ATIPROTON - A TOOL FOR NUCLEAR STUDIES

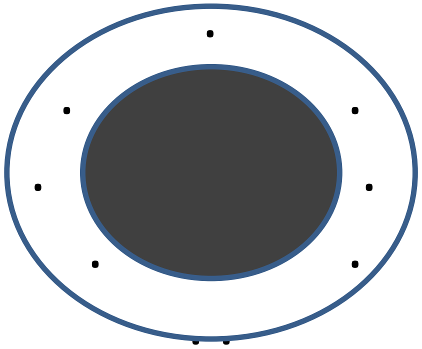
Sławomir Wycech

SPECIAL FEATURES OF ANTIPROTON

STRONG ABSORPTION IN NUCLEI

$\sigma_{abs} \sim 200$ mb

free path in nuclei $1/\sigma\rho = 0.3$ fm

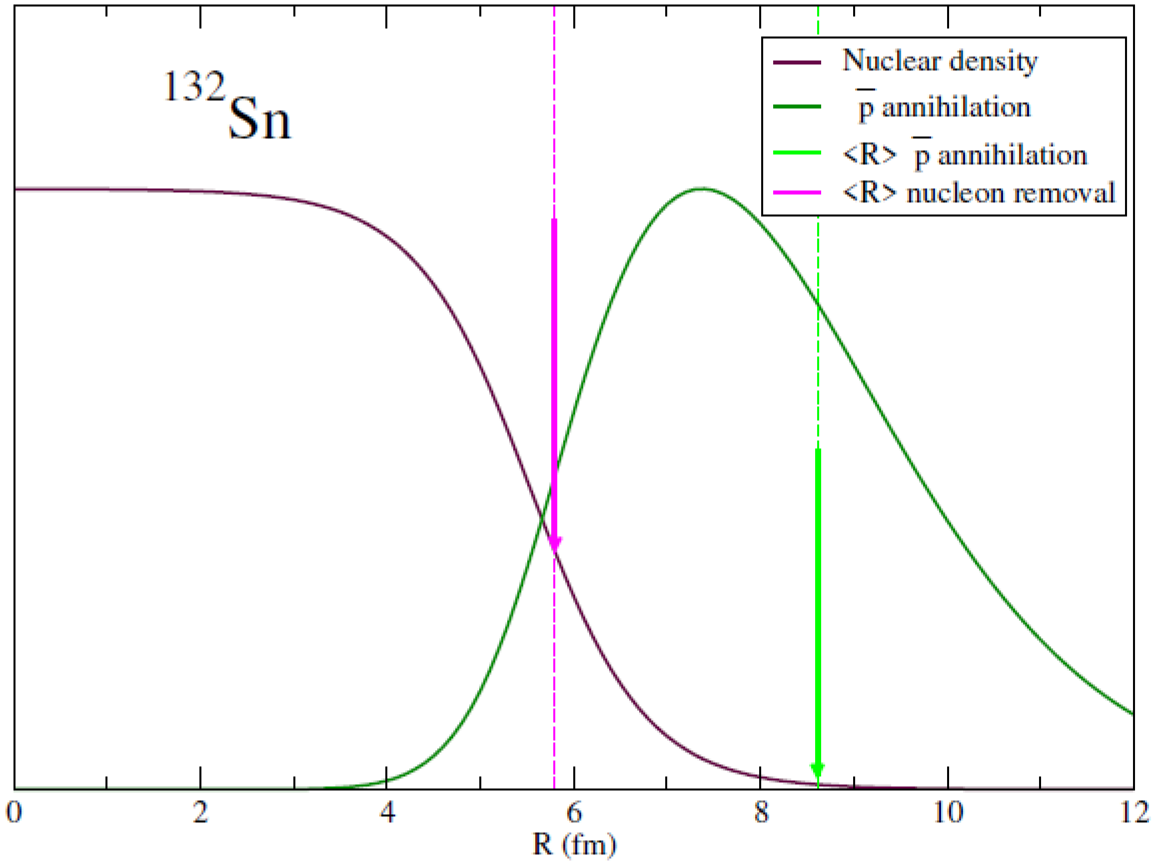


does not enter nuclei

CHARACTERISTIC TRACE N Nbar → π..π.. π..π 2 – 8 mesons

2/3 charged

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



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

$E_{(\text{binding})}/A = a_V - S_N \beta^2 + \ldots\ldots\ldots$

attractive repulsive due to Pauli

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

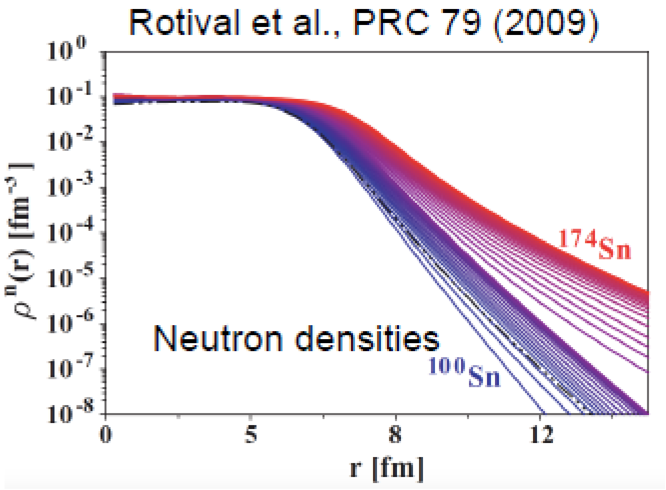
** ARE THERE (np.) or (nnpp) CORRELATIONS AT DISTANT SURFACE.

*** WHAT IS THE FERMI MOMENTUM AT SURFACE

EXPECTATION - an EXAMPLE

from A. Obertelli

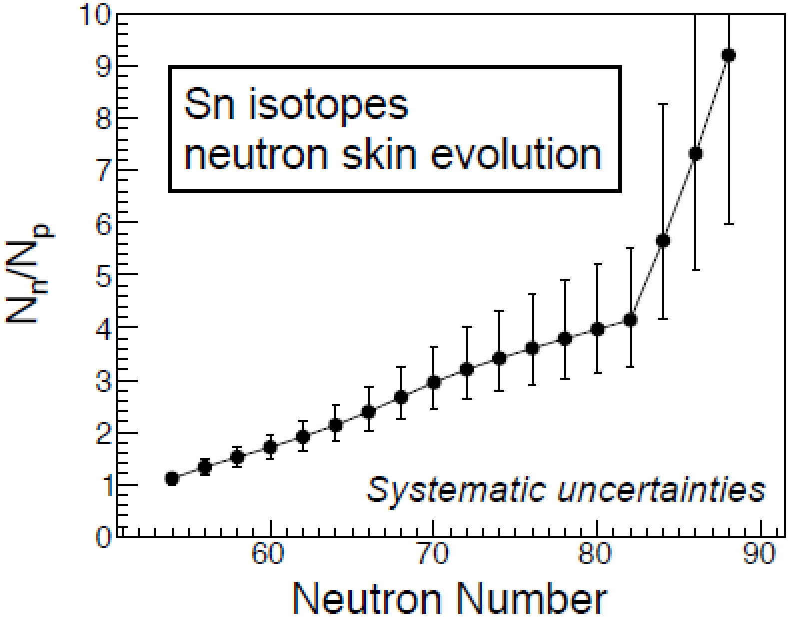
Neutron tails



Rotival et al., PRC 79 (2009)

Pbar nuclear absorption region

n/p ratio expected at capture radius



MOTIVATION

PUMA at CERN :   From
Alexandre Obertelli

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

PUMA EXPERIMENT

PRODUCES ANTIPROTONS

TRANSPORTS in A „BOTTLE”

COLLIDES ANTIPROTONS WITH UNSTABLE NUCLEI
MAKES ANTIPROTONIC ATOMS

waits for X ray cascade, and nuclear capture

DETECTS CHARGED π MESONS FROM ANNIHILATION

ANALYSIS , FOR THEORISTS (J.C.. ; G.H., S.W)

ESTABLISH ATOMIC ORBITS OF NUCLEAR CAPTURE

done

CALCULATE ABSORPTION RATIO

in progress

σ (Pbar –n) / σ(Pbar – p)

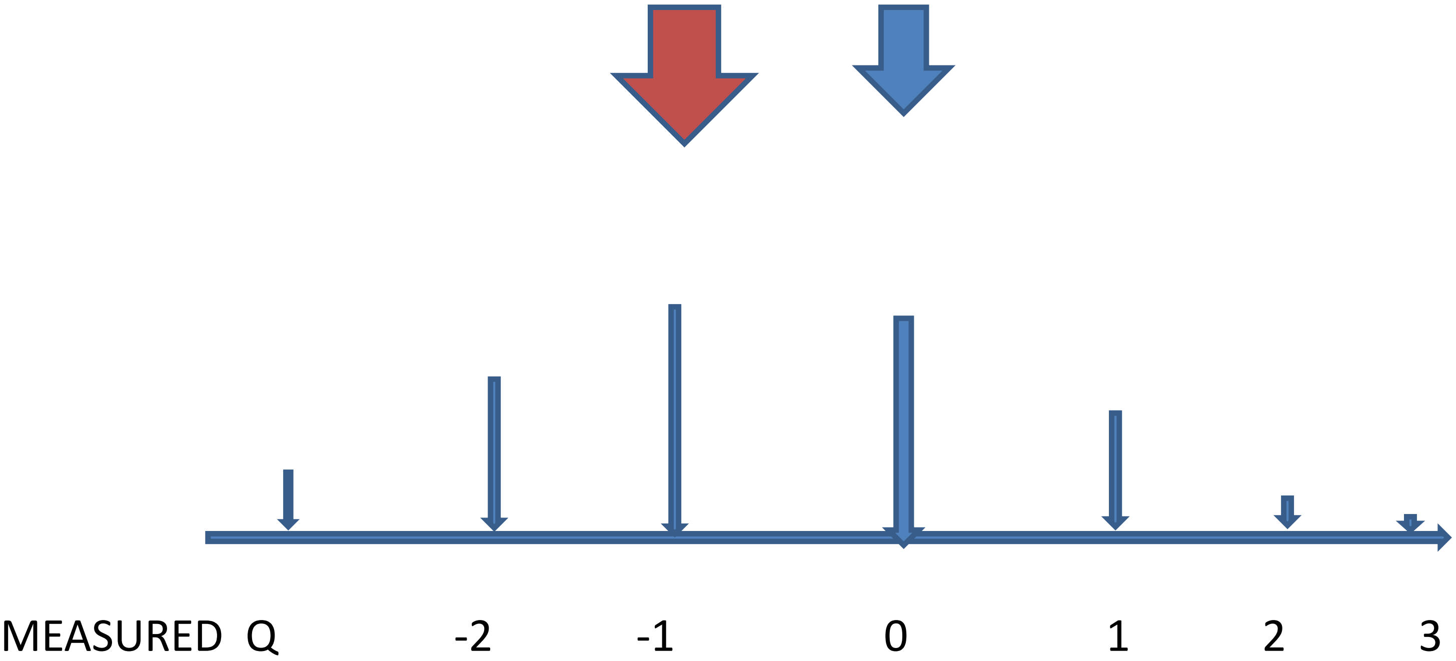
➔ NEUTRON HALO (SKIN)

➔ NN , PPNN CORRELATIONS ON SURFACE

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 $\pi^+ \rightarrow \pi^0$, $\pi^0 \rightarrow \pi^+$
$\pi^- \rightarrow \pi^0$, $\pi^0 \rightarrow \pi^-$

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

extract the orbits of captures

calculate neutron haloes

CAPTURE ORBITS
IN PIONISATION
MEASURMENTS

VERSUS X RAY DATA

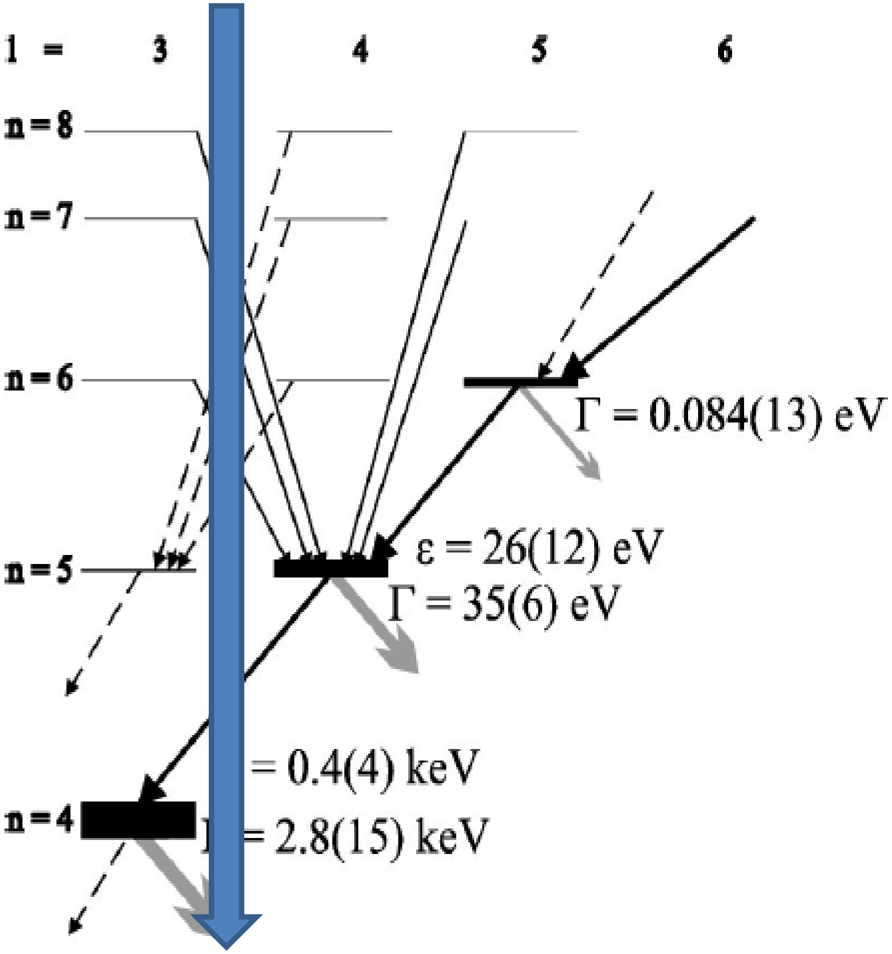


FIG. 3. Mean widths and shifts of all levels with measurable strong interaction effects. The weight of the different calcium iso-

RESULTS

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

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

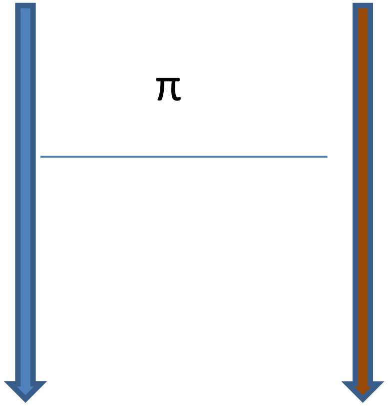
DOMINANT CAPTURE ORBITS :
THE LOWEST STATES REACHED IN ATOMIC CASCADE

Rms RADII OF NEUTRON DENSIES CONSISTENT
WITH OTHER EXPERIMENTS

SIZABLE ERRORS -
uncetrain ratio of captures on protons relative to neutrons

SECOND ESSENTIAL JOB FOR THEORY

A MODEL FOR NUCLEON-ANTINUCLEON INTERACTIONS



+ π- π CORRELATED BY DISPERSION RELATIONS
+ PHENOMENOLOGY MODEL DEPENDENT

EXTEND BEST MODEL TO LOW ENERGY ,
FIND BOUND STATES

COMPARISON N-Nbar Interaction OF MODELS

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 ?

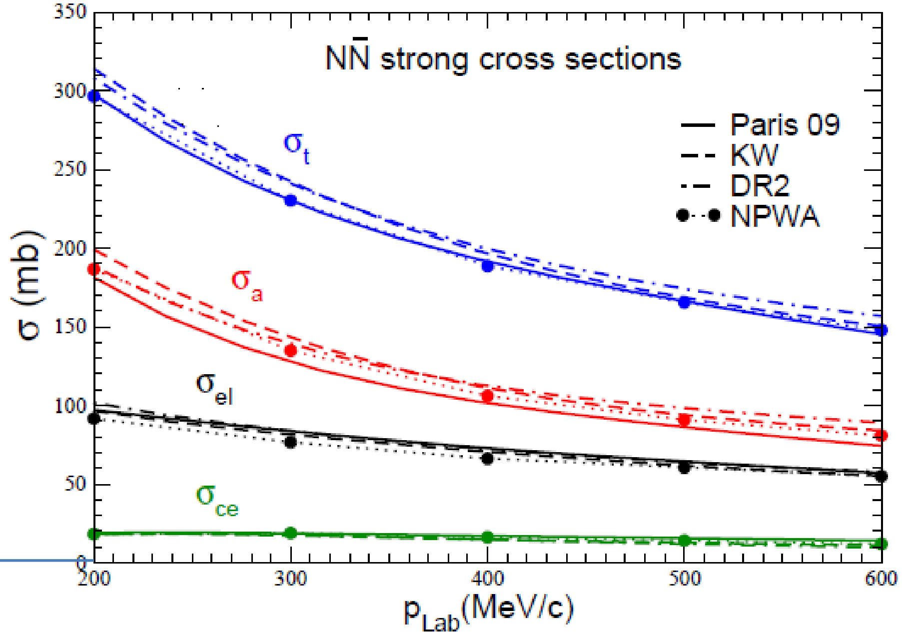


Fig. 1 Integrated strong $\bar{N}N$ cross sections – elastic σ_e (black), annihilation σ_a (red), charge-exchange σ_{ce} (green) and their sum σ_t (blue) – as functions of the $\bar{N}$ laboratory momenta for DR2 (dashed dotted line), KW (dashed line) and Paris 2009 (solid line) optical models. The results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

DATA 4000 BUT

TOO MANY PARTIAL WAVES
NO EXCLUSION PRINCIPLE AS IN N- INTERACTION

POSSIBLE BARYONIA

INCONSISTENT MODELS

PARIS : Meson Exchange ,
Dispersion relations

BONN : Chiral expansion
NIMEGHEN Phenomenology

KIOT0-MUNICH Meson exchange

EXAMPLE

S-WAVE BARYONIUM

BES III

P-Pbar

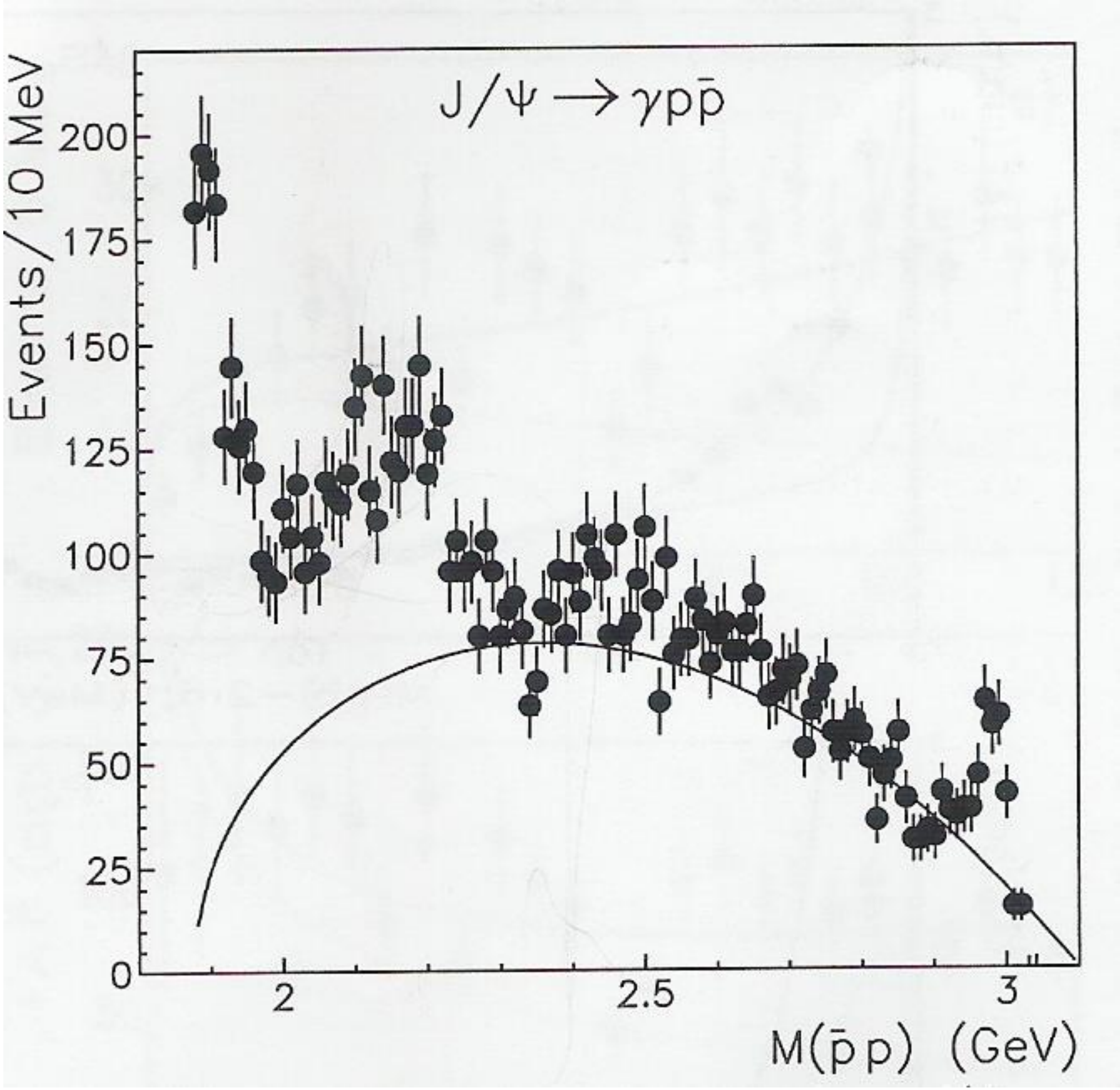
BOUND

STATE

INDICATED

ISOSPIN

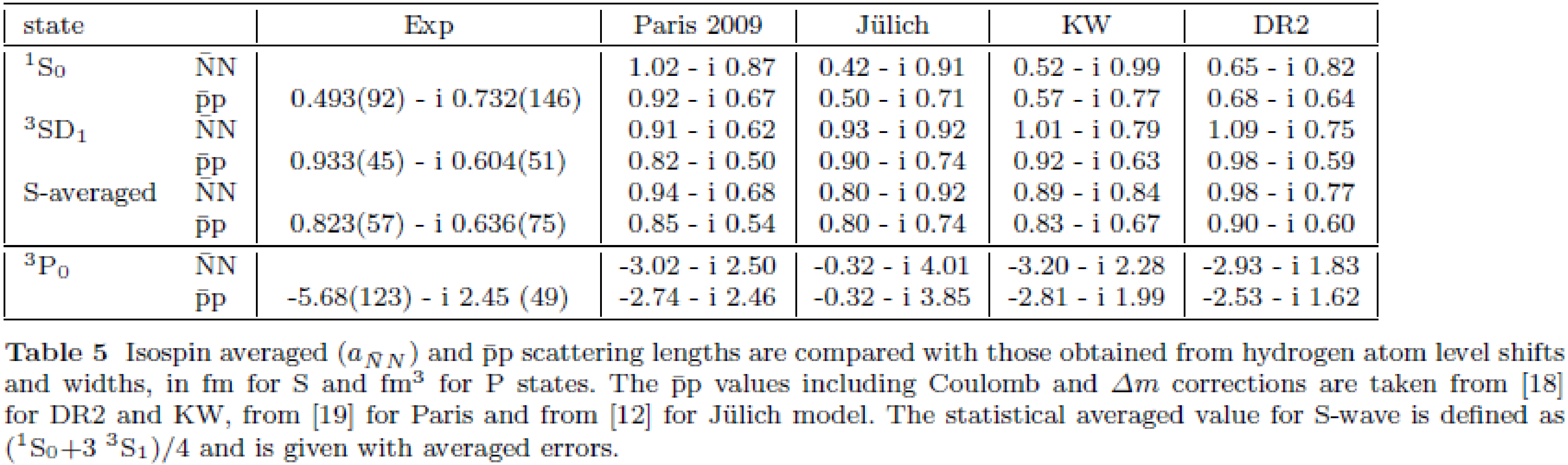
UNKNOWN



TESTING S - WAVE AMPLITUDES AT THRESHOLD
Antiprotonic –hydrogen : 1S , 2P levels

➔ 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.

CHAOTIC POTENTIALS FOR S-singlet PARTIAL WAVE

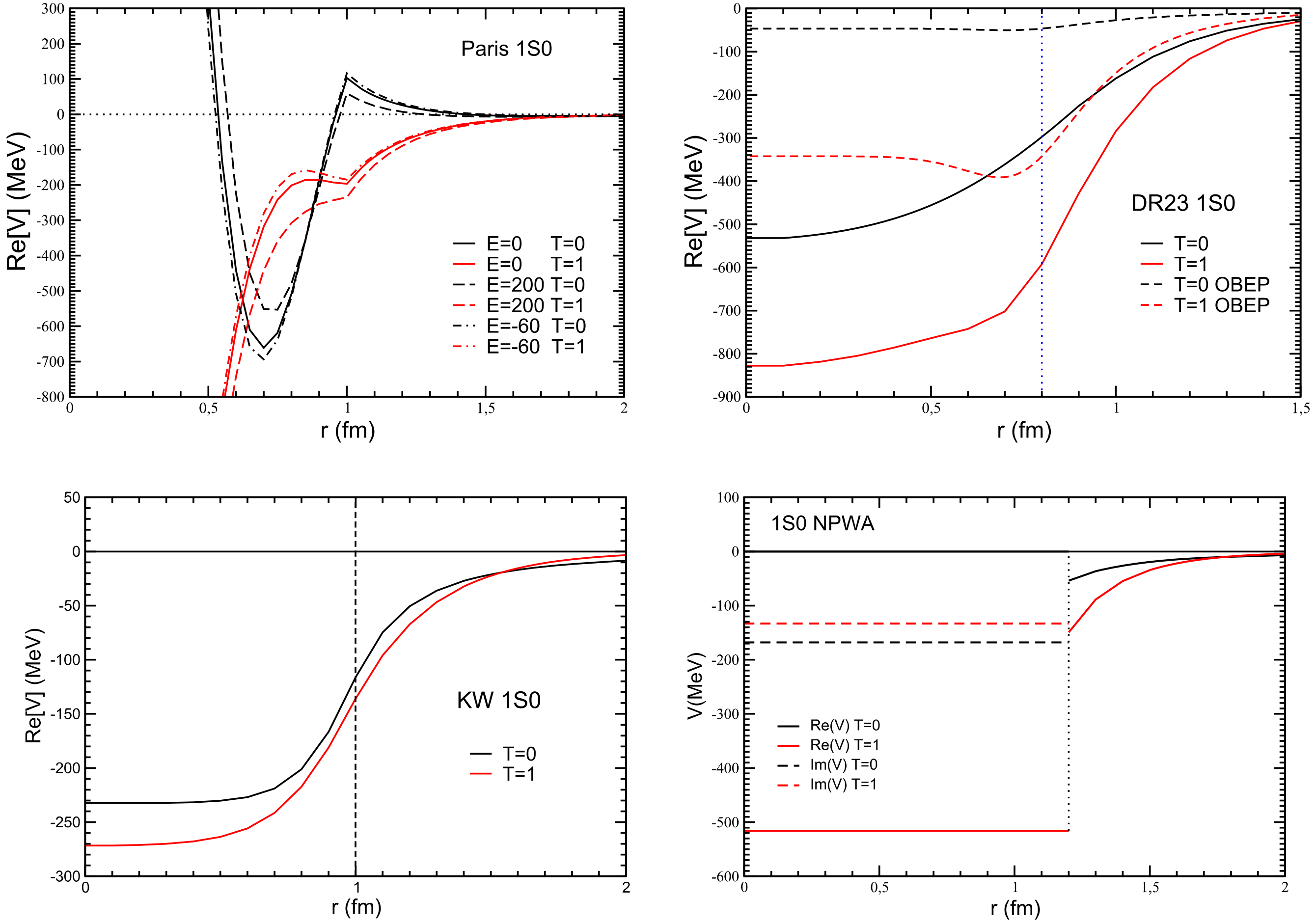


Fig. 15 Real parts of $^1S_0$ potentials for both isospins (T)

OUR PROGRAM

CHECKING INCONSISTENCIES IN EXISTING N-Nbar THEORIES

J.C ,G.H. ,SW EUR. Phys. J A

NEW MODEL FOR N-Nbar INTERACTIONS

INCLUDING : SCATTERING DATA = AMPLITUDES IN PHYSICAL REGION

ATOMIC LEVELS = AMPLITUDES FOR NEGATIVE KINETIC ENERGIES

(2) CALCULATE ANTIPROTONIC NUCLEAR STATES

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

THANK YOU

APPENDICES – 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.

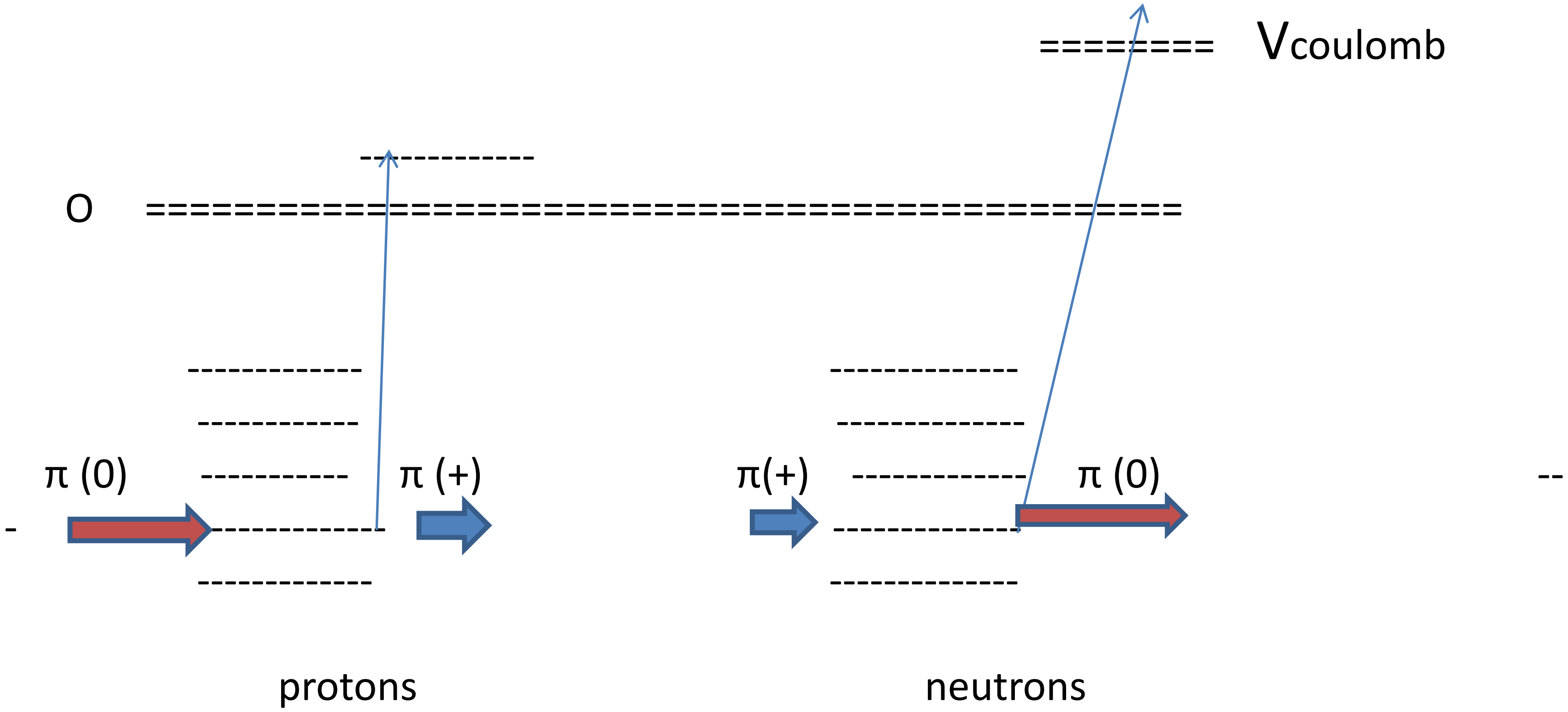
CHIOCE OF PARAMETERS TO DESCRIBE FINAL MESON INTERACTIONS and P(Q)

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

π (+) NN → NN	Q→ Q-1	
π (+) n → π (0) p	Q→ Q -1	ω(+)
π (-) NN → NN	Q→ Q+1	
π (-) p → π (0) n	Q→ Q+1	ω(-)
⬇ different		
π (0) n → π (-) p	Q→ Q-1	λ(-)
π (0) p → π(+) n	Q→ Q+1	λ(+)
π (0) → lost		ω(0)

ω ~ 0.1- 0.2 ; λ~ 0.15 - 0. 40 from data

PAULI BLOCKING depends on nucleon binding and momentum



Vcoulomb

O

π (0)

π (+)

π(+)

π (0)

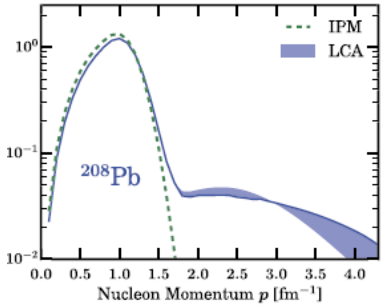
protons

neutrons

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



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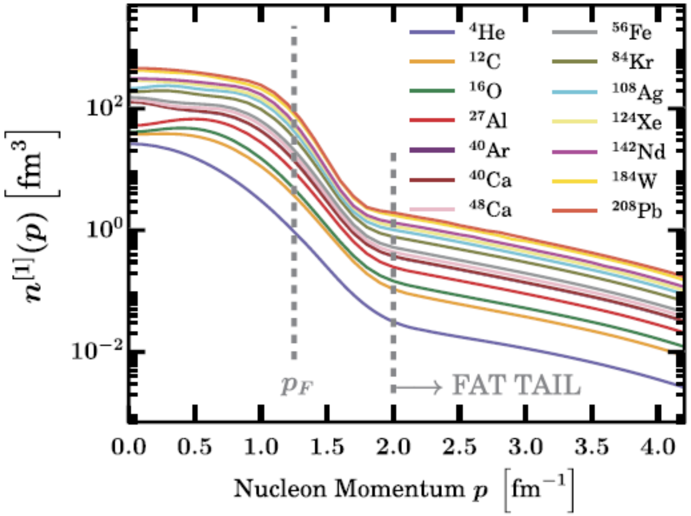


Fig. 2. The momentum distribution for 14 nuclei across the nuclear mass table. The $n^{[1]}(p)$ are computed in LCA with a "hard" central correlation function g_c adopting the normalization convention $\int dp\, p^2 n^{[1]}(p) = A$.

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

SHORT LIFE of ATOMS

Radii = 57 /Z n^2 fm

High l levels

Ψ / r^l ~ const

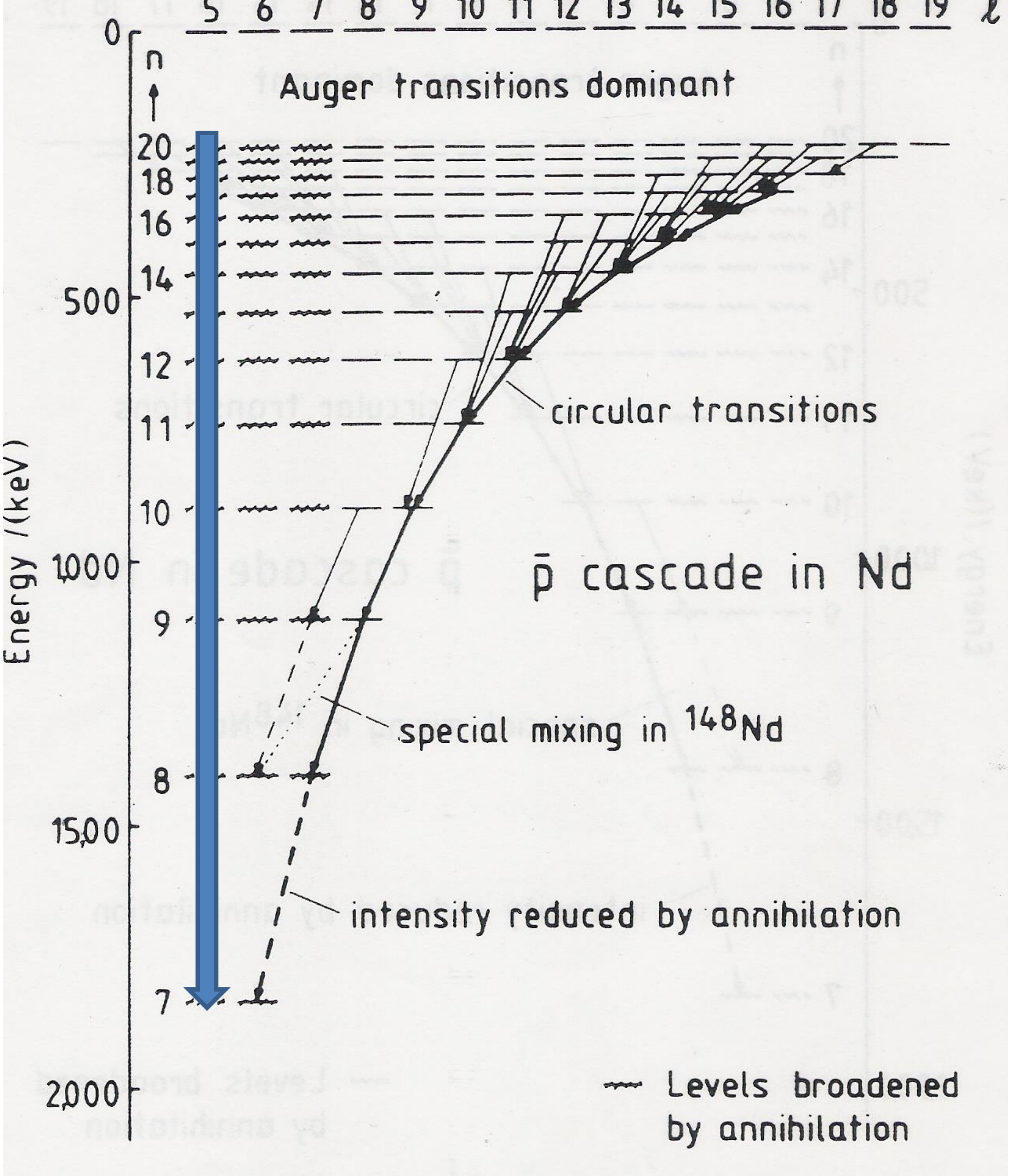
inside nuclei

FINAL PRODUCTS

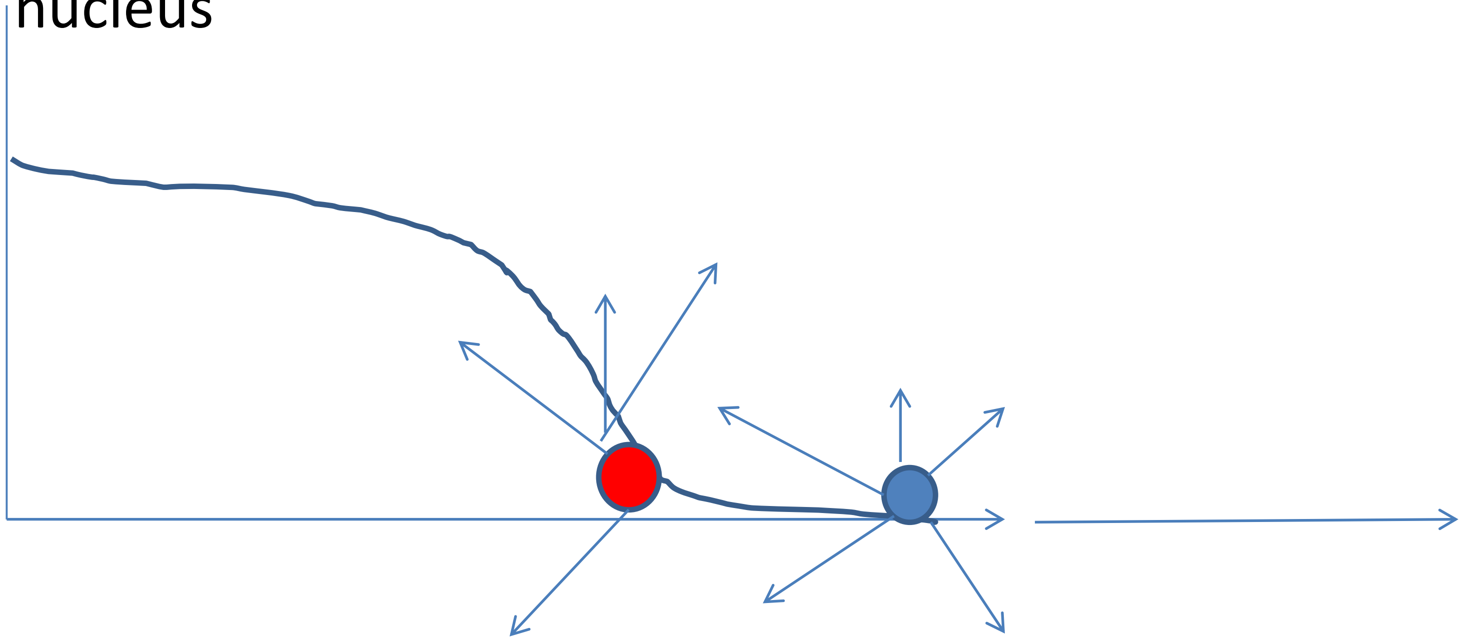
X-rays

Nuclei

Pions



Antiproton 🔵 a 2000 MeV bomb on the side of nucleus



→ Mesons from NN-bar → π π π

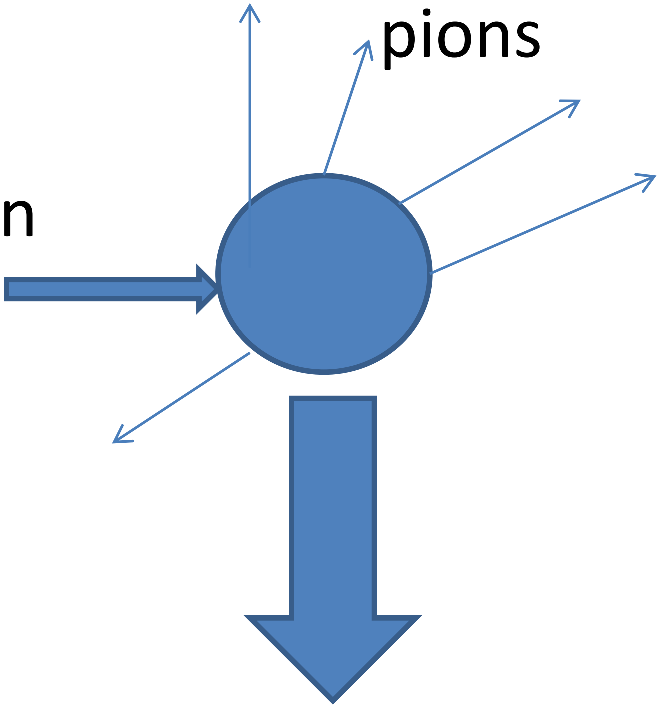
🔴 Nucleus destroyed , pions detected , less peripheral

🔵 Cold residual nuclei detected , more peripheral

X – rays regions in between

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

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

$R_{n/p}$ 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

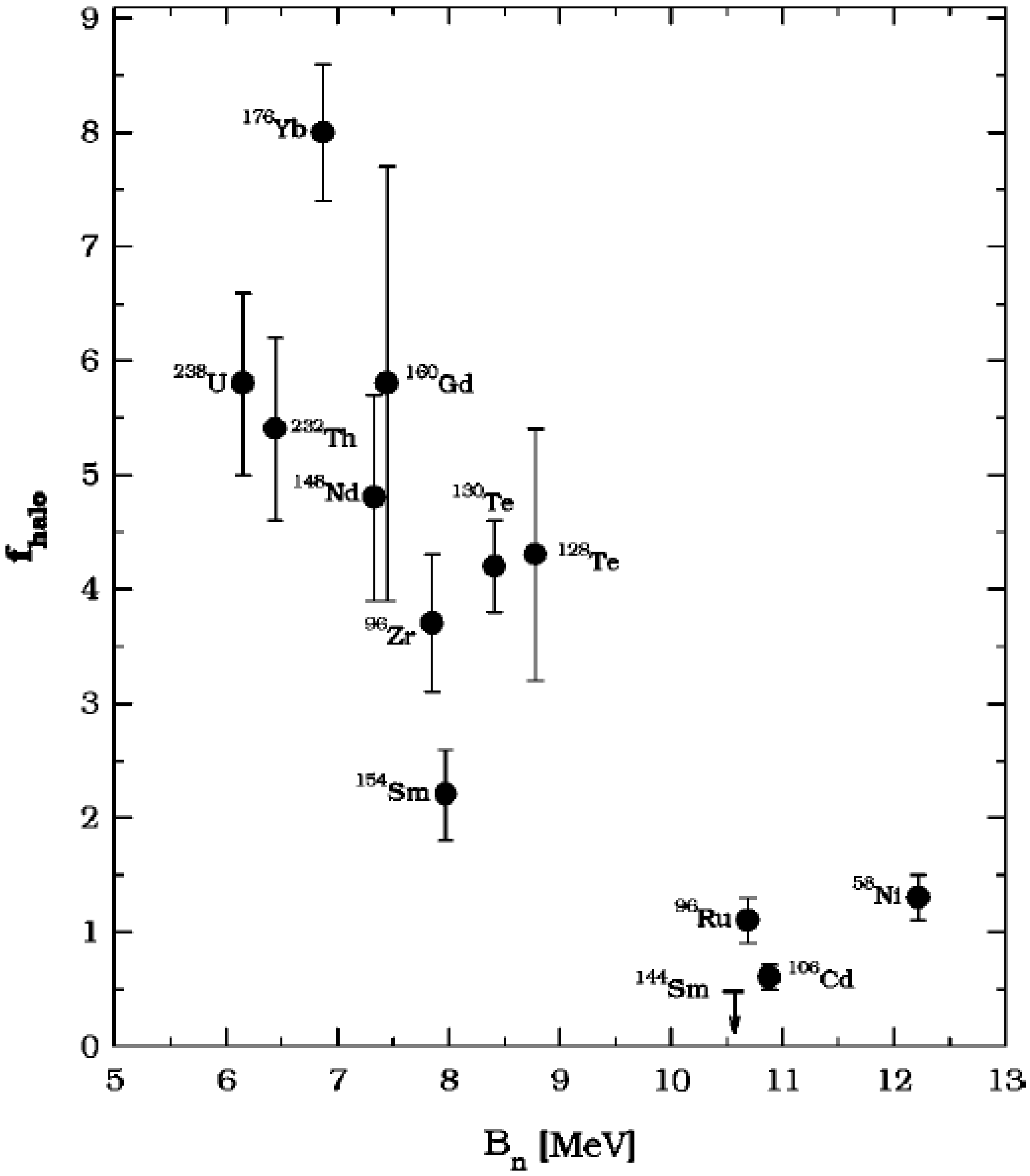
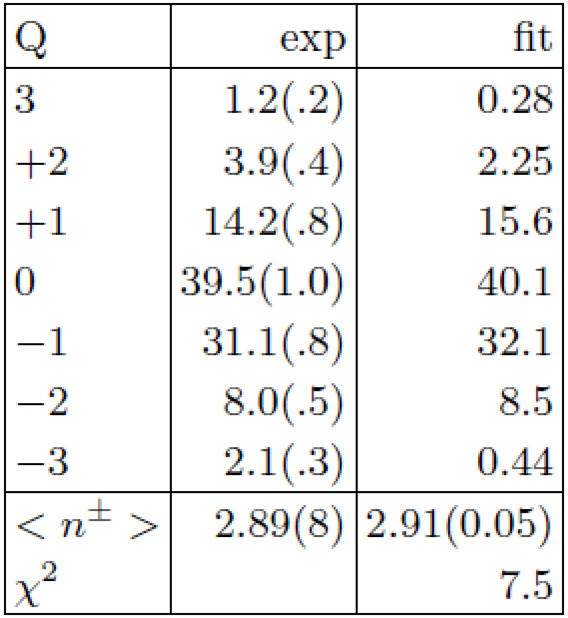


FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy B_n .

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

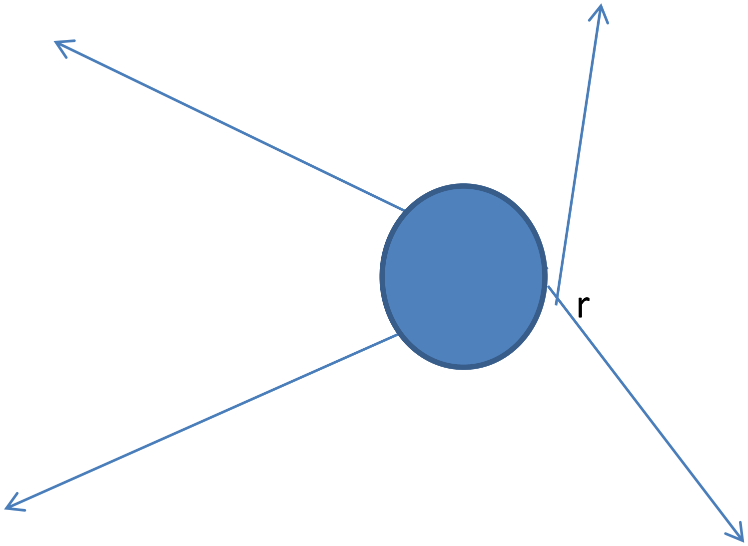
$$R_{n/p} \cdot f^h = 0.77(.04).$$

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

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

CALCULATION OF PARAMETERS

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



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

Survival amplitude T =1 - ω

Average over momenta , directions
number of mesons

Charge exchange λ = σ * Pauli Blocking factor mostly surface

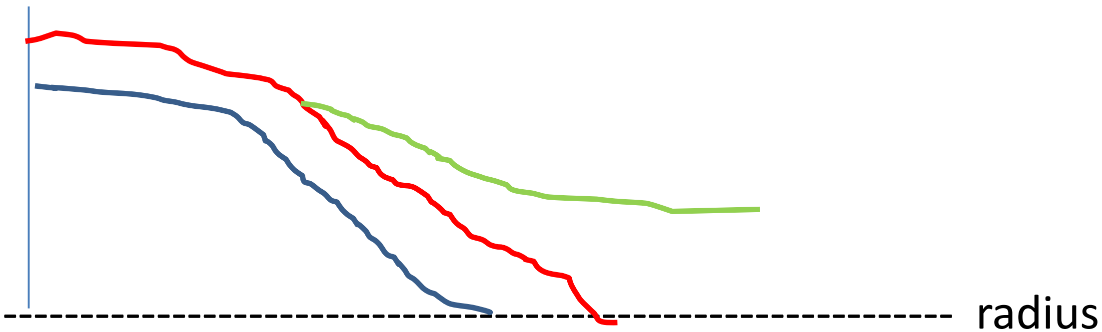
NN absorption ρ → ρρ mostly centre

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**

WHY SUBTHRESHOLD ENERGY

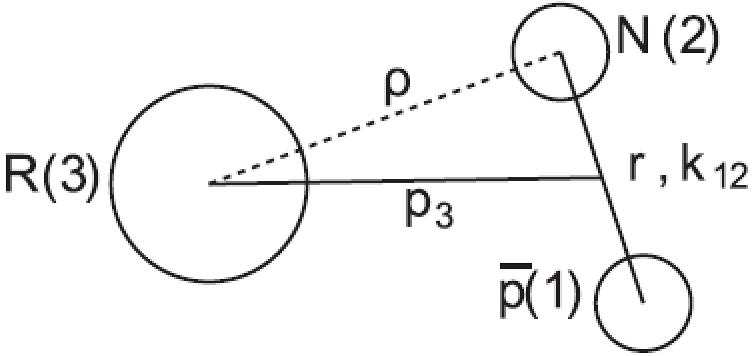


FIG. 1. Quasi-three-body system: (1) antiproton, (2) nucleon, and (3) residual system. Jacobi coordinates: momentum $\boldsymbol{p}_3, \boldsymbol{k}_{12}$ and space $\boldsymbol{\rho}, \boldsymbol{r}$.

In atoms

Kinetic N-Nbar ENERGY in CM system is negative

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

$\bar{N} - N$ quasi- bound states

-