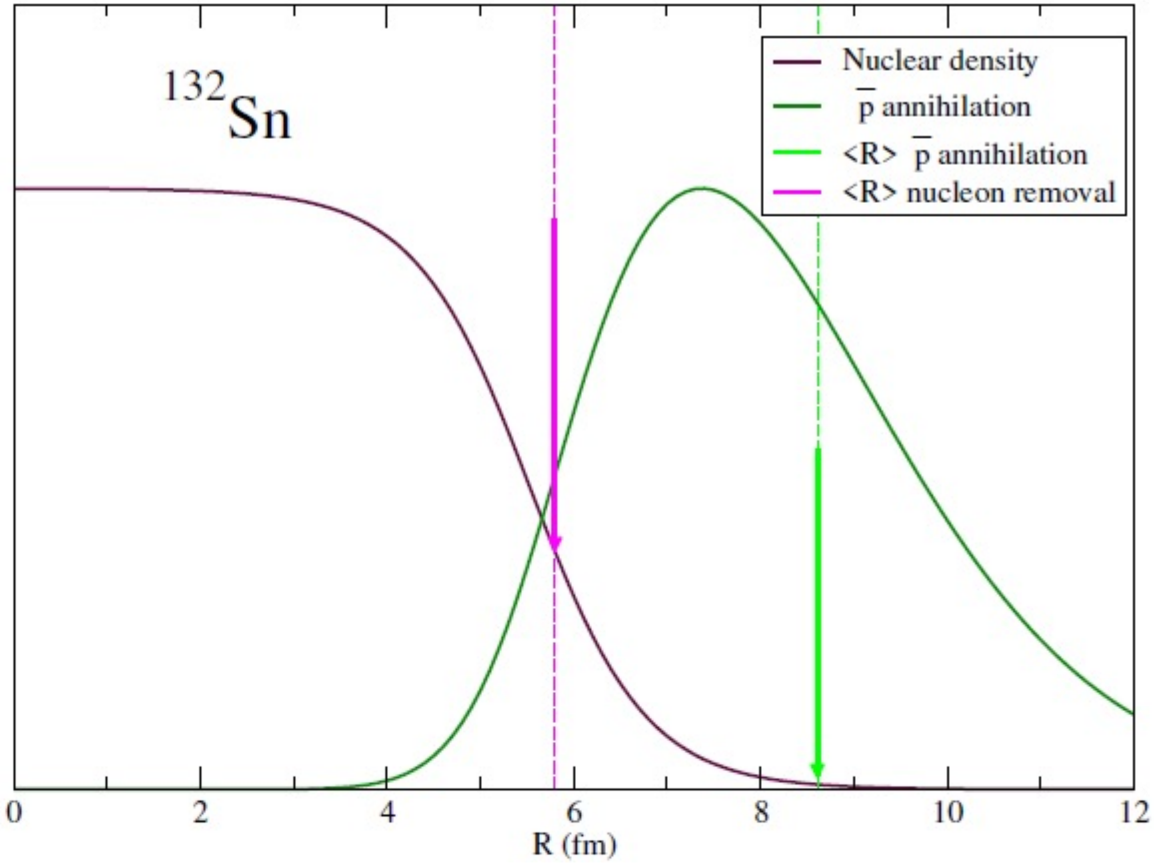
Neutron tails





Pbar nuclear absorption region

Z= 50 , N = 88 : a fancy nucleus to study by PUMA
Expected atomic – nuclear density overlap



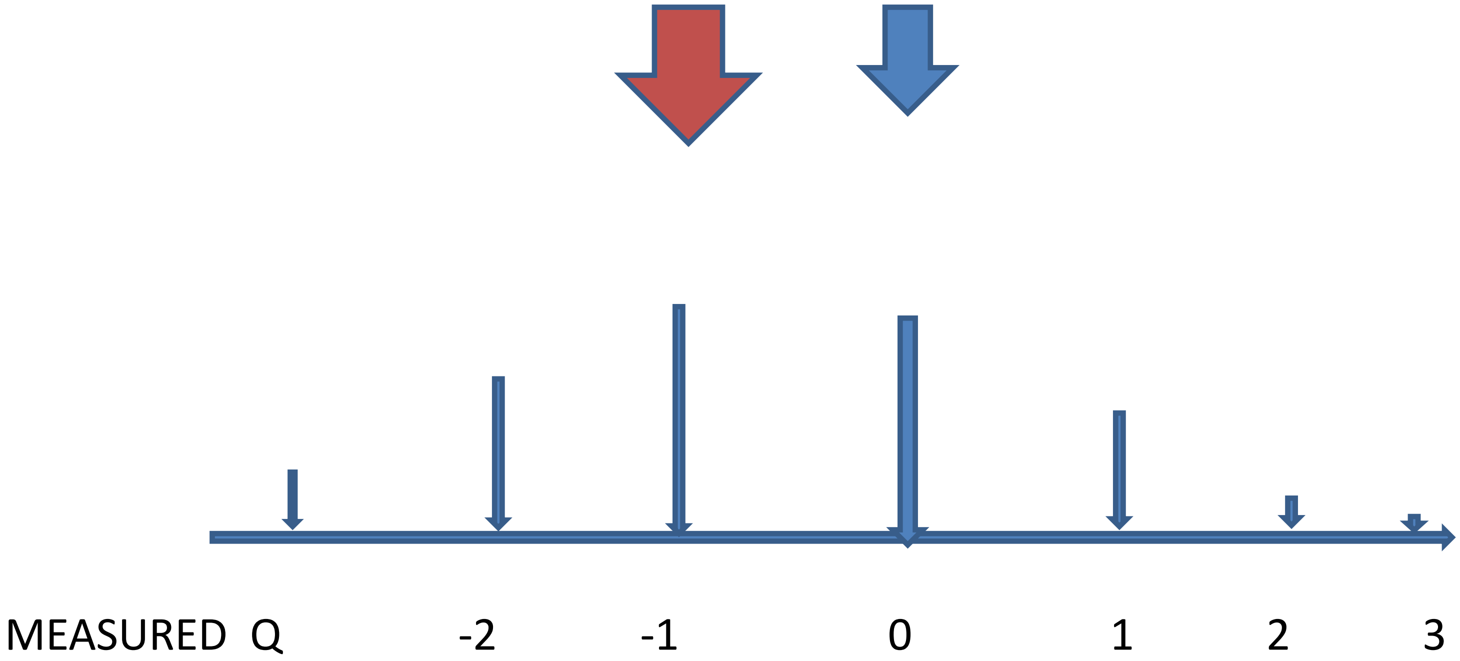
A JOB FOR THIS COLLABORATION

FIND ATOMIC ORBITS FROM WHICH PIONIC DECAYS HAPPEN

EXRRACTION OF CAPTURE ORBITALS FROM TOTAL MESONIC CHARGE

INITIAL Q= O capture on proton 5 mesons mitted

Q = -1 capture on neutron 5 mesons emitted



ANALYSIS OF FINAL STATE MESONIC REACTIONS

(0) CHOSE PARAMETERS FOR ABSORPTION $\pi NN \rightarrow NN$,
CHARGE EXCHANGE $\pi+ \rightarrow \pi0$, $\pi0 \rightarrow \pi+$
$\pi- \rightarrow \pi0$, $\pi0 \rightarrow \pi-$

(1) FIT PARAMETERS TO P(Q) DATA
(2) CALCULATE PARAMETERS
(3) COMPARE FITTED TO CALCULATED

extract the orbits of captures

calculate neutron haloes

RESULTS

OLD DATA : N, C, Ti, Ta, Pb analysed

S.W.,K.P. Phys Rev. C (2023) 108

DOMINANT CAPTURE ORBITS :
THE LOWEST STATES REACHED IN ATOMIC CASCADE

Rms RADII OF NEUTRON DENSIES CONSISTENT
WITH OTHER EXPERIMENT

RELATED STUDIES , ESSENTIAL

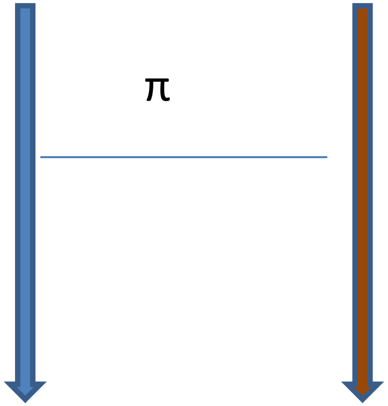
Problem: 10 % uncertainty of absorption ratio σ (Pbar –n) / σ(Pbar – p)

Problem : mesonic charge exchanges are sensitive to np correlations

Problem of interest :
Nuclear states of antiprotons

ANOTHER ESSENTIAL JOB FOR THIS COLLABORATION

(1) COMPARE MODELS FOR NUCLEON_ANTINUCLEON INTERACTIONS



+ PHENOMENOLOGY MODEL DEPENDENT

(2) EXTEND BEST MODEL TO LOW ENERGY ,
FIND BOUND STATES

COMPARISON OF MODELS : RESULTS

J.Carbonell, G.Hupin. S.W. : EPJA59(2023)259

IMPROVING N- Nbar INTERACTION POTENTIAL

DATA CROSS SECTIONS ONLY , MANY PARTIAL WAVES (NO PAULI)
NO LOW ENERGY DATA

WHAT HAPPENS
BELOW 200 MV/C ?

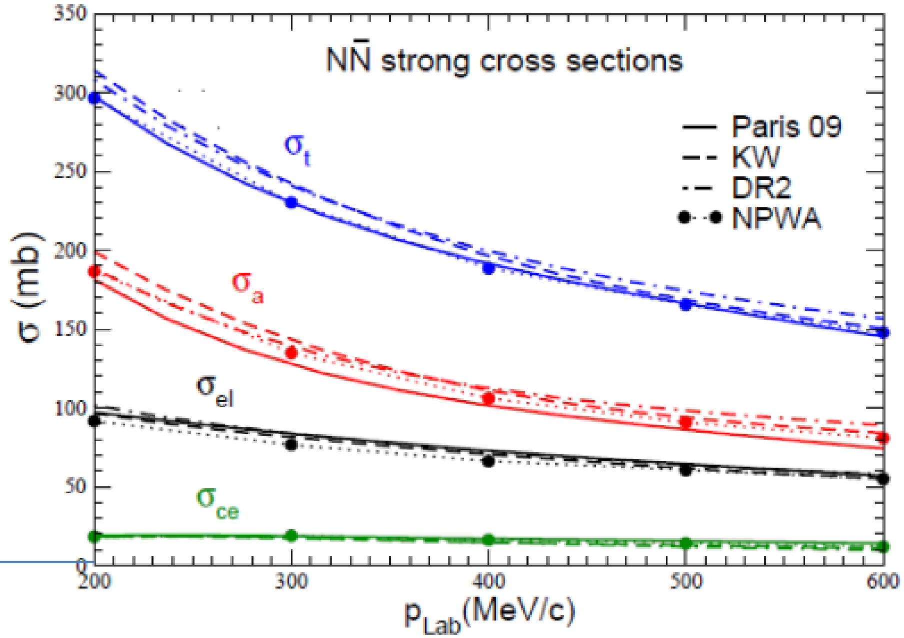


Fig. 1 Integrated strong $\bar{N}N$ cross sections – elastic σ_e (black), annihilation σ_a (red), charge-exchange σ_{ce} (green) and their sum σ_t (blue) – as functions of the $\bar{N}$ laboratory momenta for DR2 (dashed dotted line), KW (dashed line) and Paris 2009 (solid line) optical models. The results of the Nijmegen Partial Wave analysis [7] are indicated by filled circles.

BES III:

X(1869)

P-Pbar

BOUND

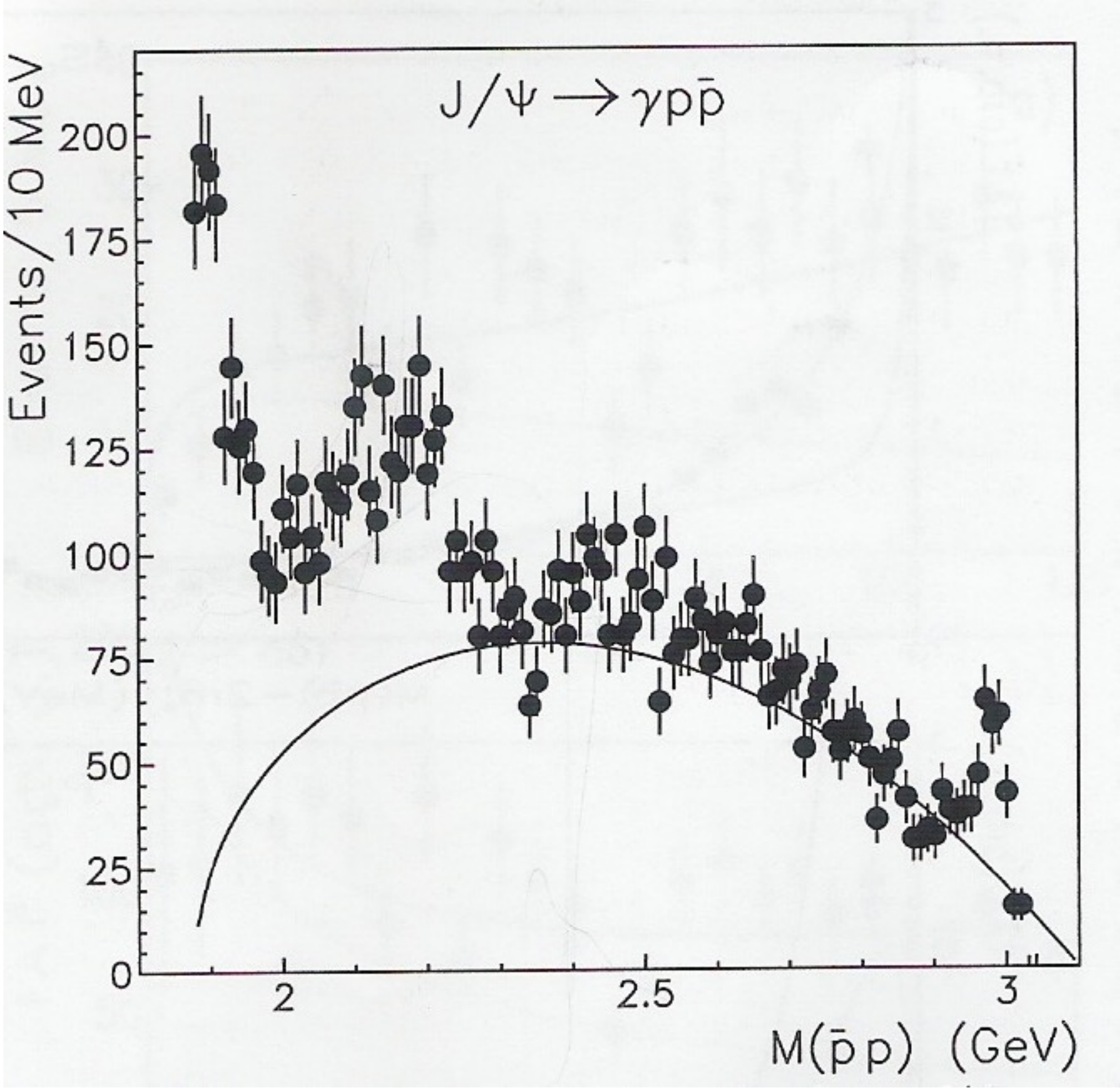
STATE

INDICATED

ISOSPIN

UNNOWN

X(2170)

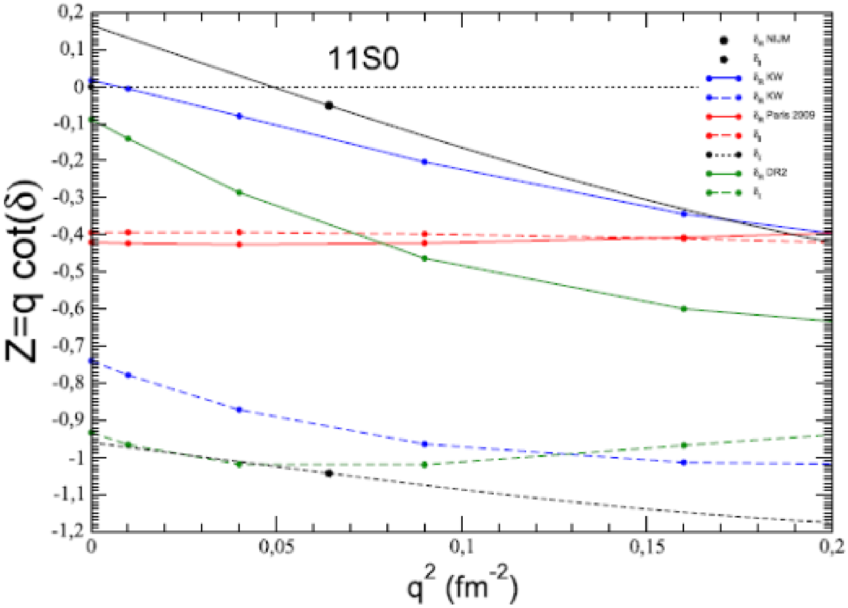


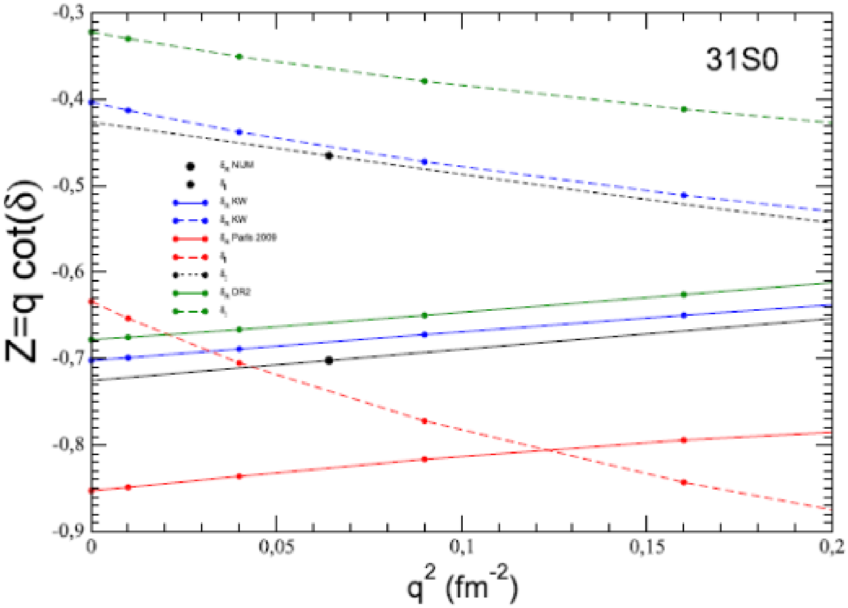
S WAVE SCATTERING AMPLITUDES

SOME INDICATE ATTRACTION OR DEEPLY BOUND STATE
(negative)

SOME INDICATE BOUND STATE CLOSE TO THRESHOLD
(positive)

CHAOS





SAME CHAOS WHEN COMPARING MODELS (same partial wave !)

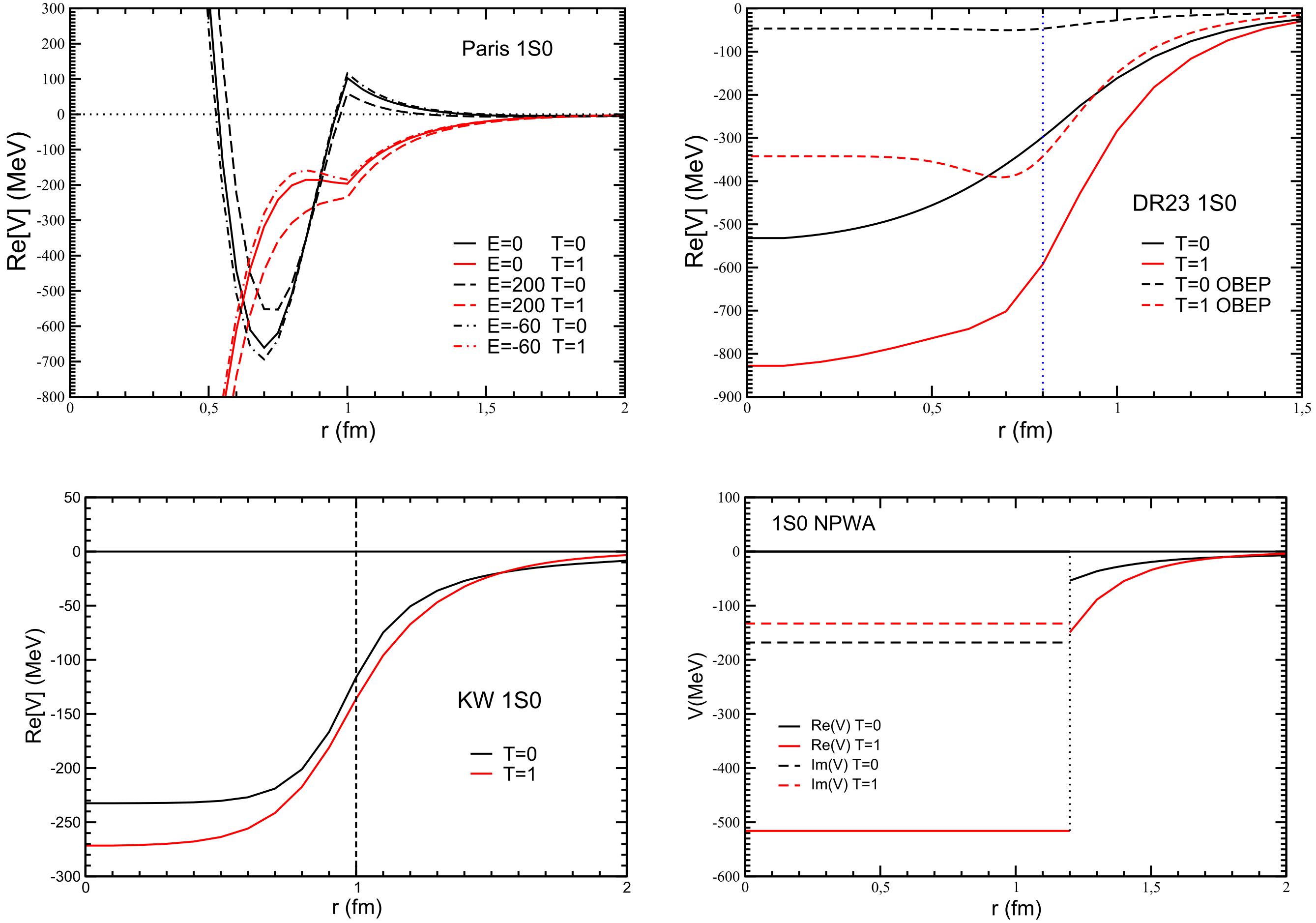
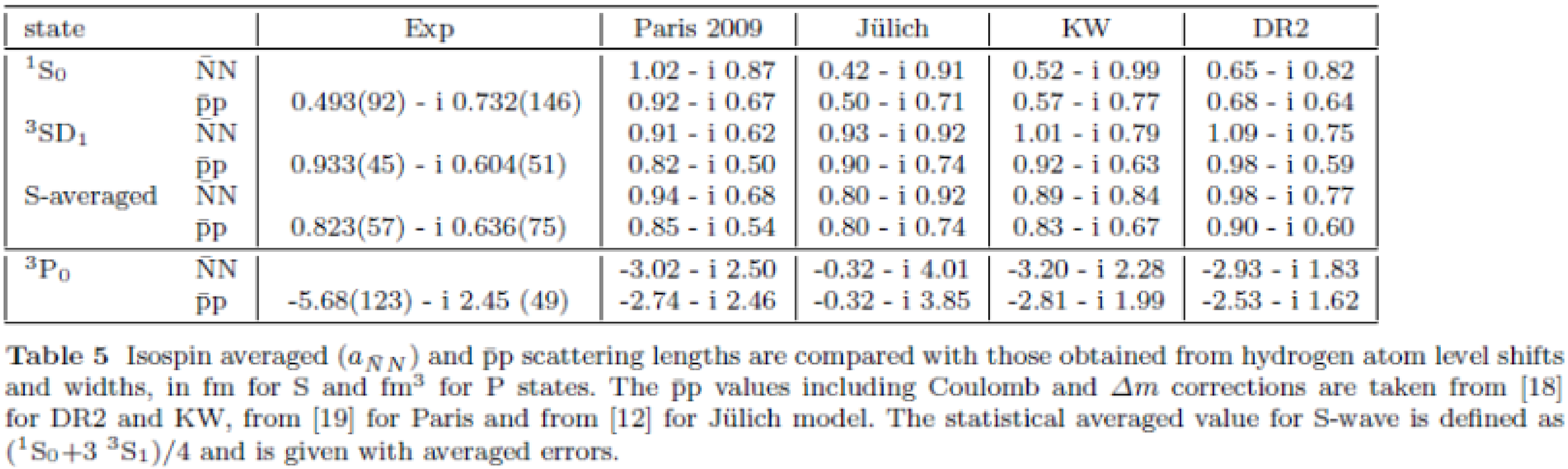


Fig. 15 Real parts of $^1S_0$ potentials for both isospins (T)

Antiprotonic –hydrogen : selected partial waves

➔ P-Pbar scattering lengths : large differences
scattering volumes : dramatic differences



state		Exp	Paris 2009	Jülich	KW	DR2
$^1S_0$	$\bar{N}N$		1.02 - i 0.87	0.42 - i 0.91	0.52 - i 0.99	0.65 - i 0.82
	$\bar{p}p$	0.493(92) - i 0.732(146)	0.92 - i 0.67	0.50 - i 0.71	0.57 - i 0.77	0.68 - i 0.64
$^3SD_1$	$\bar{N}N$		0.91 - i 0.62	0.93 - i 0.92	1.01 - i 0.79	1.09 - i 0.75
	$\bar{p}p$	0.933(45) - i 0.604(51)	0.82 - i 0.50	0.90 - i 0.74	0.92 - i 0.63	0.98 - i 0.59
S-averaged	$\bar{N}N$		0.94 - i 0.68	0.80 - i 0.92	0.89 - i 0.84	0.98 - i 0.77
	$\bar{p}p$	0.823(57) - i 0.636(75)	0.85 - i 0.54	0.80 - i 0.74	0.83 - i 0.67	0.90 - i 0.60
$^3P_0$	$\bar{N}N$		-3.02 - i 2.50	-0.32 - i 4.01	-3.20 - i 2.28	-2.93 - i 1.83
	$\bar{p}p$	-5.68(123) - i 2.45 (49)	-2.74 - i 2.46	-0.32 - i 3.85	-2.81 - i 1.99	-2.53 - i 1.62

Table 5 Isospin averaged ($a_{\bar{N}N}$) and $\bar{p}p$ scattering lengths are compared with those obtained from hydrogen atom level shifts and widths, in fm for S and fm^3 for P states. The $\bar{p}p$ values including Coulomb and Δm corrections are taken from [18] for DR2 and KW, from [19] for Paris and from [12] for Jülich model. The statistical averaged value for S-wave is defined as ($^1S_0$+3 $^3S_1$)/4 and is given with averaged errors.

HENCE , NEXT TOPICS FOR THE COLLABORATION

1) FIND NEW MODEL FOR N-Nbar INTERACTIONS

INCLUDING : NIJMEGHEN PARTIAL WAVE ANALYSIS
LEVEL SHIFTS AND WIDTHS FOR H, 2H, 3He , 4He ATOMS

(2) FIND ANTIPROTONIC NUCLEAR STATES „ AB INITIO „ CALCULATIONS , Z <= 6

(3} STUDY SHORT RANGE p-n CORRELATION S IN NUCLEI WITH PUMA,
a by-product of the experiment

THANK YOU

Appendix - if needed

	a_1	r_1	a_1	r_1	a_1	r_1	a_1	r_1
T=0	$^{11}P_1$		$^{13}P_0$		$^{13}P_1$		$^{3}PF_2$	
Nijm*	-3.34-1.22i	9.3-1.2i	-3.06-7.23i	-1.7-1.5i	4.36-0.00i	-3.5-0.0i	–	–
Jülich	-2.87-0.36i	–	-2.83-7.82i	–	4.61-0.05i	–	-0.74-1.13i	–
Paris 09	-3.62-0.34i	3.8-0.8i	-8.78-4.99i	0.23-1.1i	5.12-0.02i	-3.4-0.02	-0.49-0.87i	–
KW	-3.36-0.62i	3.7-1.6i	-8.83-4.45i	0.25-0.97i	4.73-0.08i	-3.5-0.1i	-0.46-1.09i	–
DR2	-3.28-0.78i	4.2-2.3i	-8.53-3.50i	0.63-1.0i	5.14-0.09i	-3.4-0.1i	-0.59-0.85i	–
T=1	$^{31}P_1$		$^{33}P_0$		$^{33}P_1$		$^{3}PF_2$	
Nijm*	0.66-0.18i	3.3-20i	2.33-0.92i	-10-0.7i	-2.02-0.70i	4.7-2.8i	–	–
Jülich	0.80-0.34i	–	2.18-0.19i	–	-2.04-0.55i	–	-0.48-0.34i	–
Paris 09	1.00-0.77i	-3.7-9.8i	2.74-0.00i	-5.2-0.01i	0.28-4.11i	-3.0-2.0i	-0.13-0.21i	–
KW	0.71-0.47i	-8.3-21i	2.43-0.11i	-5.8-0.43i	-2.17-0.95i	2.7-3.5i	-0.30-0.45i	–
DR2	1.02-0.43i	-11-10i	2.67-0.15i	-5.4-0.53i	-2.02-0.70i	4.6-3.9i	-0.04-0.53i	–

Table 3 P waves $\bar{N}N$ low energy parameters (in fm^3) for the considered optical models: Jülich results are taken from Tab 3 of Ref. [12], KW and DR2 from [18], Paris 2009 have been recomputed and are in agreement with [44]. The values of Nijmegen are obtained by extrapolating the phase shifts from Figures 2 and 3.

	a_0	r_0	a_0	r_0
T=0	^{11}S$_0$		^{13}SD$_1$	
Nijm*	-0.17 -1.01i	-6.9-2.9 i	–	–
Jülich	-0.21 -1.23i	–	1.42-0.88i	–
Paris 09	1.27 -1.18i	-0.53+0.14i	1.20-0.80i	–
KW	-0.03 -1.35i	-4.7-7.9i	1.23-0.77i	–
DR2	0.10 -1.07i	-11-6.2i	1.28-0.78i	–
T=1	^{31}S$_0$		^{33}SD$_1$	
Nijm*	1.02 -0.60i	0.7-1.2i	–	–
Jülich	1.05 -0.58i	–	0.44-0.96i	–
Paris 09	0.76 -0.56i	0.9-3.9i	0.61-0.44i	–
KW	1.07 -0.62i	0.7-1.9i	0.78-0.80i	–
DR2	1.20 -0.57i	0.6-1.6i	0.89-0.71i	–

Table 2 S-wave $\bar{\text{N}}$N low energy parameters (in fm) for the considered optical models: Jülich results are taken from Tab 3 of Ref. [12], KW and DR2 from [18], Paris 2009 have been recomputed and are in agreement with [44]. The values of Nijmegen are obtained by extrapolating the phase shifts from Figures 2 and 3.

J.Hartmann PRC 65

CAPTURE ORBITS
IN PIONISATION
MEASURMENTS

VERSUS X RAY DATA

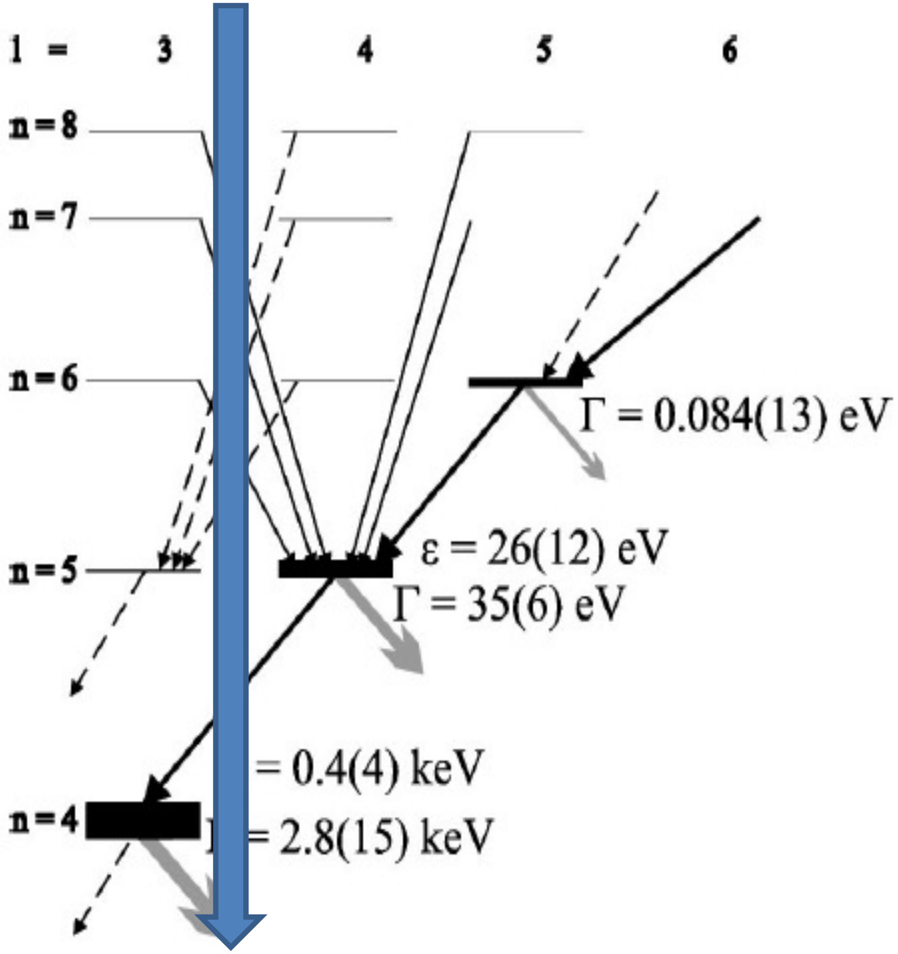


FIG. 3. Mean widths and shifts of all levels with measurable strong interaction effects. The weight of the different calcium iso-

CHIOCE OF PARAMETERS TO DESCRIBE FINAL MESON INTERACTIONS and P(Q)

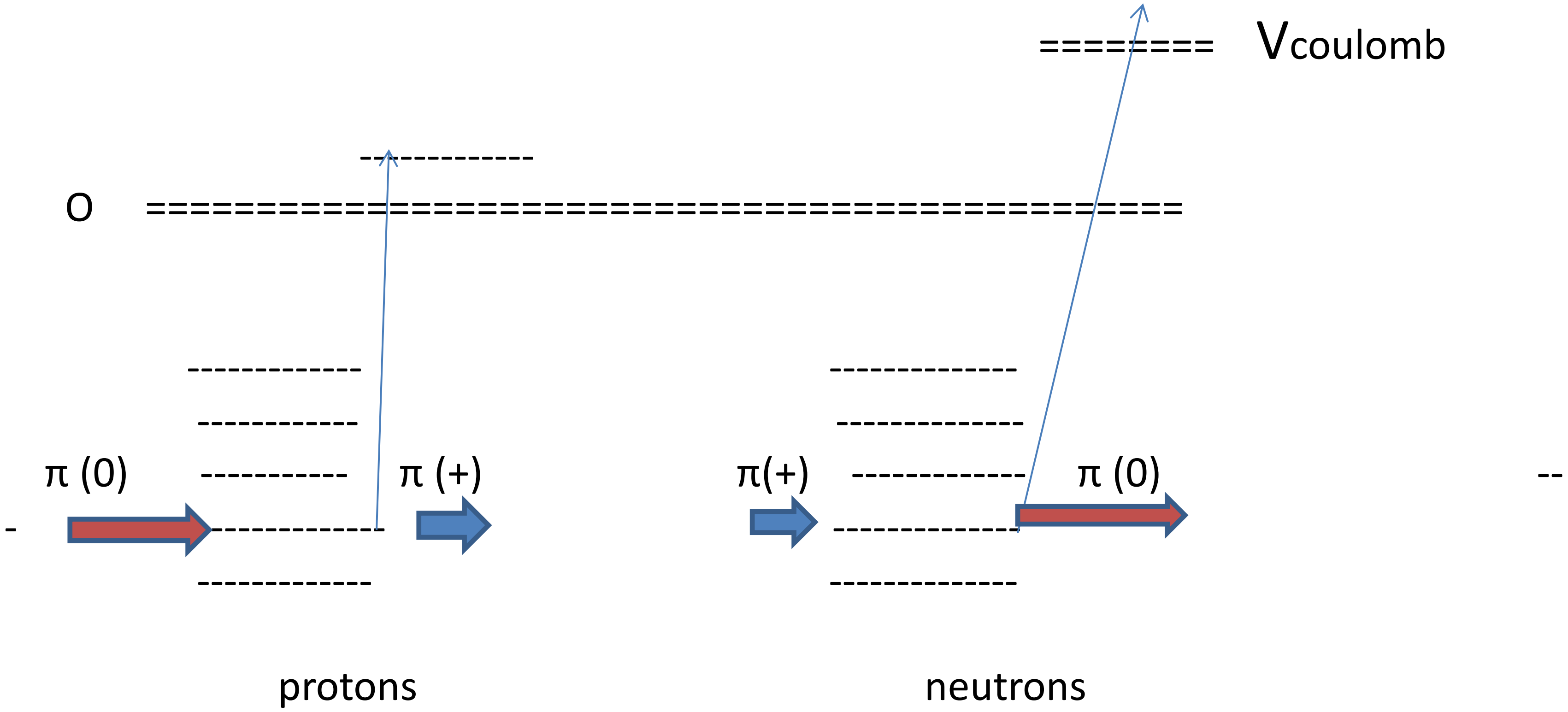
$p\bar{p} \rightarrow Q_{ini} = 0$; $n\bar{p} \rightarrow Q_{ini} = -1$ PARAMETER

$\pi(+)\ NN \rightarrow NN$	$Q \rightarrow Q-1$	
$\pi(+)\ n \rightarrow \pi(0)\ p$	$Q \rightarrow Q-1$	$\omega(+)$
$\pi(-)\ NN \rightarrow NN$	$Q \rightarrow Q+1$	
$\pi(-)\ p \rightarrow \pi(0)\ n$	$Q \rightarrow Q+1$	$\omega(-)$
$\pi(0)\ n \rightarrow \pi(-)\ p$	$Q \rightarrow Q-1$	$\lambda(-)$
$\pi(0)\ p \rightarrow \pi(+)\ n$	$Q \rightarrow Q+1$	$\lambda(+)$
$\pi(0) \rightarrow$ lost		$\omega(0)$

different

$\omega \sim 0.1 - 0.2$; $\lambda \sim 0.15 - 0.40$ from data

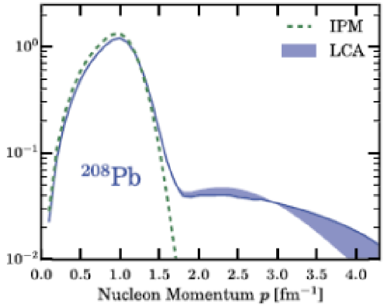
PAULI BLOCKING depends on nucleon binding and momentum



Charge exchange differs from its inverse due to exclusion and Coulomb barrier

Difference depends on nucleon momenta.

Nucleon momenta in a nucleus
Fermi gass sector and p-n short range correlations sector.
M Duer+ Phys Rev Let 112 J. Lab electron scattering



Ryckebush +
Phys L. B792

J. Ryckebusch et al. / Physics l

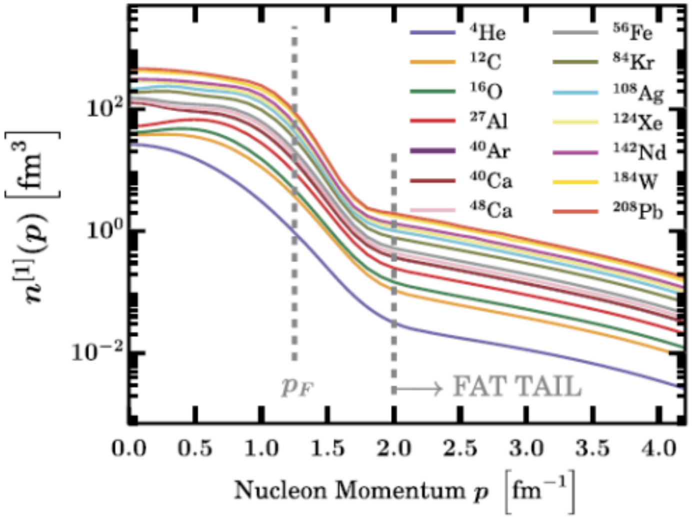
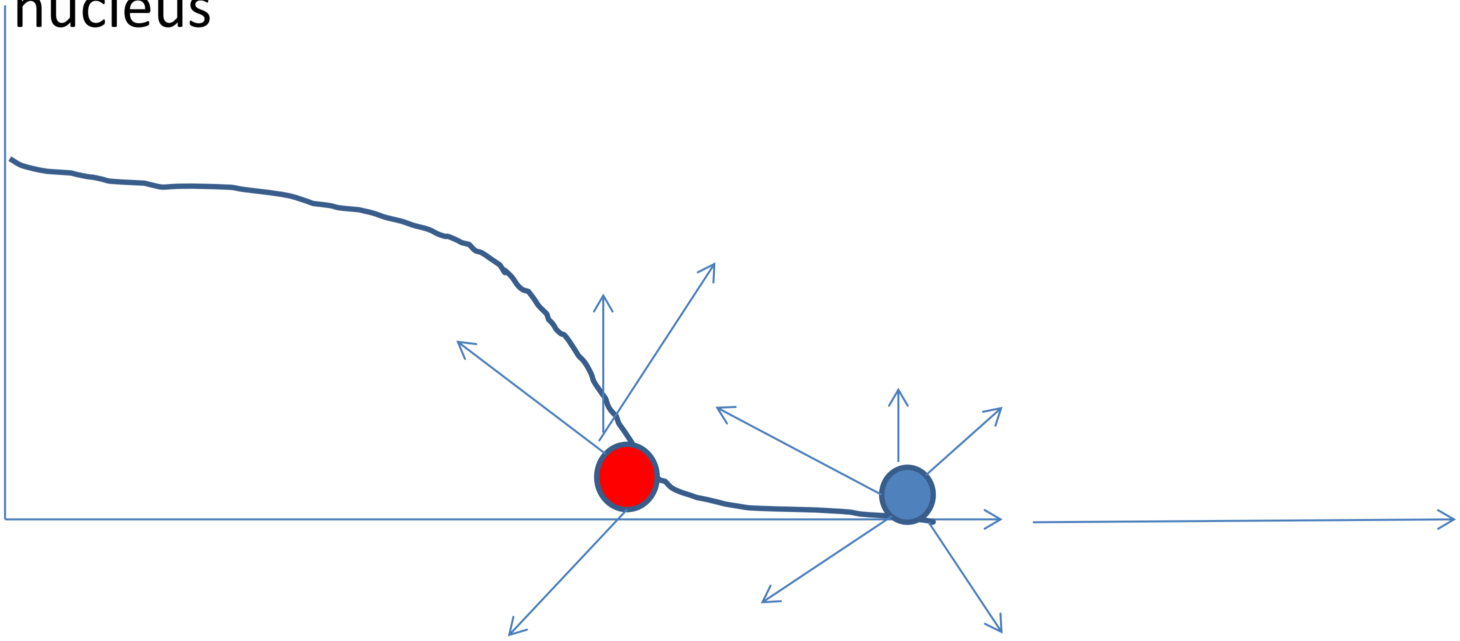


Fig. 2. The momentum distribution for 14 nuclei across the nuclear mass table. The $n^{[1]}(p)$ are computed in LCA with a "hard" central correlation function g_c adopting the normalization convention $\int dp\, p^2 n^{[1]}(p) = A$.

Initiated by Campi and Bouysy , old problem of correlations revived with different physics

Antiproton 🔵 a 2000 MeV bomb on the side of nucleus



→ Mesons from
NN-bar → π π π

🔴 Nucleus destroyed , pions detected , less peripheral

🔵 Cold residual nuclei detected , more peripheral

X – rays regions
in between

state		Exp	Paris 2009	Jülich	KW	DR2
$^1S_0$	$\bar{N}N$		1.02 - i 0.87	0.42 - i 0.91	0.52 - i 0.99	0.65 - i 0.82
	$\bar{p}p$	0.493(92) - i 0.732(146)	0.92 - i 0.67	0.50 - i 0.71	0.57 - i 0.77	0.68 - i 0.64
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SHORT LIFE OF ATOMS

CAPTURE into atomic orbit : emission of a valence AUGER eletron

CASCADE : emission of AUGER electrons

BELOW electron cloud : Emission of X - RAYS

DEATH : nuclear capture emision of ~ five π mesons

SHORT LIFE of ATOMS

Radii = 57 /Z n^2 fm

High l levels

Ψ / r^l ~ const

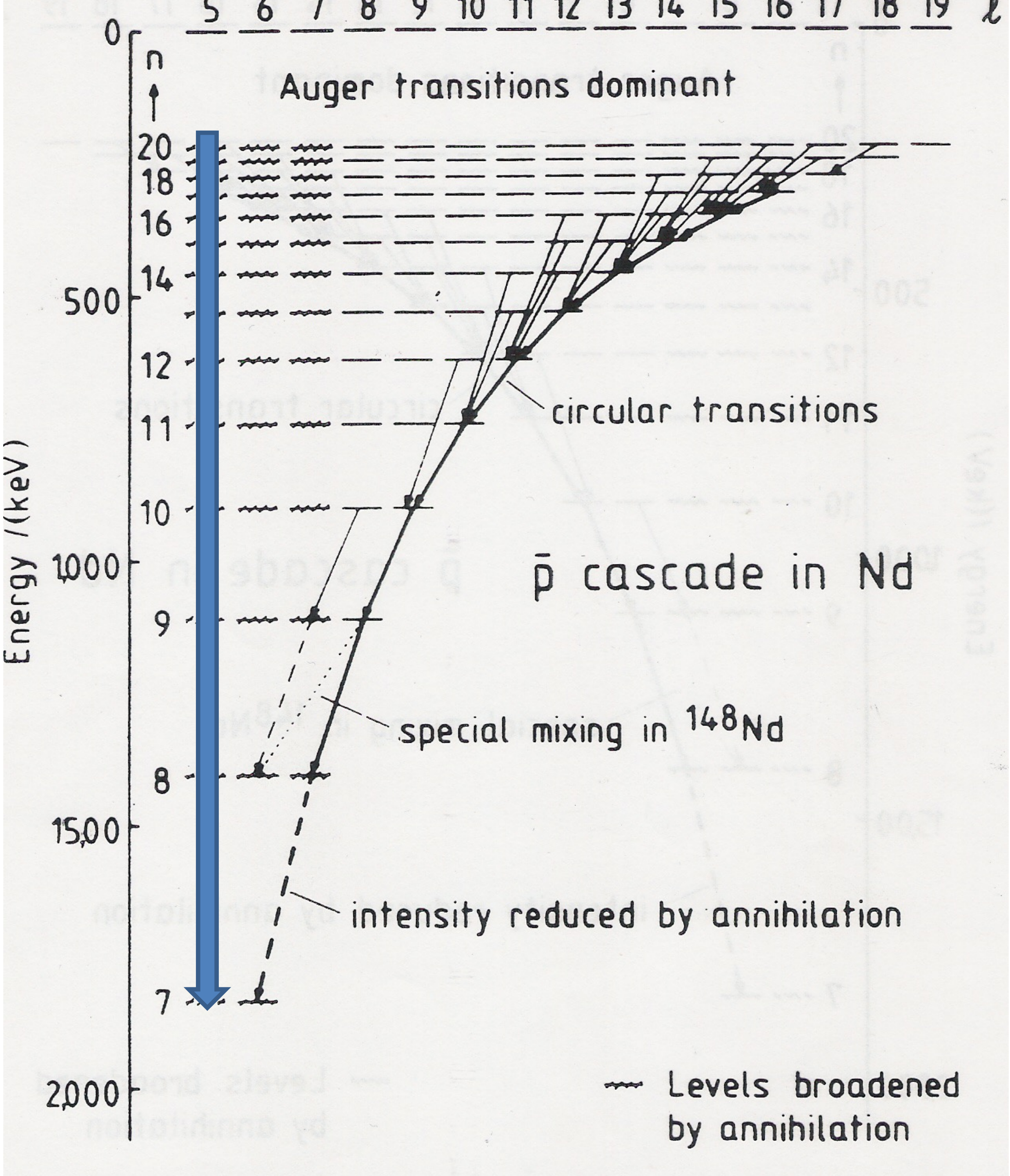
inside nuclei

FINAL PRODUCTS

X-rays

Nuclei

Pions



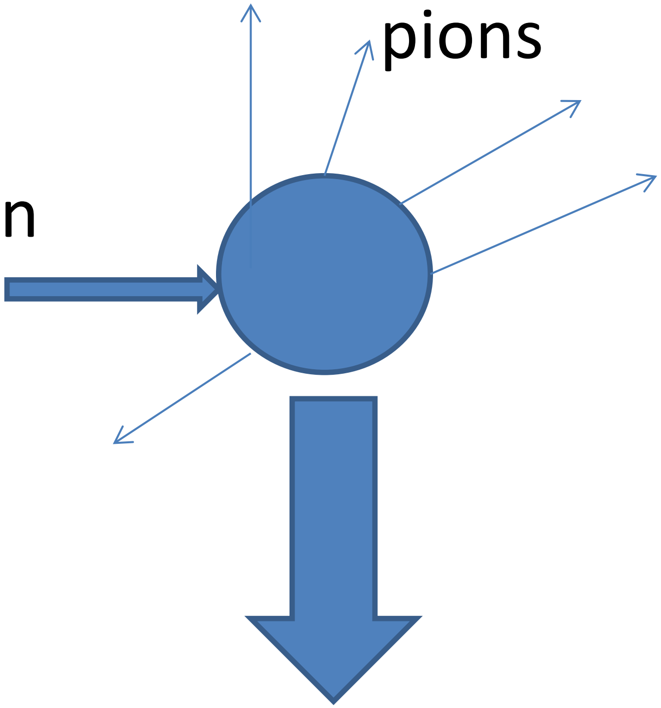
ANTIPROTONIC ATOM - A TOOL TO STUDY NUCLEI

Three different – related measurements

ATOMIC LEVELS via X RAYS	3
DETECTION OF FINAL COLD NUCLEI	2
DETECTION OF FINAL PIONS	8

NUMBER OF DATA / ATOM

Radiochemical measurements of final non excited nuclei
Munich – Warsaw /CERN



pions

do not excite target

antiproton

A-1 NUCLEI MEASURED ➔ RATIO (N-1)/(Z-1)

DETERMINATION OF CAPTURE ORBIT via (A-1)/ TOTAL

ANALYSIS OF COLD CAPTURES

$$\frac{\sigma(N-1)}{\sigma(Z-1)} = \frac{N \quad P_{emissionN}}{Z \quad P_{emissionZ}} R_{n/p} \quad f_{HALO}$$

$R_{n/p}$ relative rate of absorptions (p-bar n) / (p-bar p)

$P_{emission}$ chance for mesons not to excite the nucleus ~10%

Result f_{HALO} excess of neutrons in the capture region

estimated from σ (A-1) / σ (total)

Presentation : if capture region is known

=> Rn - Rp = difference of Rms radii is calculated

Excess of neutrons
over protons
Reduced by N/Z

Lubinski PRC 57
Munich Warsaw

With known
capture orbit

$R_{ms}(n) - R_{ms}(p)$
Extracted

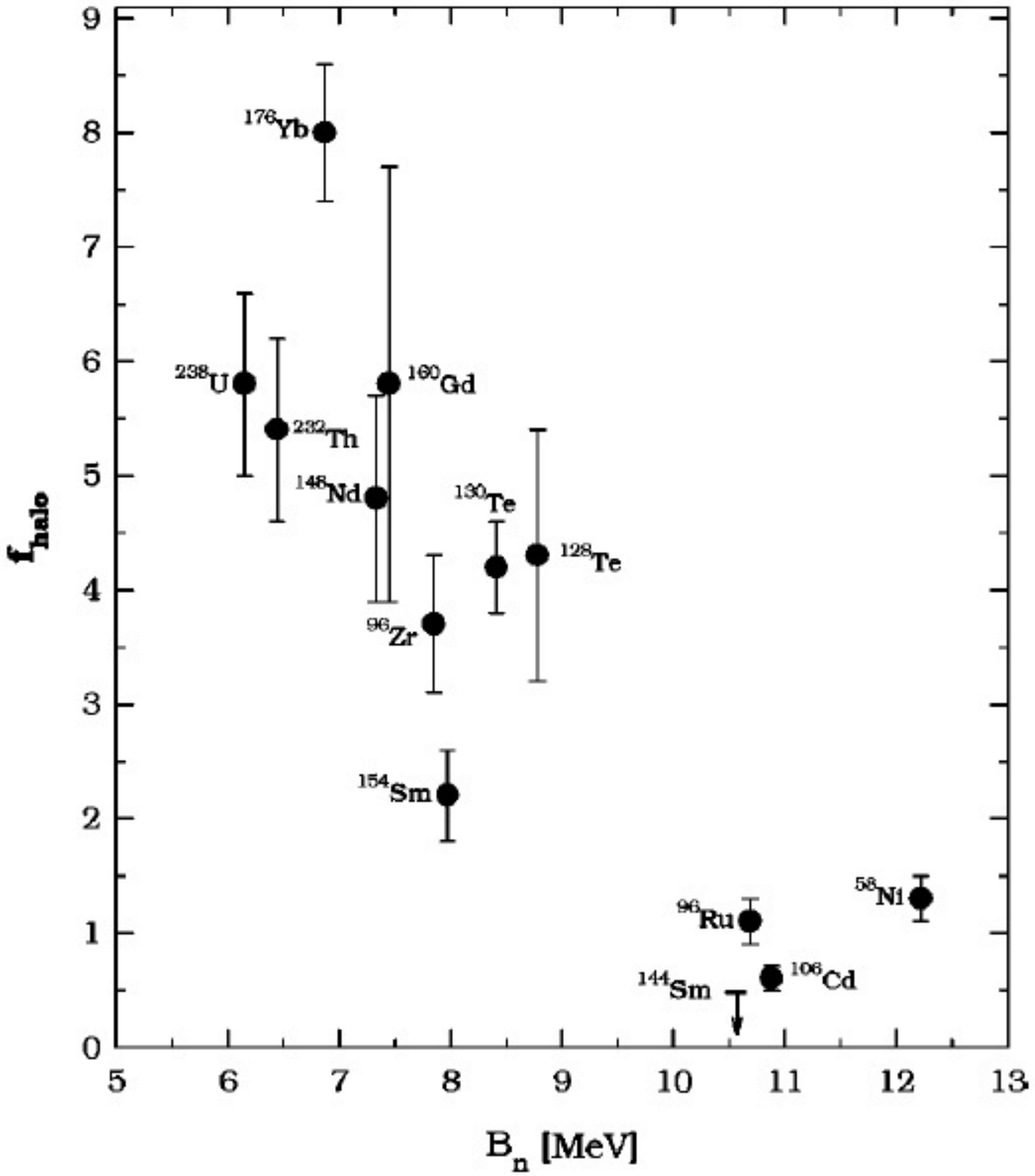


FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy B_n .

WHY NUCLEAR SURFACE IS INTERESTING

* Symmetry energy

$$\beta = (N - Z)/A,$$

$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,0) + S_N(\rho)\beta^2 + \cdots$$ n,p Fermi Gas $$S_N = \frac{1}{3}E_F$$

ρ = density

Droplet Model

$E_{(binding)}$ /A = a_V - S_N β^2 + ...

attractive repulsive due to Pauli

THESE CANCEL AT NUCLEAR SURFACE WITH THE INCREASING NEUTRON/ PROTON RATIO ? NUCLEAR MODEL DEPENDENT

** ARE THERE (np.) or (nnpp) CORRELATIONS AT DISTANT SURFACE.

*** WHAT IS THE FERMI MOMENTUM AT SURFACE

OLD CHAMBER EXPERIMENTS

L. Agnew et.al Phys.ReV 118(1960) 1371
W. Bugg et al. Phys.Rev. Lett 31 (1973) 4761
C,Ti ,Ta,Pb hydrogen chamber
M.Wade, V.G.Lind Phys Rev D (1976) 1182
C propane chamber

MAGNETIC SPECTROMETER , CERN

J. Riedlberger et al Phys Rev C40 (1989) 2717
N

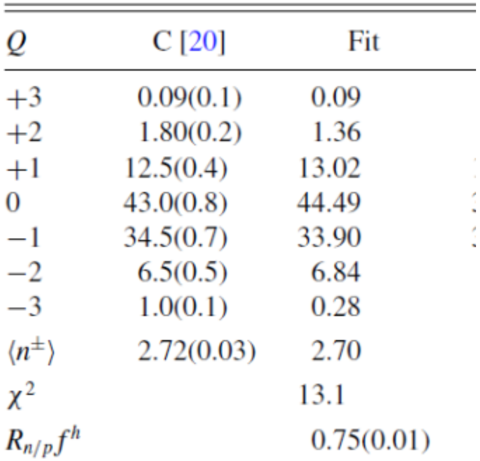
NEW ERA OF PIONISATION EXPERIMENTS
PUMA PROJECT AT CERN (Alexander Obertelli)

ATOMS BUILT ON UNSTABLE – RADIOACTIVE - NUCLEI

First project : M. Wada , Y. Yamazaki
Produce antiprotons at CERN
carry to RIKEN : make atoms of unstable nuclei there

FIT TO CARBON DATA

Wade, Lind ,Phys Rev D14 (1976) 1184
freon chamber

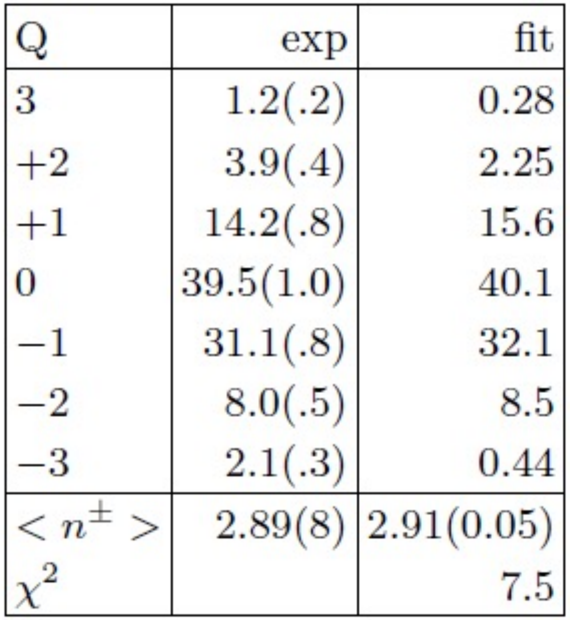


Q	C [20]	Fit
+3	0.09(0.1)	0.09
+2	1.80(0.2)	1.36
+1	12.5(0.4)	13.02
0	43.0(0.8)	44.49
−1	34.5(0.7)	33.90
−2	6.5(0.5)	6.84
−3	1.0(0.1)	0.28
$\langle n^{\pm} \rangle$	2.72(0.03)	2.70
χ^2		13.1
$R_{n/p} f^h$		0.75(0.01)

CONSISTENT with Rp = Rn , R n/p from Paris model ,
No hydrogen contamination

Nitrogen , Riedlberger + PRev C40 (1989) High statistics , No hydrogen contamination, magnetic spectrometer

: Experimental,[21], and fitted charge multiplicities $P[Q]$ in Nitrogen .



Q	exp	fit
3	1.2(.2)	0.28
+2	3.9(.4)	2.25
+1	14.2(.8)	15.6
0	39.5(1.0)	40.1
−1	31.1(.8)	32.1
−2	8.0(.5)	8.5
−3	2.1(.3)	0.44
$< n^{\pm} >$	2.89(8)	2.91(0.05)
χ^2		7.5

$$R_{n/p} \cdot f^h = 0.77(.04)$$

$$\omega^+ = 0.16 \; ; \; \omega^- = .17 \; ; \; \lambda^+ = .16 \; ; \; \lambda^- = 0.10$$

END POINTS INDICATE DOUBLE PION CHARGE EXCHANGE ON RESIDUAL Carbon = ααα

CALCULATIONS OF FINAL STATE INTERACTION PARAMETERS

INTENTION

CALCULATE FINAL STATE PARAMETERS FOR SEVERAL ORBITALS L

FIND L THAT FULFILS

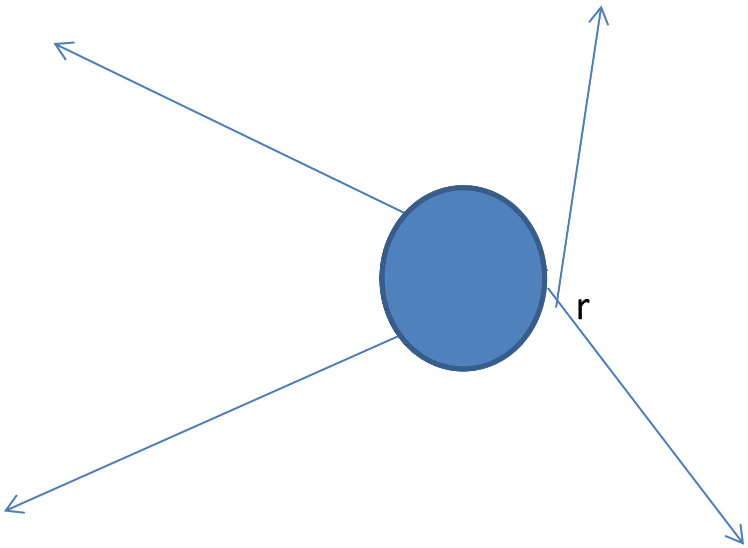
$\omega(L+1) < \omega(\text{best fit}) < \omega(L)$

$\lambda(L+1) < \lambda(\text{best fit}) < \lambda(L)$

Extract probabilities of two dominant orbitals

CALCULATION OF PARAMETERS

MESONS ARE FAST average momenta ~ 400 MeV/c ➔ eikonal approximation



$$T_{\rm expt}(\mathbf{r},\mathbf{k}) = \exp\left[-\lambda_{\rm expt}\int_0^\infty ds\,\rho_p(\mathbf{r}-s\widehat{\mathbf{k}})\right].$$

Survival amplitude T =1 - ω

Average over momenta , directions
number of mesons

Charge exchange λ = σ * Pauli Blocking factor mostly surface
NN absorption ρ → ρρ mostly centre

NUCLEAR PHYSICS OF PIONS

π NN → N Δ(1232) → π NN absorption via unitarity
many old models fairly
consistent with phenmenology
(W R Gibbs , Johnson and Satchler)

Charge exchange π(-) p → Δ → π(0) n cross sections measured
Breitschopf P. Let 639 B 2009

strongly changed in nuclear matter ,

Nuclear cross section , absorption, charge exchange
D Ashery + , OLD and uncertain

LOCAL DENSITY APPROXIMATION FOR NUCLEAR MOMENTA

$K_{FERMI} \sim \rho^{(1/3)}$

GOOD UNDERSTANDING OF SUMS

$\omega(+) + \omega(-)$ and $\lambda(+) + \lambda(-)$
ALLOWS TO FIX ORBITALS OF CAPTURE

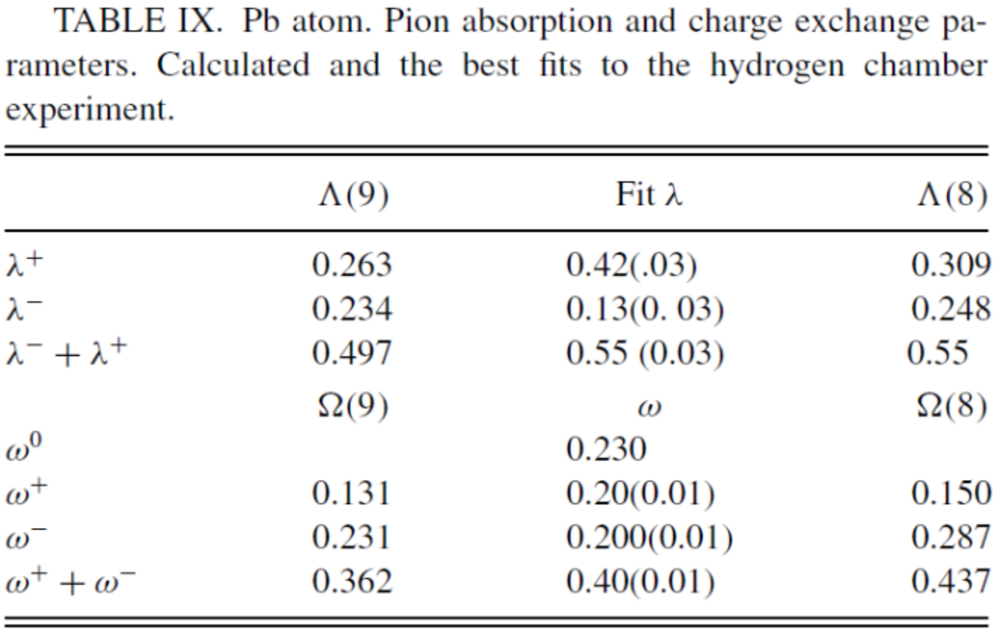


TABLE IX. Pb atom. Pion absorption and charge exchange parameters. Calculated and the best fits to the hydrogen chamber experiment.

	$\Lambda(9)$	Fit λ	$\Lambda(8)$
λ^+	0.263	0.42(.03)	0.309
λ^-	0.234	0.13(0. 03)	0.248
$\lambda^- + \lambda^+$	0.497	0.55 (0.03)	0.55
	$\Omega(9)$	ω	$\Omega(8)$
ω^0		0.230	
ω^+	0.131	0.20(0.01)	0.150
ω^-	0.231	0.200(0.01)	0.287
$\omega^+ + \omega^-$	0.362	0.40(0.01)	0.437

Example neutron radius in Pb

Pionisation { W.Bugg }

$R_{ms}(n) - R_{ms}(p) = 0.20(0.03)\ \mathrm{fm}$ $\qquad$ $R_{n/p} = 0.92$

Cold capture { Munich-Warsaw}

$R_{ms}(n) - R_{ms}(p) = 0.16 \pm (0.02) \pm (0.04)\ \mathrm{fm}$ $\qquad$ $R_{n/p} = 1,$

THE SAME HALO , difference due to choce of Rn/p

PROBLEMS BE SOLVED FOR PUMA BY THEORISTS

(1)
Why sums of absorption ω(+) + ω(-) ;
and charge exchange λ(-) + λ(-) are understood
and each term is not ? An additional advantage of PUMA ?

(2)
Refine the n/p capture ratio R n/p (BARYONIA ?)

(3)
Could we detect α- type structure on surface
indicated by experiment in Nitrogen

OTHER PROBLEMS OF RELATED INTEREST

Baryonia, nuclear states of antiprotons

(1)

SUBTLE EFFECTS OF NUCLEON MOMENTUM DISTRIBUTION

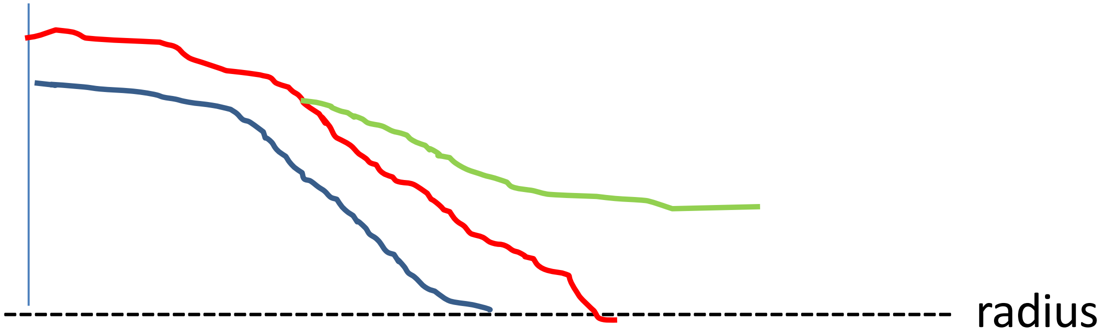
DO WE KNOW FERMI MOMENTUM AT SURFACE

FERMI MOMENTUM AT NUCLEAR SURFACE ?

Fermi gas $K_{FERMI} \sim \rho^{1/3}$

$\rho(x.x') = \sum \phi(x)\,\phi(x')^*$ Wigner function

$= \rho\,(x/2+x'/2)\;\; j_1(K_{FERM}|x-x'|\,)$ correlation function



K_{FERMI} (r) Fermi gas : **K_{fermi} shellmodel** **X Campi, A Bouyssy , 1973**

Pion charge exchange on short-range correlated
(p,n) pairs
A 3 body problem in external field

In the bulk of nuclei

$\varpi(+) + \varpi(-)$
and
$\lambda(+) + \lambda(-)$ effects of p-n corelation cancel out

Individual terms $\lambda(+)$, $\lambda(-)$ $\varpi(+)$, $\varpi(-)$
change by 20% (an estimate) in the directon of data

CONCLUSION
if PUMA is very precise one may extract changes of (p,n) correlations with increasing neutron numbers

(2) INPUT R n/p

ANTIPROTON - NUCLEON SCATTERING AMPLITUDES IN UNPHYSICAL REGION

NUCLEONS ARE BOUND $E = 2M - \Delta$

Δ from 0 to - 34 MeV

REGION OF QUASI – BOUND STATES

WHY SUBTHRESHOLD ENERGY

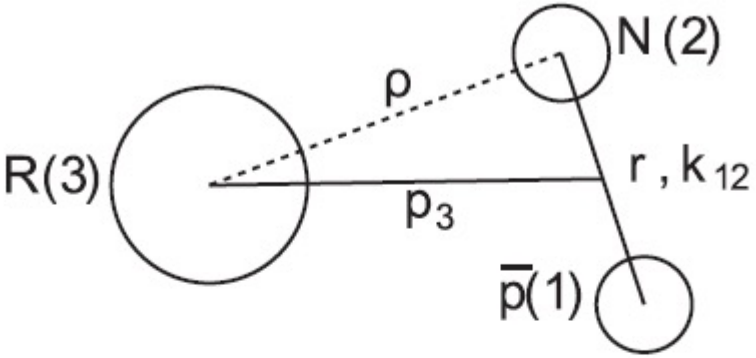


FIG. 1. Quasi-three-body system: (1) antiproton, (2) nucleon, and (3) residual system. Jacobi coordinates: momentum $\boldsymbol{p}_3, \boldsymbol{k}_{12}$ and space $\boldsymbol{\rho}, \boldsymbol{r}$.

In atoms
Kinetic N-Nbar ENERGY in CM system is negative

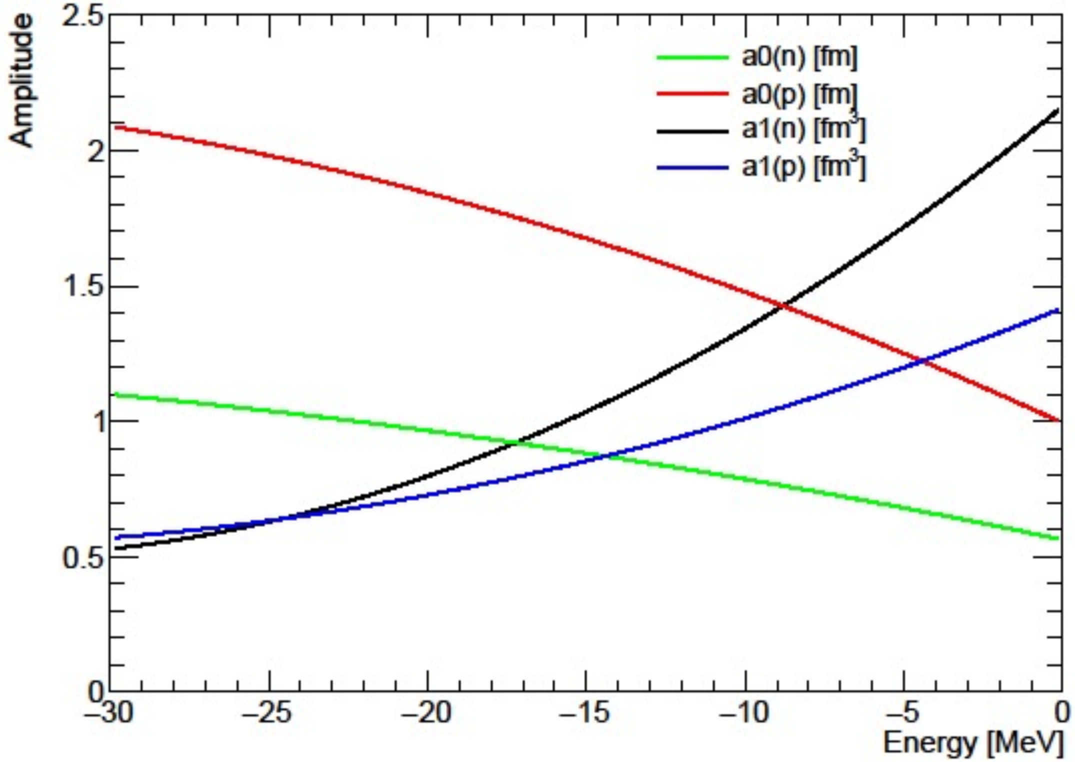
$E_{CM} = 2M - \text{Binding} - \text{Recoil}$

$\bar{N}$ – N quasi- bound states

-

Absorptive p-bar N scattering lengths a0 and scattering volumes a1

Neutron/proton capture rates is energy (state) dependent



Next week seminar by J.Carbonell

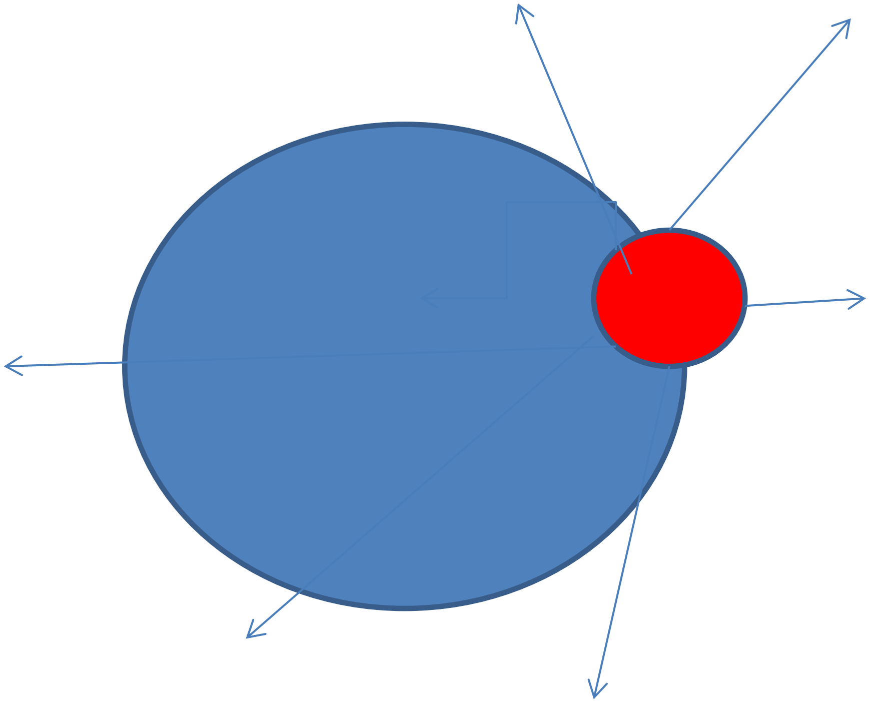
THANK YOU

Initial vector mesons ρ =====➔ π π

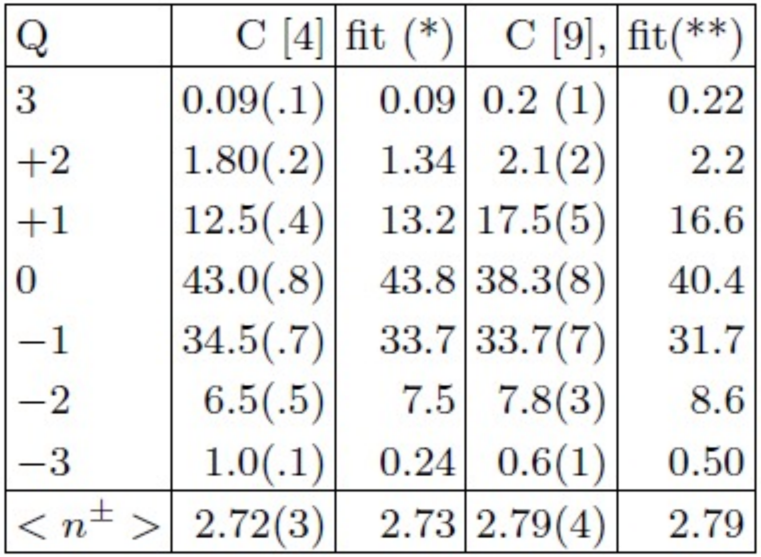
1 fm

Spherical angle of the nucleus „ seen by pions” does not change much

SW. PRevC 54(1996)



TWO EXPERIMENTS DIFFERING BY HYDROGEN CONTAMINATION
(BUUG vs WADE)
LARGE DIFFERENCE S IN Q = -1,0 channels
(proton and/ or hydrogen sectors)



Q	C [4]	fit (*)	C [9],	fit(**)
3	0.09(.1)	0.09	0.2 (1)	0.22
+2	1.80(.2)	1.34	2.1(2)	2.2
+1	12.5(.4)	13.2	17.5(5)	16.6
0	43.0(.8)	43.8	38.3(8)	40.4
−1	34.5(.7)	33.7	33.7(7)	31.7
−2	6.5(.5)	7.5	7.8(3)	8.6
−3	1.0(.1)	0.24	0.6(1)	0.50
$< n^{\pm} >$	2.72(3)	2.73	2.79(4)	2.79

ABOUT 10% of residuals are A-1 nuclei

fixes orbitals of capture

mostly „upper” levels

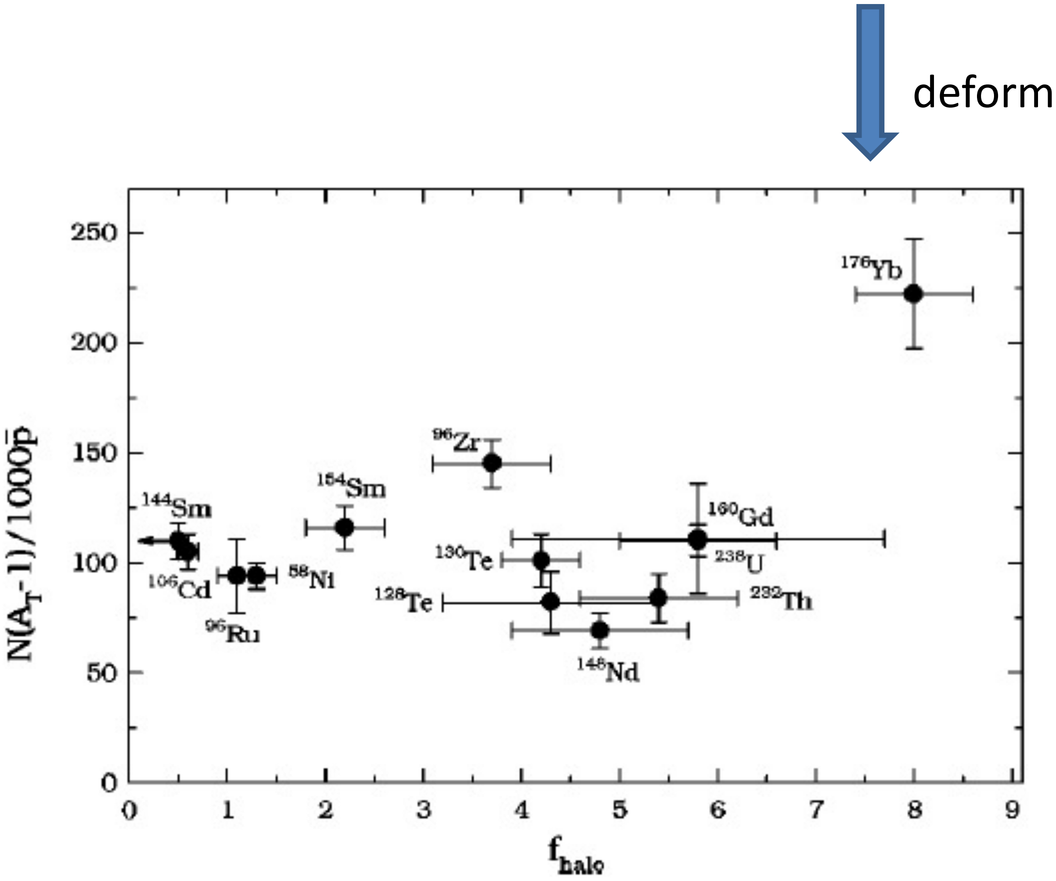

deformed nucleus

FIG. 5. Correlation between halo factor and absolute production yield for $A_t - 1$ nuclei.

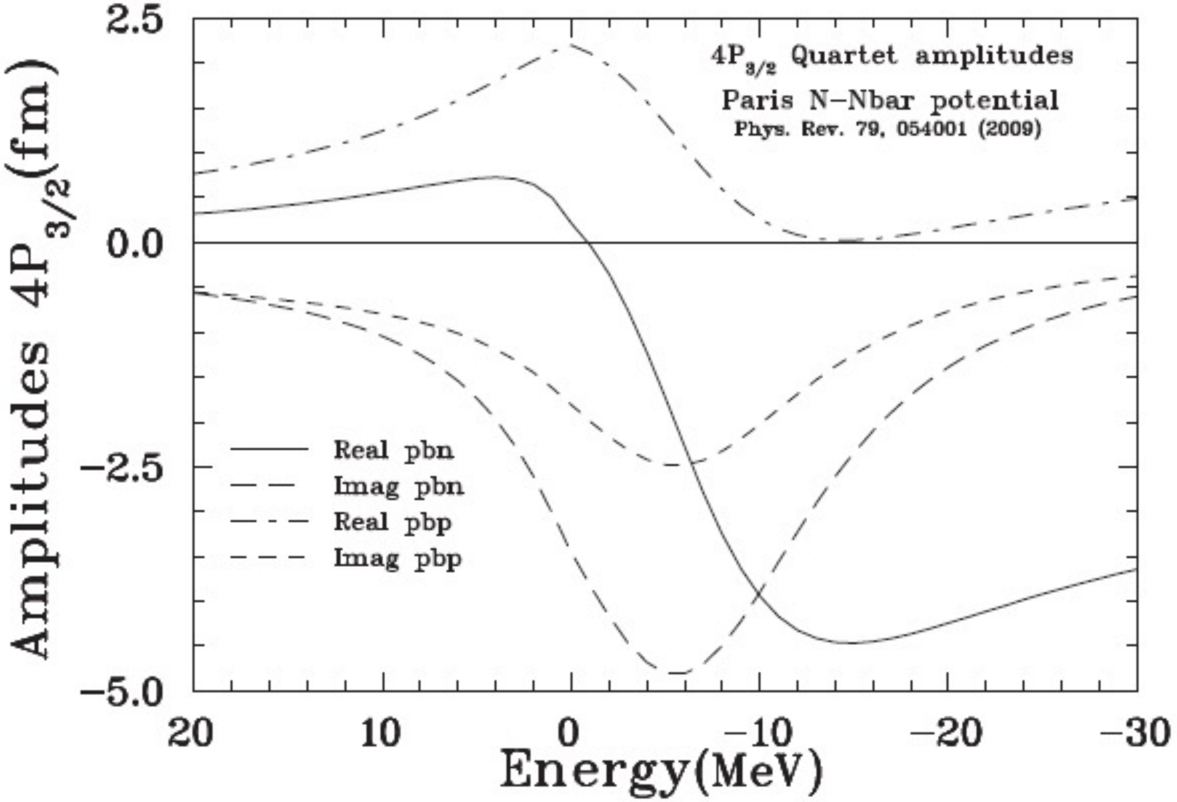


FIG. 2. Subthreshold amplitudes generating the $4P_{3/2}$ hyperfine structure component in deuterium. With the Paris 09 solution this amplitude is strongly dominated by the resonant $a(^{33}P_1)$ amplitude.

Not under full
controll

PUMA EXPERYMENT

ANTIPROTONIC ATOMIC EXPERIMENTS

(1) Measurements of atomic level shifts and widths

CERN ERA SINCE 1980

➔ DEEP ~ 100 MeV ATTRACTIVE NUCLEAR POTENTIAL

➔ STRONG ~ 100 MeV ABSORBTIVE POTENTIAL

never tested inside nuclei

nuclear quasi-bound states expected , not found (too broad)

(2) Detection of residual nuclei

CERN Munich –Warsaw collaboration T. v. Egidy , J. Jastrzebski

➔ neutron haloes Rms (neutrons) – Rms(protons)

(3) π mesons detected old experiments L. Agnew, W. Bugg ~ 1980)

NEW ERA 2021 PUMA / CERN / A. Obertelli

Collaboration

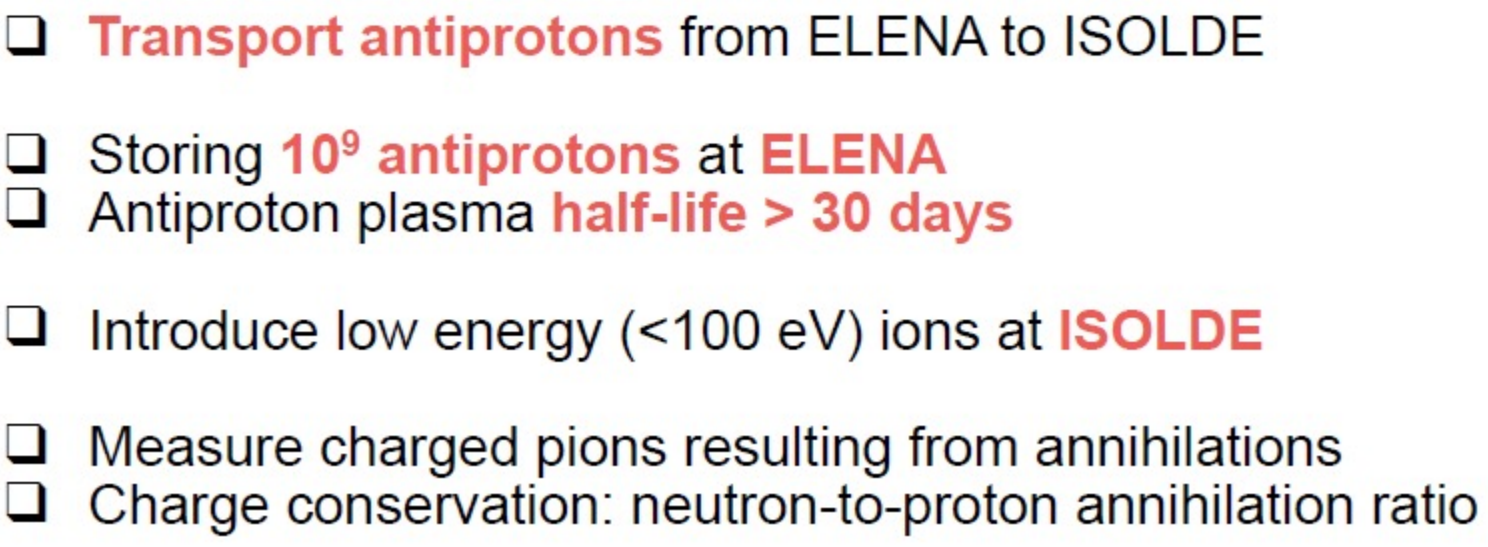
TECHNISCHE
UNIVERSITÄT
DARMSTADT

---

49 collaborators (39 staffs, 6 postdocs, 4 PhDs) from 13 laboratories, including 42 experimentalists and 7 theorists

T. Aumann, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, F. Ehm, J. Ferreira Somoza, J. Fischer, M. Fraser, E. Friedrich, M. Gomez-Ramos, J.-L. Grenard, G. Hupin, K. Johnston, Y. Kubota, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, D. Neidherr, G. Neyens, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, D. Rossi, H. Scheit, R. Seki, A. Schmidt, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, F. Wienholtz, S. Wycech, S. Zacarias

PUMA PROJECT

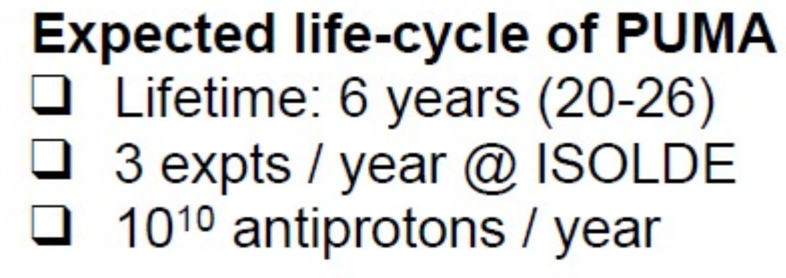


- ☐ **Transport antiprotons** from ELENA to ISOLDE

- ☐ Storing **10^9 antiprotons** at **ELENA**
- ☐ Antiproton plasma **half-life > 30 days**

- ☐ Introduce low energy (<100 eV) ions at **ISOLDE**

- ☐ Measure charged pions resulting from annihilations
- ☐ Charge conservation: neutron-to-proton annihilation ratio



Expected life-cycle of PUMA
- ☐ Lifetime: 6 years (20-26)
- ☐ 3 expts / year @ ISOLDE
- ☐ 10^{10} antiprotons / year