# Miękka i twarda struktura w jądrze atomowym

badania atomowe i elektronowe

Sławomir Wycech : NCBJ Warsaw

# BADANIE    POWIERZCHNI   JĄDROWEJ

przy gęstościach  poniżej   10  %

# BADANIE KORELACJI   n-n, p-n,  p-p w  JĄDRACH

Na odległościach    poniżej 1 fm

Są  związane w eksperymentach antyprotonowych

PO CO NAM WIEDZA O POWIERZCHNI JADROWEJ

„HISTORYCZNE” ARGUMENTY

1) NIE MA TAM NEUTRONOW BO BY SIĘ ROZPADŁY

2) NIE MA TAM PROTONOW BO BARIERA KULOMBOWSKA SPYCHA JE W GŁAB JĄDRA

# * 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

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

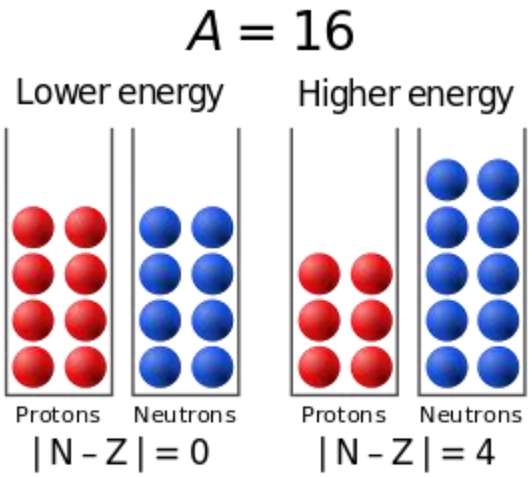
attractive repulsive due to Pauli

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

** ARE THERE STRONG (nnpp) CORRELATIONS ON DISTANT SURFACE.

*** IS THERE FERMI MOMENTUM AT THE SURFACE

# THE ORIGIN OF SYMMETRY ENERGY

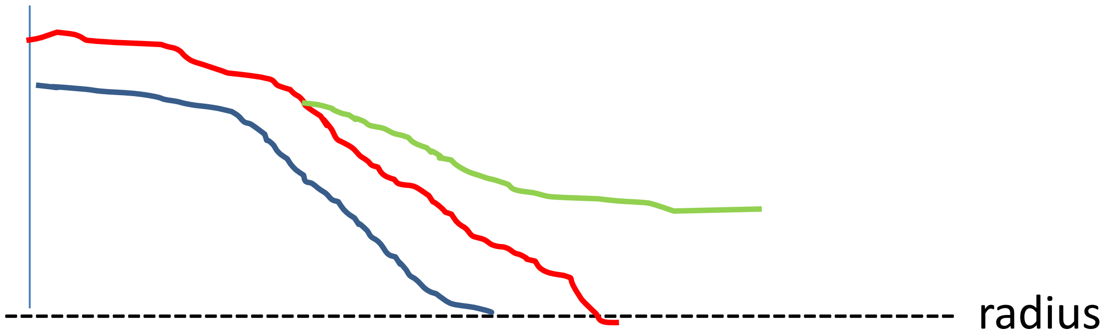


FERMI MOMENTUM AT NUCLEAR SURFACE ?

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**

Experymenty w Jefferson  Lab 2018-2024  ,   few GeV electron

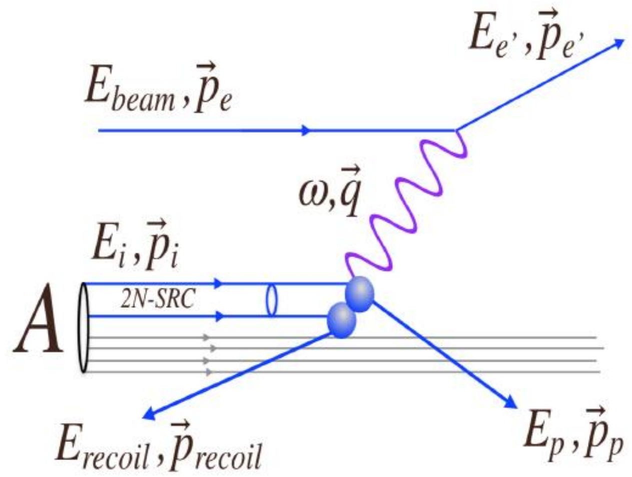
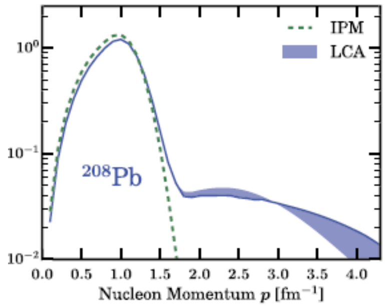



FIG. 1: (color online) Kinematics of the hard breakup of a $pp$-SRC pair in a hard two-nucleons knockout $A(e, e'pp)$ reaction. See text for details.

E.O.Cohen etal 2018 , Jeff.Lab

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

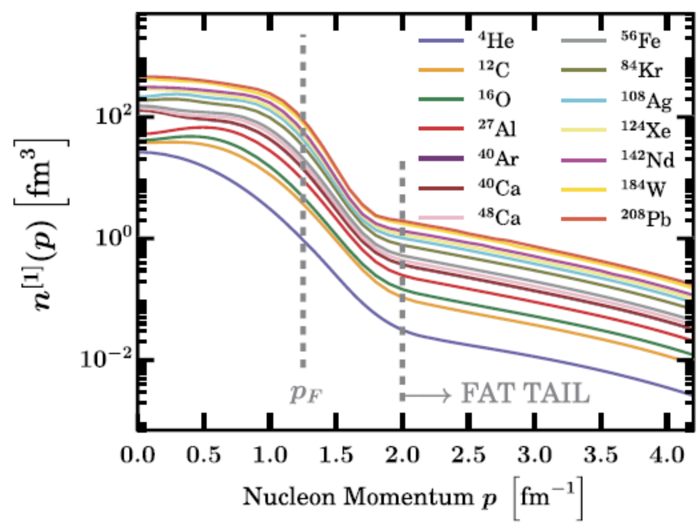



**Fig. 2.** The momentum distribution for 14 nuclei across the nuclear mass table. The $n^{[1]}(p)$ are computed in LCA with a "hard" central correlation function $g_c$ adopting the normalization convention $\int dp\, p^2 n^{[1]}(p) = A$.

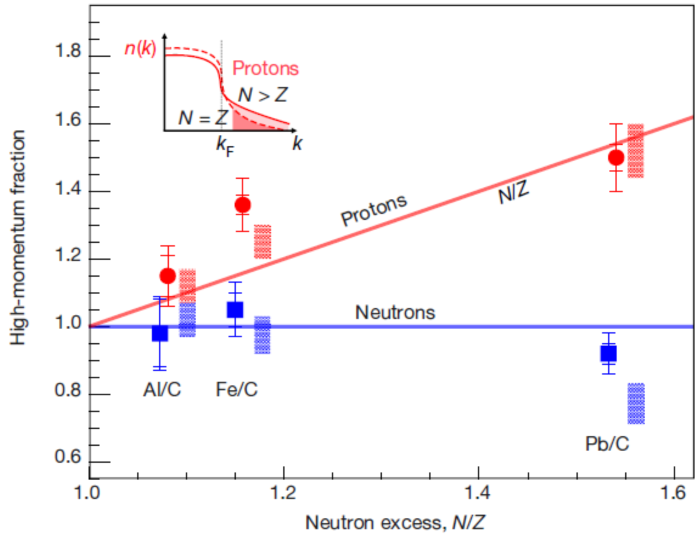



**Fig. 3 | Relative high-momentum fractions for neutrons and protons.** Red circles with error bars denote the double ratio of the number of $(e,e'p)$ high-momentum proton events to low-momentum proton events for nucleus A relative to carbon. The inner error bars are statistical and the outer ones include both statistical and systematic uncertainties, both at the $1\sigma$ or 68% confidence level. Blue squares with error bars show the same for neutron events. Red and blue rectangles show the range of predictions of the phenomenological *np*-dominance model for proton and neutron ratios, respectively (see Supplementary Information). The red line (high-momentum fraction equal to $N/Z$) and the blue line (high-momentum fraction equal to 1) are drawn to guide the eye. The inset demonstrates how adding neutrons to the target nucleus (solid red curve) increases the fraction of protons in the high-momentum tail (shaded region).

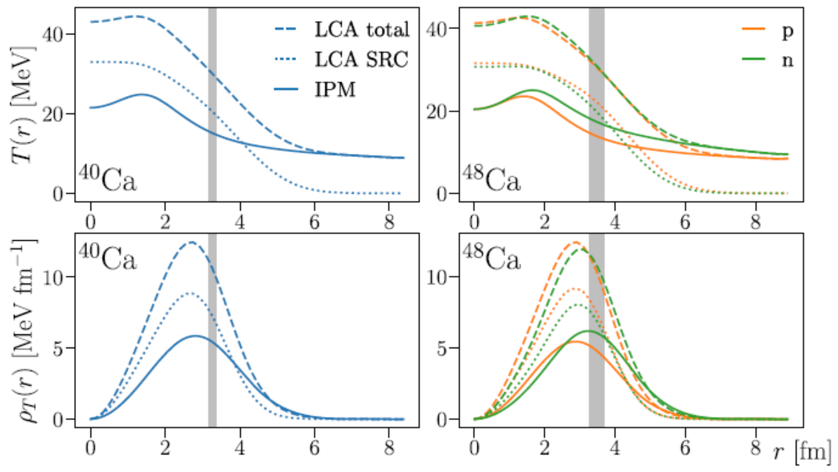



**Fig. 4.** $^{40}$Ca and $^{48}$Ca radial dependence of kinetic energy expectation value $T(r)$ (top row) and density $\rho_T(r)$ (bottom row). All LCA results use the $\hbar\omega[d]/f_c[R]$ input, IPM uses $\hbar\omega[d]$. Proton and neutron results are identical in $^{40}$Ca. Normalization of "LCA SRC" as in Fig. 3. Legends (linestyle/color) apply to all panels. The vertical bands cover the range of point rms radii for the depicted models, see Table 2.

Cosyn, Ryckebush PLB 820 (2021)

Experymenty z atomami antyprotonowymi

Motywacja

Badanie oddziaływania nukleon – antynukleon

Ocena skóry neutronowej (halo) = nadmiar neutronów powyżej N/ Z na powierzchni

## 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

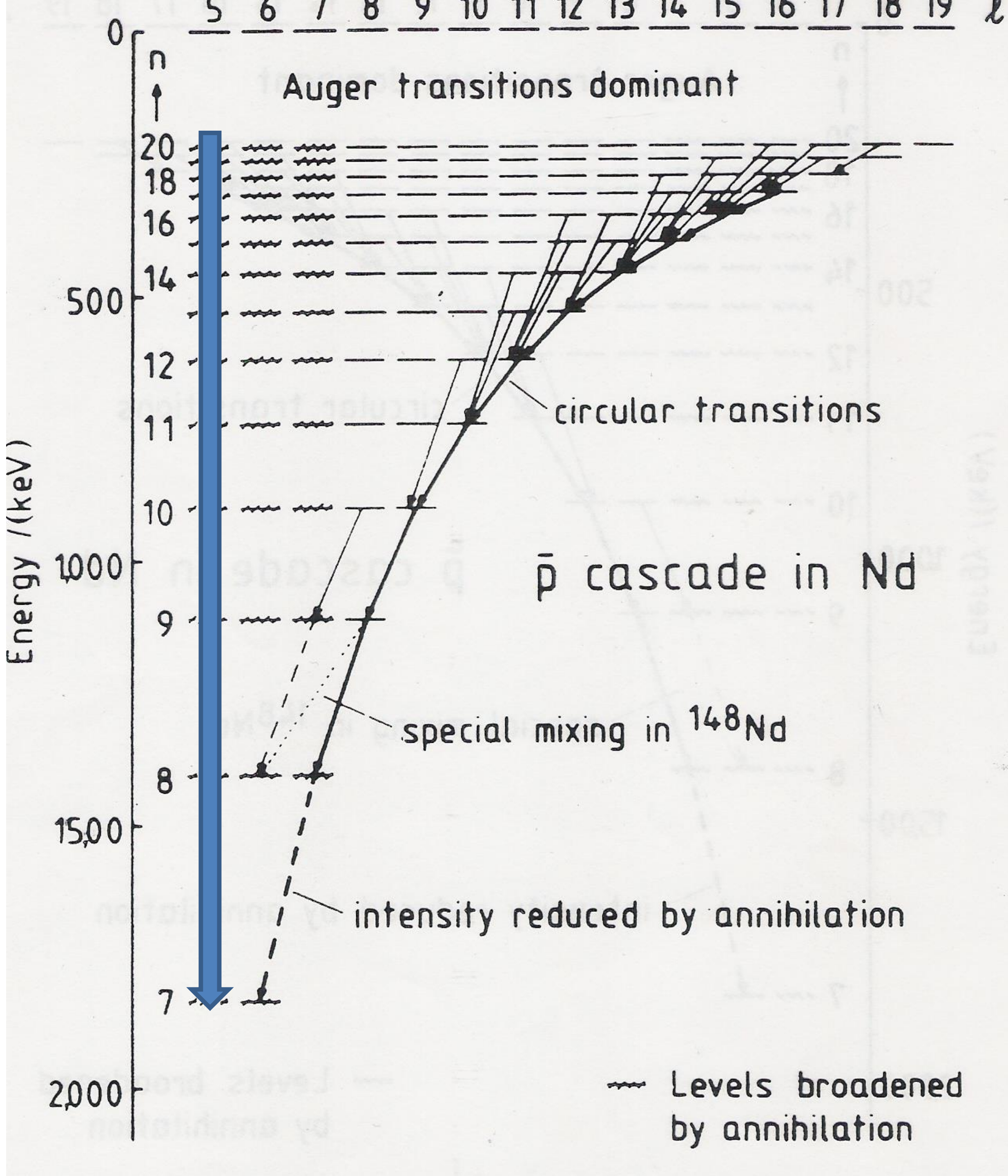
High l levels
$\Psi / r^l$ ~ const
inside nuclei

FINAL PRODUCTS

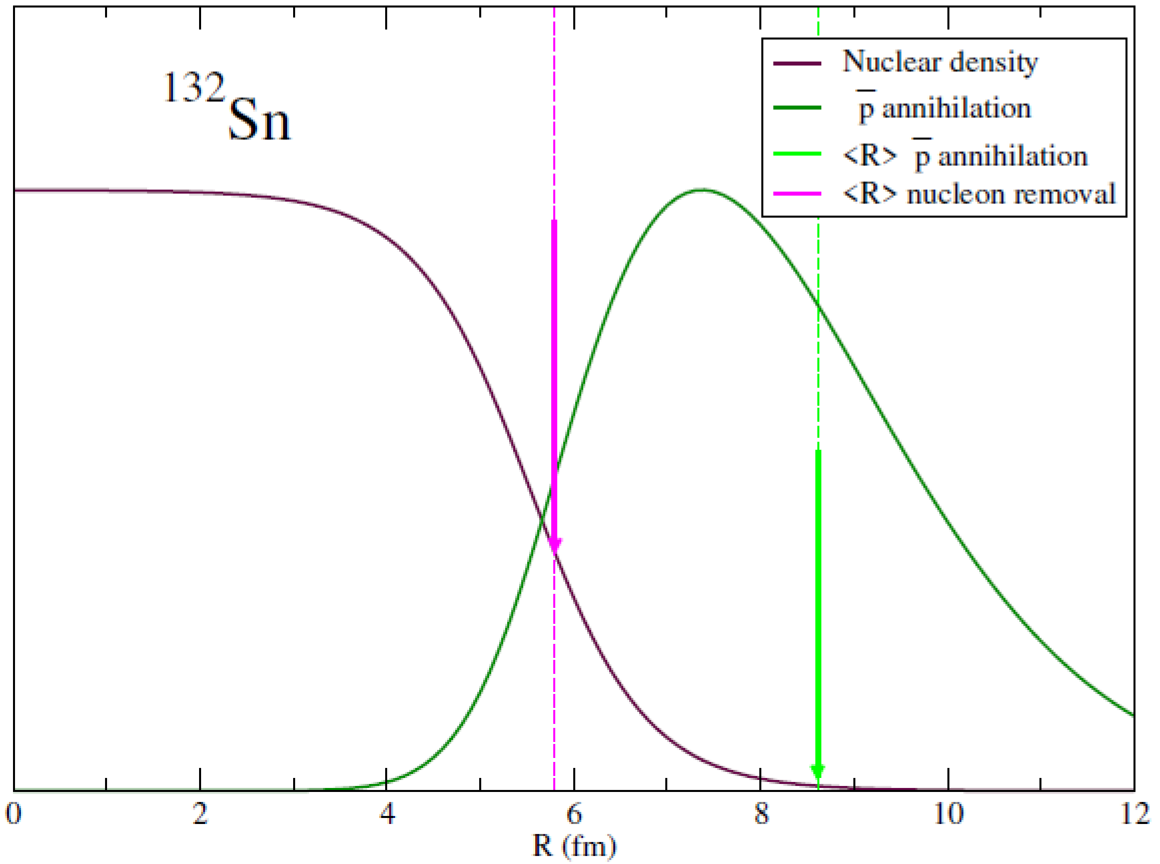
X-rays

Nuclei

Pions



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



J.Hartmann PRC 65

CAPTURE ORBITS
IN PIONISATION
MEASURMENTS

VERSUS X RAY DATA

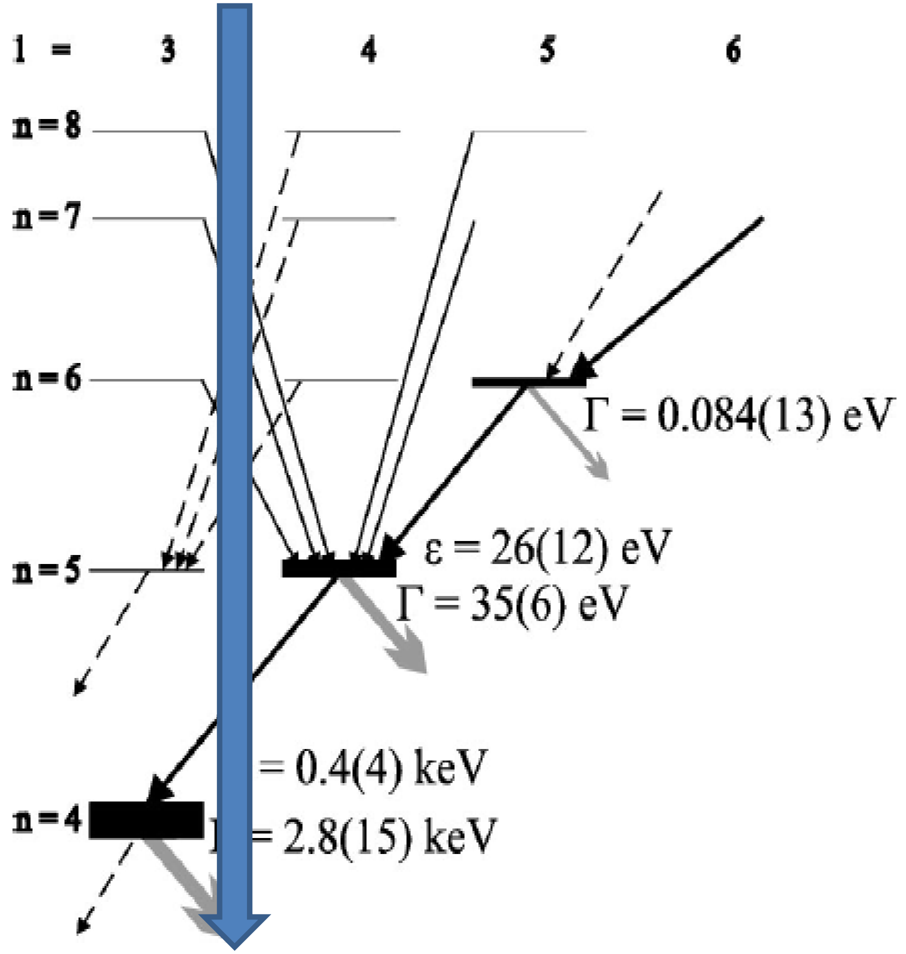
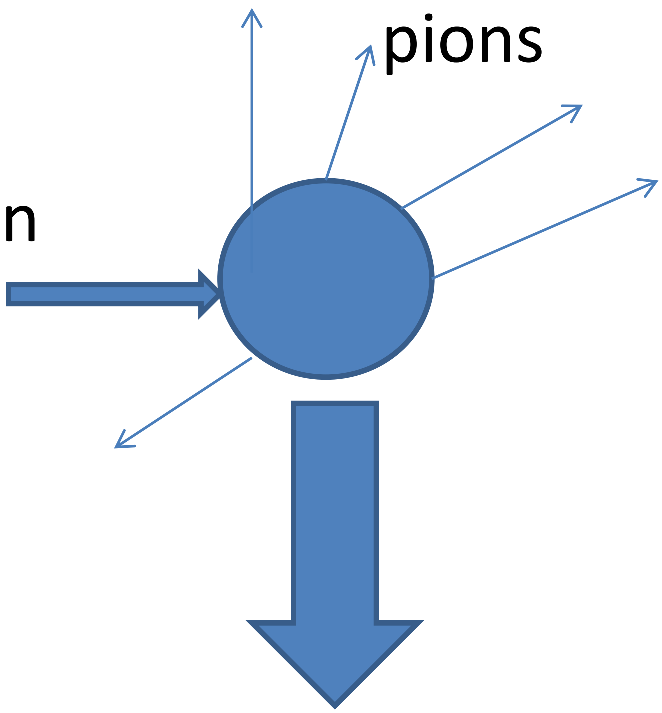



FIG. 3. Mean widths and shifts of all levels with measurable strong interaction effects. The weight of the different calcium iso-

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




do not excite target

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

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

# THE EXPERIENCE OF COLD CAPTURES

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

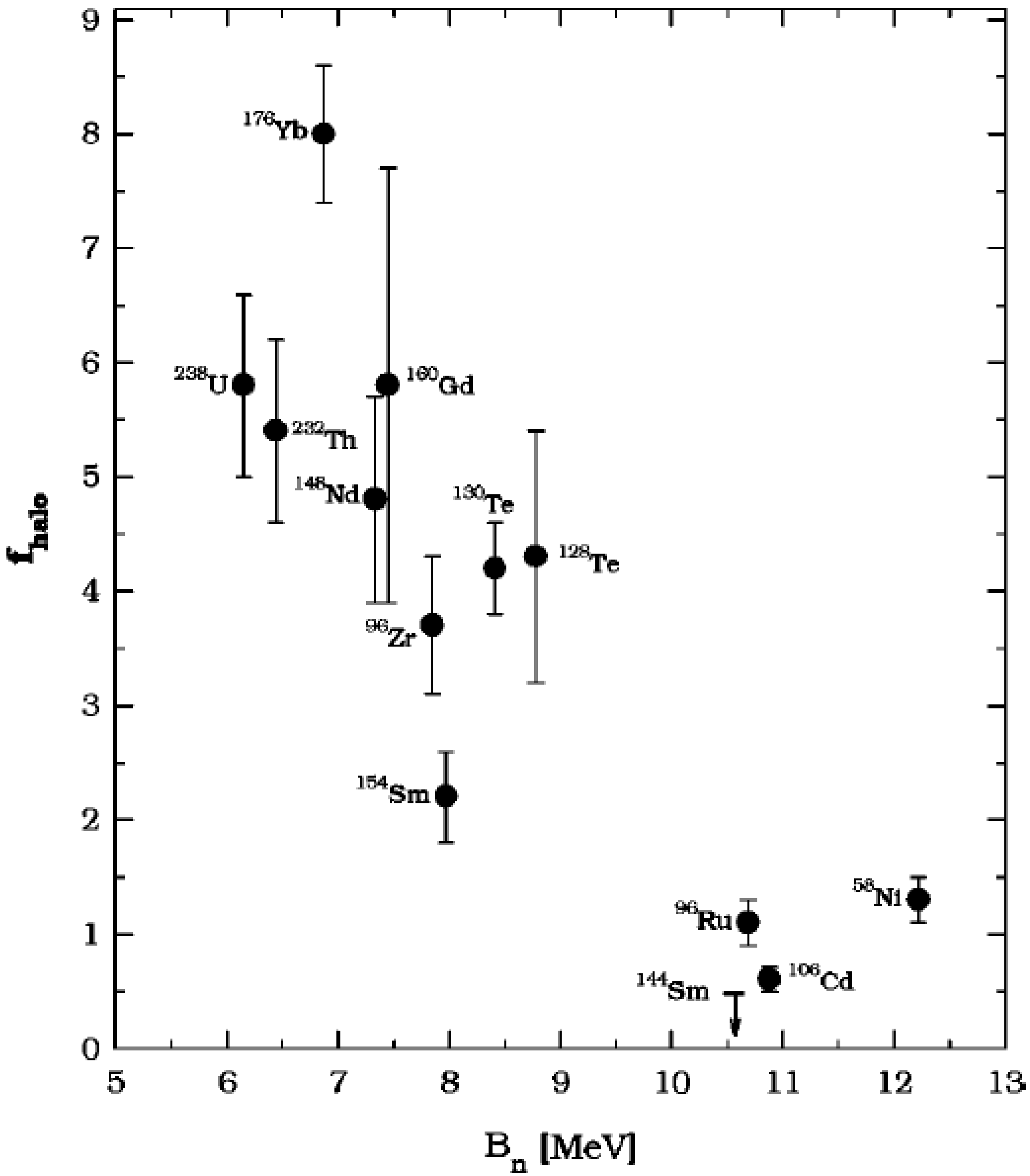



FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy $B_n$ .

# 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

PIONISATION EXPERIMENTS

Pomiar całkowitego ładunku emitowanych mezonów π....π

# 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

NOT ANALYZED , N-Nbar DATA WERE POOR

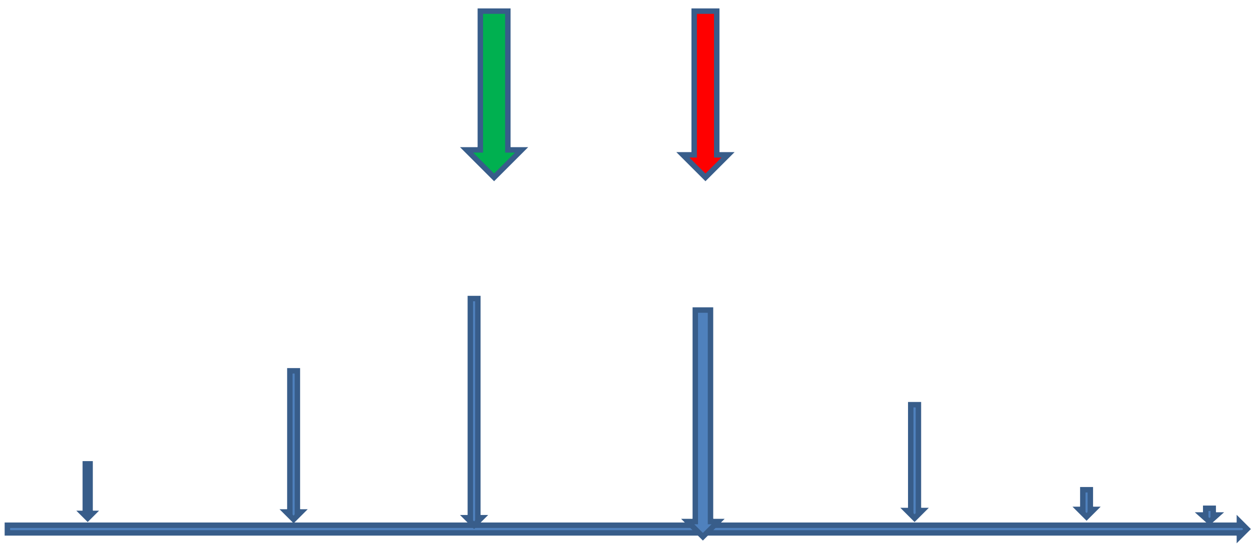
PUMA CERN 2024

PIONISATION EXPERIMENTS

TOTAL EMITTED NESONIC CHARGE Q DETECTED

INITIAL Q= O capture on proton

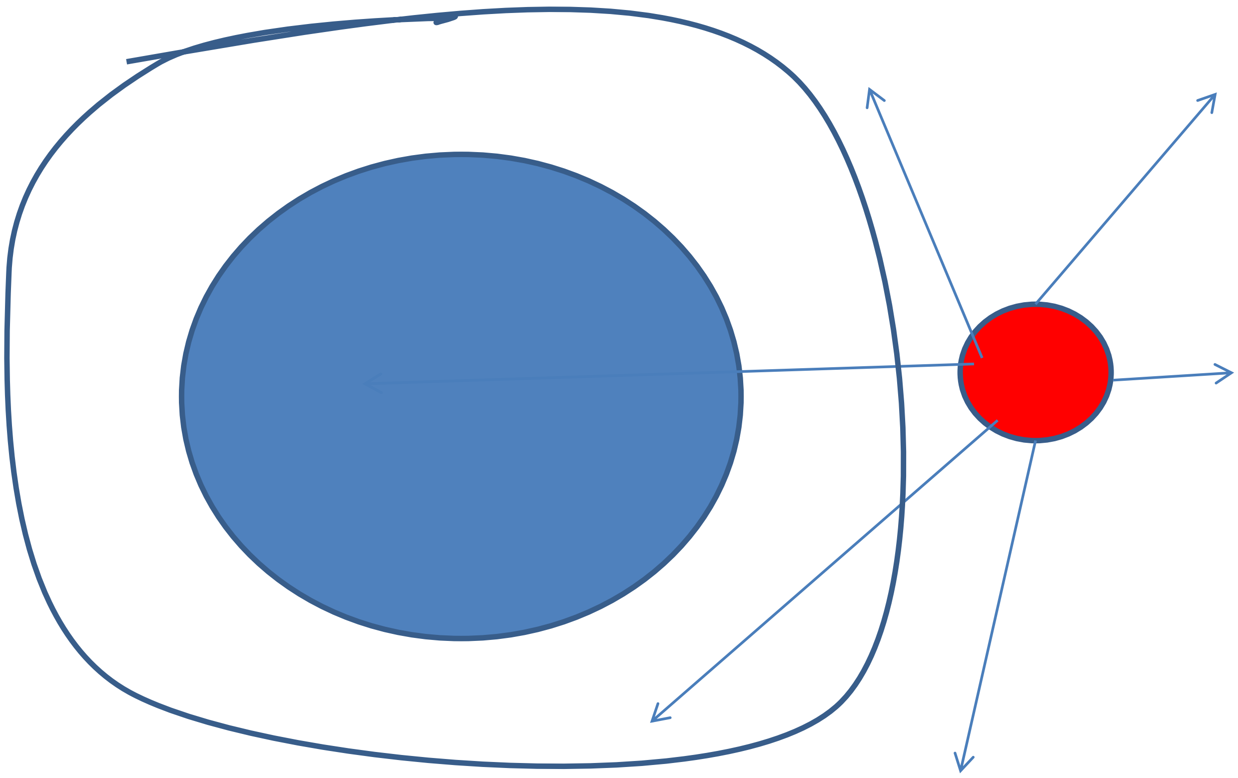
Q = -1 capture on neutron



MEASURED Q -2 -1 0 1 2 3

data = 8 numbers : P(Q) , average meson loss = $\omega$

Initial mesons ( p-bar , N ) =====➔ π π π π π



BILANS ŁADUNKU , procesy odwrotne

Pęd mezonu ~ 400 MeV/c

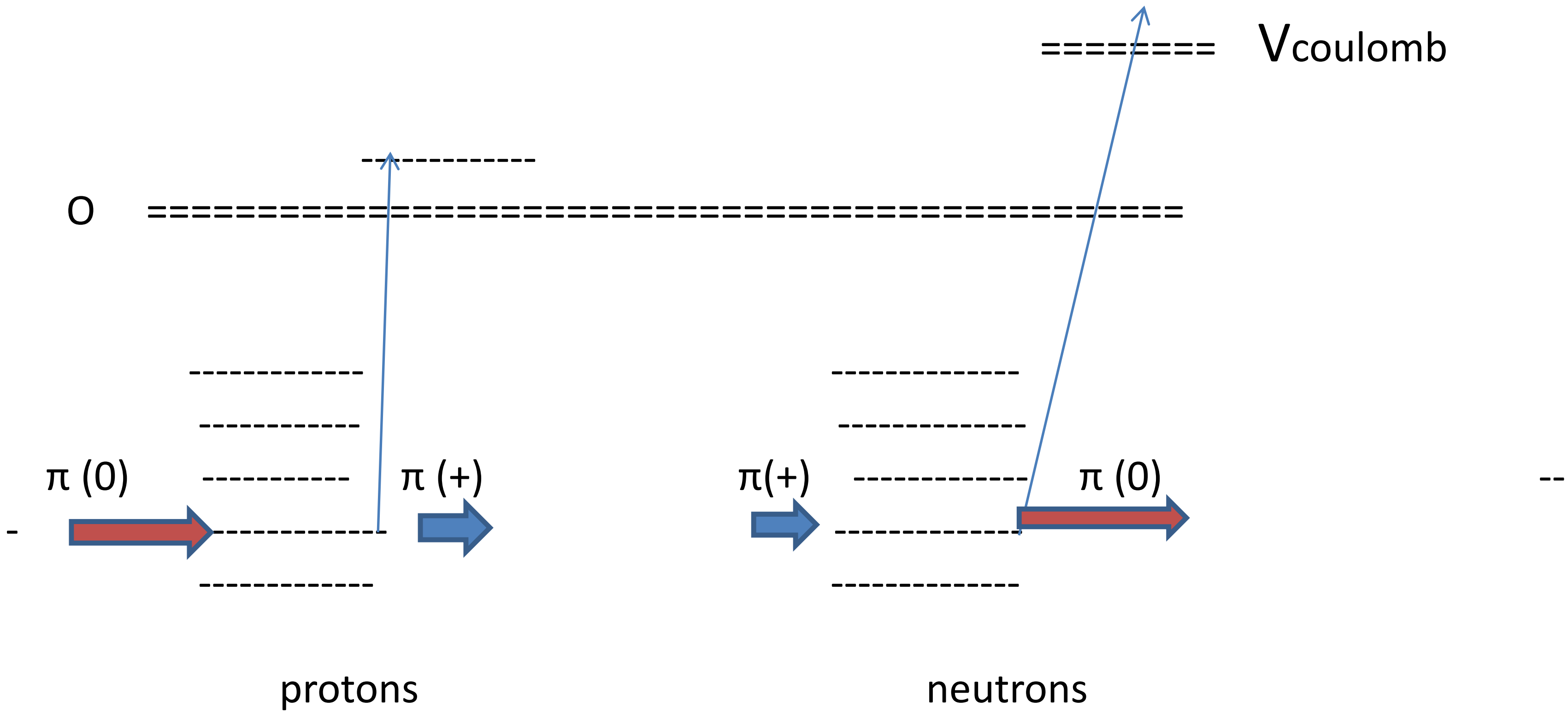
π(0) p → π(+) n idzie łatwo

π (+) n → π (0) p idzie powoli : bariera Kulomba

Przekroje czynne znane ,
problem w liczbie stanów końcowych
i pędach pierwotnych neutronów

π NN → NN idzie migiem na długościach ~ 1 fm

# 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, high momenta due to correlations .

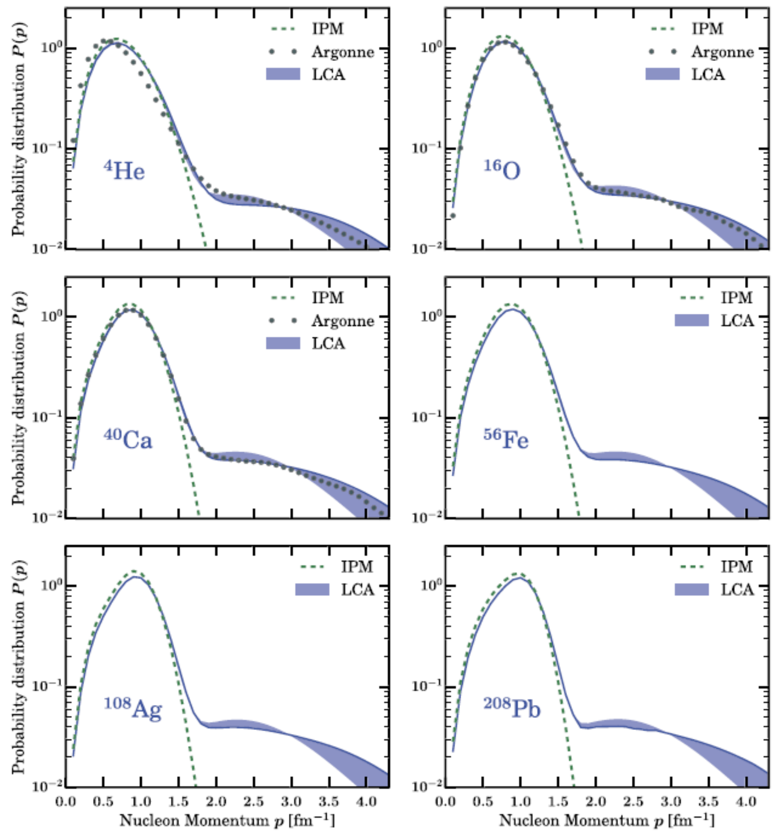


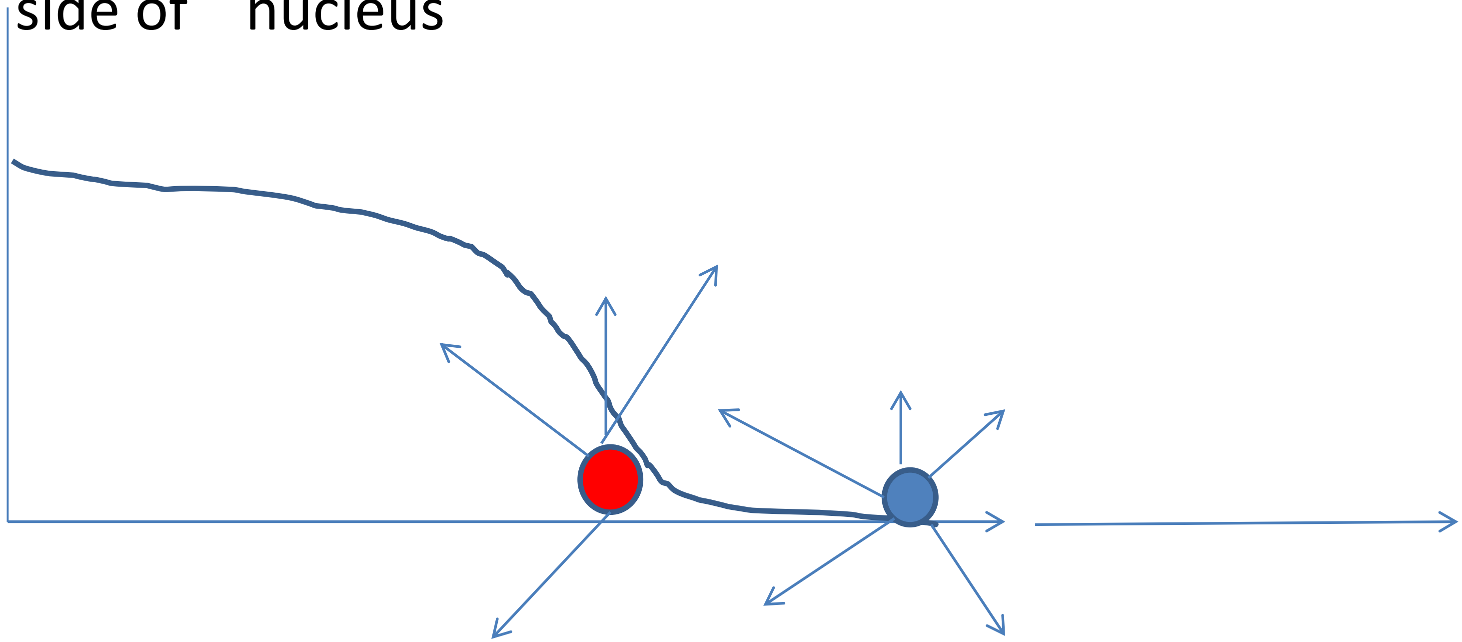

**Fig. 3.** The probability distribution $P(p)$ to find a nucleon with momentum $p$ in six nuclei. The IPM and LCA results are shown, as well as the QMC results (when available) from the Argonne group with the AV18 nucleon-nucleon interaction. The LCA bands indicate the difference between the calculations with a "soft" and a "hard" central correlation function $g_c$. The solid line is the LCA result with a "hard" $g_c$.

Sredni sukces , S.W. K.P phys rev C 2023

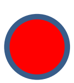
Szanse emisji mezonów uśrednione po pędach „ fermiowskich „
nie sa zależne wysokich pedów „ korelacyjnych „

Rozklad ładunków pozwala na wyznaczenie atomowych orbit
Wychwytu

Antiproton  makes 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

Excess of neutrons
over protons
Reduced by N/Z

Lubinski PRC 57
Munich Warsaw

PIONIZACJA

Halo inne

Extracted
Rms(n) –Rms(p)
Very close

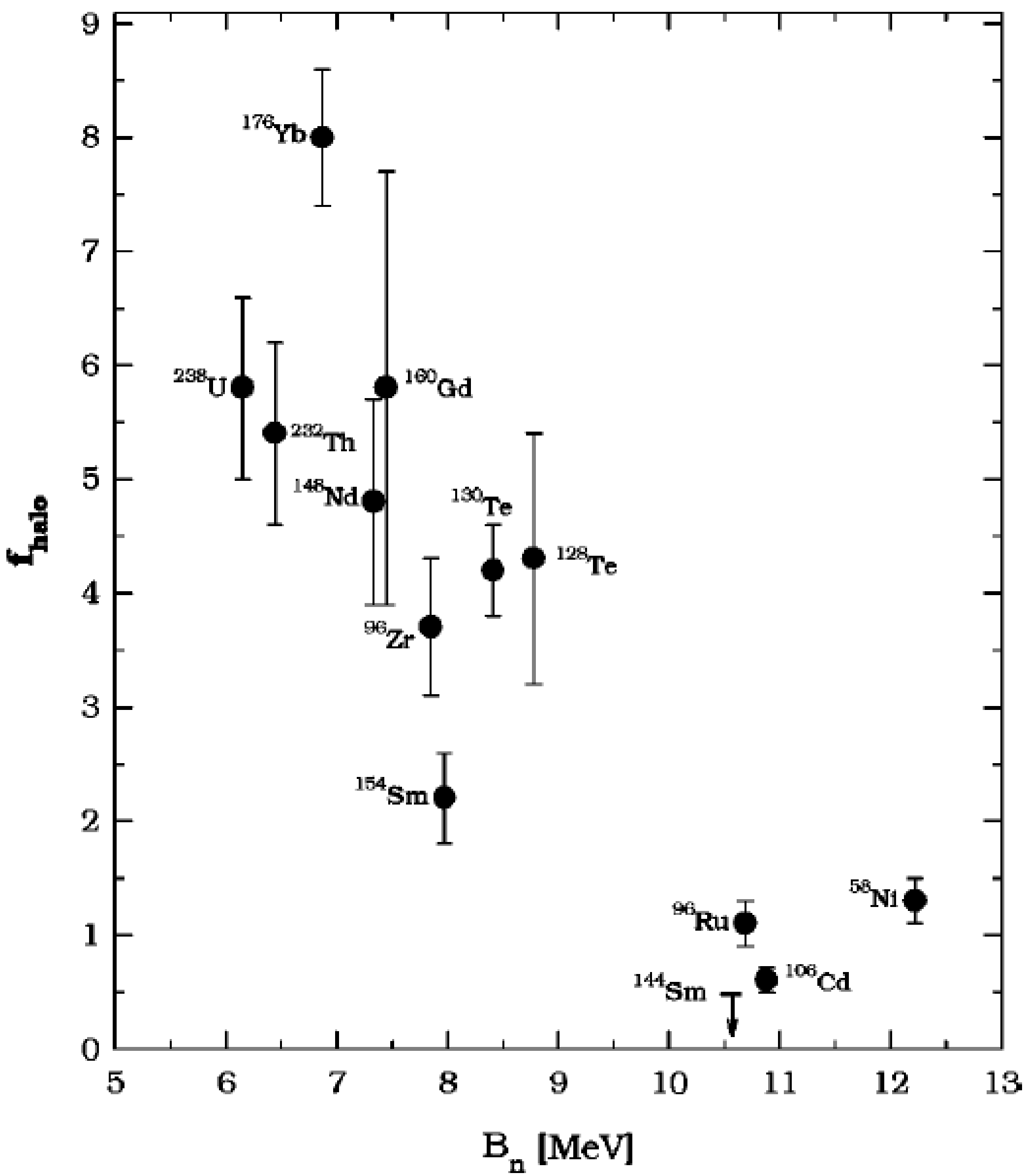



FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy $B_n$ .

# 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

MOTIVATION

PUMA at CERN : From Alexandre Obertelli

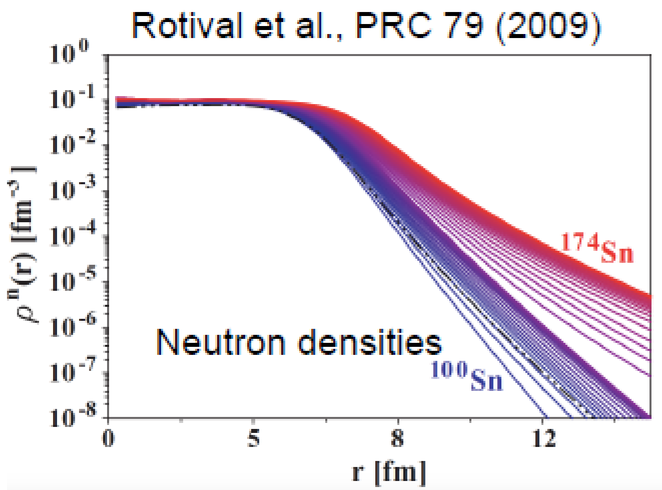

Fig. 7: Itinerary of PUMA from ELENA to ISOLDE.

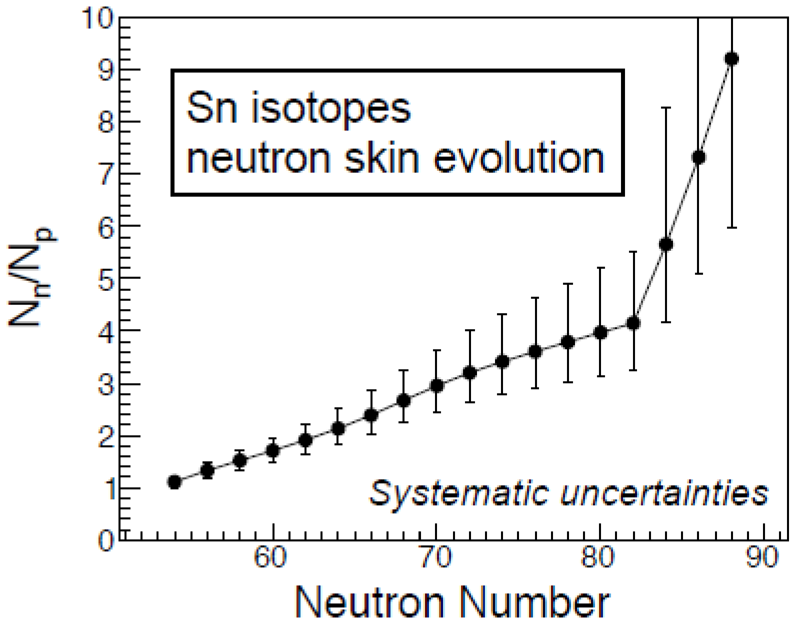
Expectations

from A. Obertelli

Neutron tails

n/p ratio at expcted at capture radius



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

AN ANALYSIS OF OLD DATA

PERSPECTIVES FOR PUMA

# PHENOMENOLOGICAL ANALYSIS OF FINAL STATE MESONIC REACTIONS

(0) CHOSE PARAMETERS
(1) FIT PARAMETERS TO DATA
(2) CALCULATE PARAMETERS
(3) COMPARE FITTED TO CALCULATED

extract the orbits of captures

calculate neutron haloes

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

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) |
| $\chi^2$ | | 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

LOCAL DENSITY APPROXIMATION FOR NUCLEAR MOMENTA

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

GOOD UNDERSTANDING OF RATES

Absorptions ω(+) + ω(-) and chargé exchange λ(+) + λ(-)

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

# PROBLEMS BE SOLVED FOR PUMA BY THEORISTS

(1)
sums of absorption π(+) + π(-) ;
charge exchange π(-) + π(-) are understood
and each term is not , effect of NN correlations

An additional advantage of PUMA ?

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

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

# OTHER PROBLEMS OF RELATED INTEREST

Baryonia, nuclear states of antiprotons

Dziękuję .

sw

## 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

$$\widehat{\mathcal{G}} = \widehat{\mathcal{S}}\left( \prod_{i<j=1}^{A} \left[ 1 - g_c(r_{ij}) + f_{t\tau}(r_{ij}) \widehat{S}_{ij} \vec{\tau}_i \cdot \vec{\tau}_j + f_{\sigma\tau}(r_{ij}) \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\tau}_i \cdot \vec{\tau}_j \right] \right),$$

# 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 |
| $\chi^2$ | | 13.1 |
| $R_{n/p} f^h$ | | 0.75(0.01) |

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

# 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

# Example neutron radius in Pb

Pionisation { W.Bugg }

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

Cold capture { Munich-Warsaw}

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

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

# OLD DATA ANALYSIS : SUMMARY

C, Ti, Te, Pb , N

Total mesonic charge spectrum P(Q) allows to determine capture orbitals .

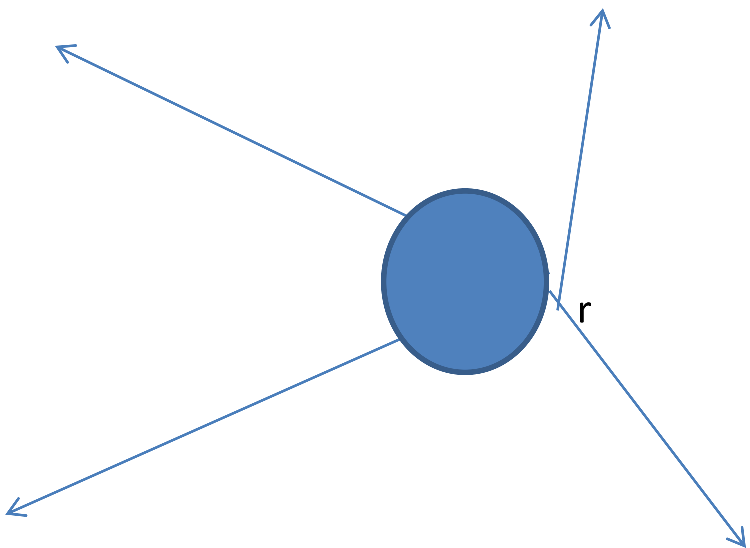
Extracted neutron haloes Rms (n) – Rms (p) consistent with other data

Ratio : ( captures on neutron) /( capture on proton ) requires better controll

Effects of (pn) correlations likely to be tested ,
(pnpn) perhaps .

CALCULATION OF PARAMETERS

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




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

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

$\pi$ NN → N $\Delta$(1232) → $\pi$ NN

absorption via unitarity
many old models fairly
consistent with phenmenology
( W R Gibbs , Johnson and Satchler)

Charge exchange $\pi(-)$ p → $\Delta$ → $\pi(0)$ n

cross sections measured
Breitschopf P. Let 639 B 2009

**strongly ch**anged in nuclear matter ,

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

(1)

SUBTLE EFFECTS OF NUCLEON MOMENTUM DISTRIBUTION

DO WE KNOW FERMI MOMENTUM AT SURFACE

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

In the bulk of nuclei

ω(+) + ω(-)
and
λ(+) + λ(-) effects of p-n corelation cancel out

Individual terms λ(+) , λ(-) ω(+) , ω (-)
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 $E = 2M - \Delta$

$\Delta$ from 0 to - 34 MeV

REGION OF QUASI – BOUND STATES

WHY SUBTHRESHOLD ENERGY

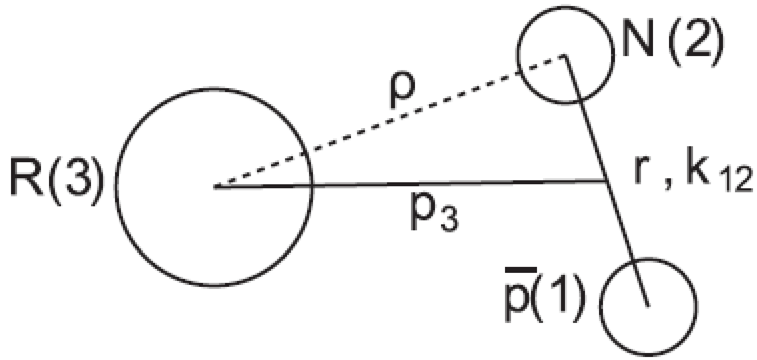



FIG. 1. Quasi-three-body system: (1) antiproton, (2) nucleon, and (3) residual system. Jacobi coordinates: momentum $\boldsymbol{p}_3, \boldsymbol{k}_{12}$ and space $\boldsymbol{\rho}, \boldsymbol{r}$.

In atoms

Kinetic N-Nbar ENERGY in CM system is negative

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

$\bar{N}$ – N quasi- bound states

-

# S - wave BARYONIUM

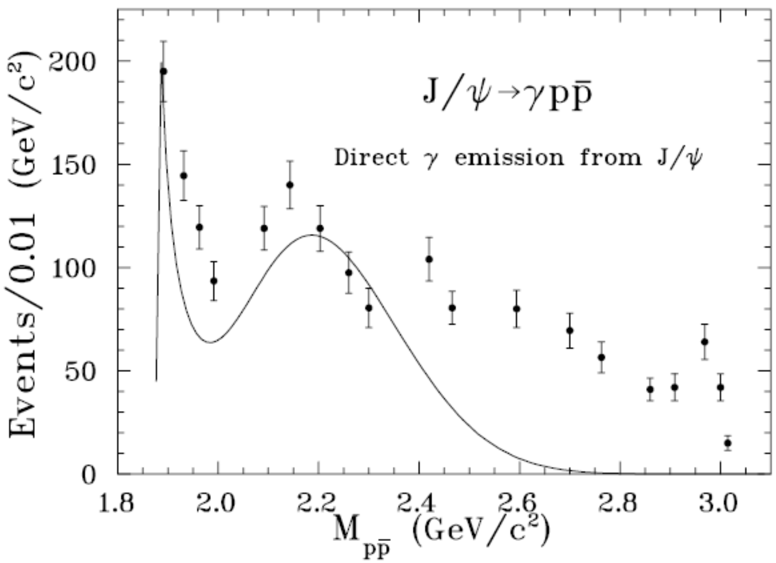
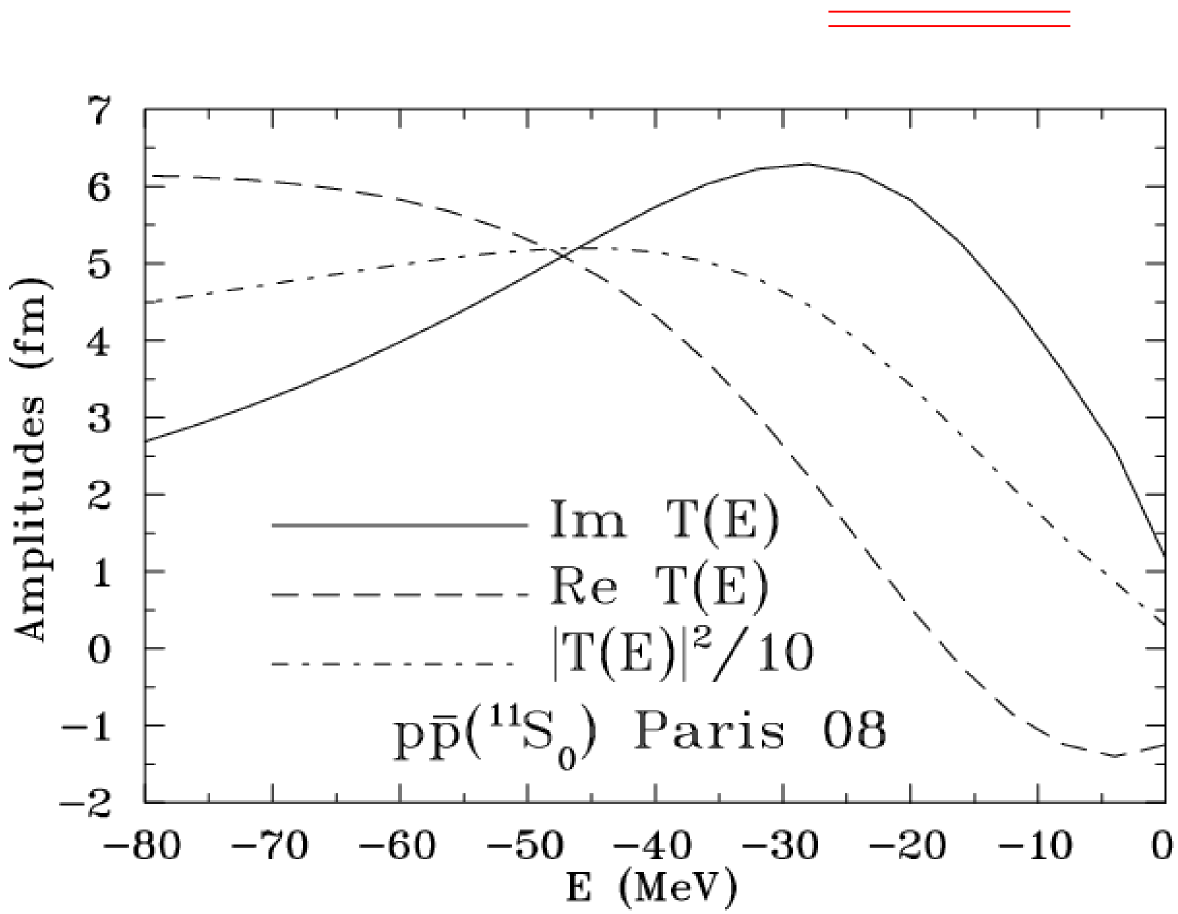



**Figure 3.** The $p\overline{p}$ invariant mass spectrum obtained under the assumption that photon is emitted before the baryons are formed. The missing strength at large $p\overline{p}$ invariant mass, $M_{p\overline{p}}$, comes from the photon radiated by final hadrons [7]

# $^{11}$S AMPLITUDE UNDER THRESHOLD

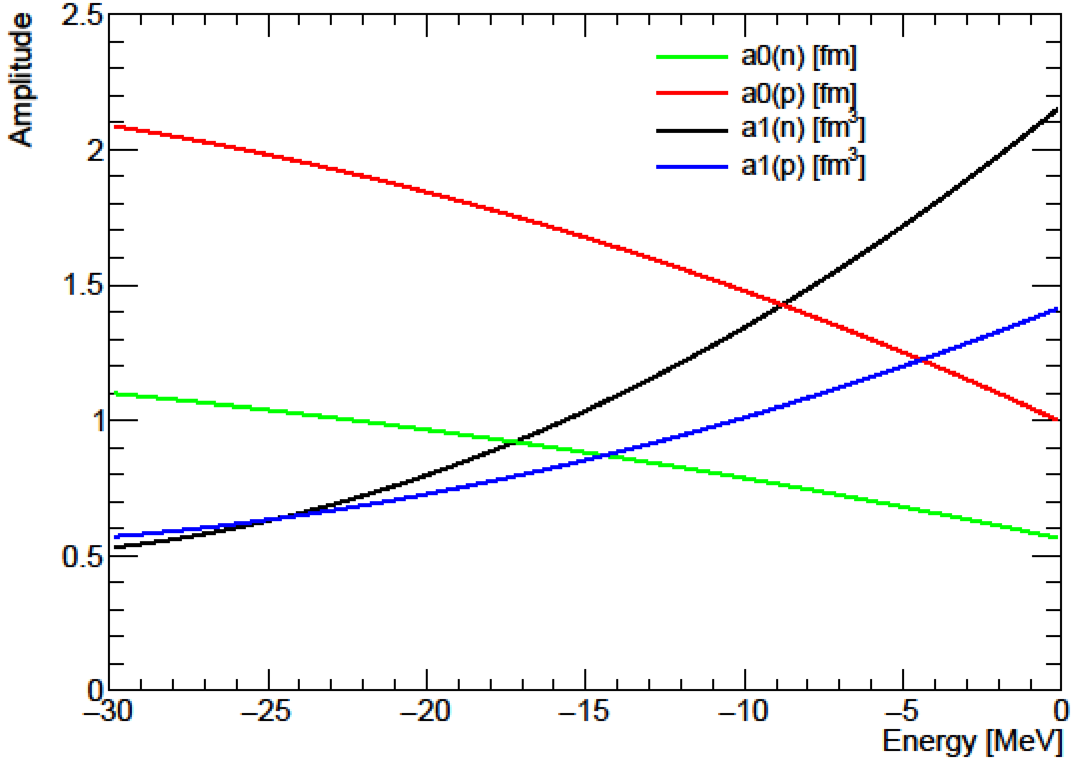
Region of **interest**




Understood

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

# WHY NUCLEAR SURFACE IS INTERESTING

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

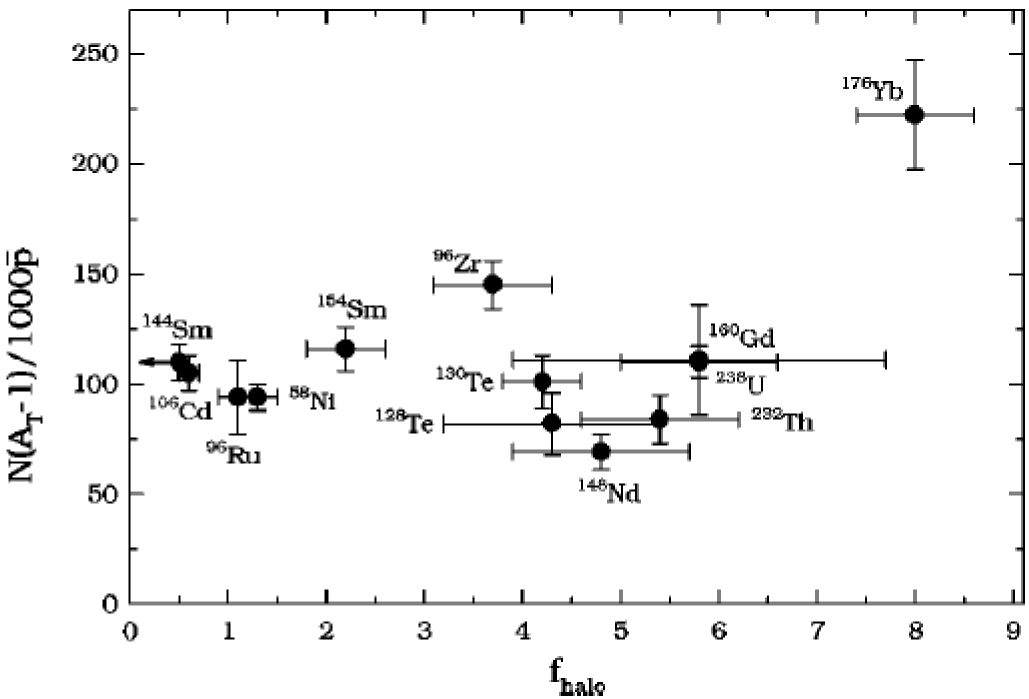



FIG. 5. Correlation between halo factor and absolute production yield for $A_t-1$ nuclei.

WHY ANTIPROTON ?

It is immediatly killed by nucleus

free passage length $L = 1/(\rho\sigma)$

Nuclear central density $\rho = .15 / fm^3$

Low energy N-Nbar cross section $\sigma \approx 30. - 40 \; fm^2$

Length for nuclear excitation ~ 0.2 fm

Length for annihilation is comparable but mechanism is more involved

** ARE THERE STRONG CORRELATIONS ON NUCLEAR SURFACES

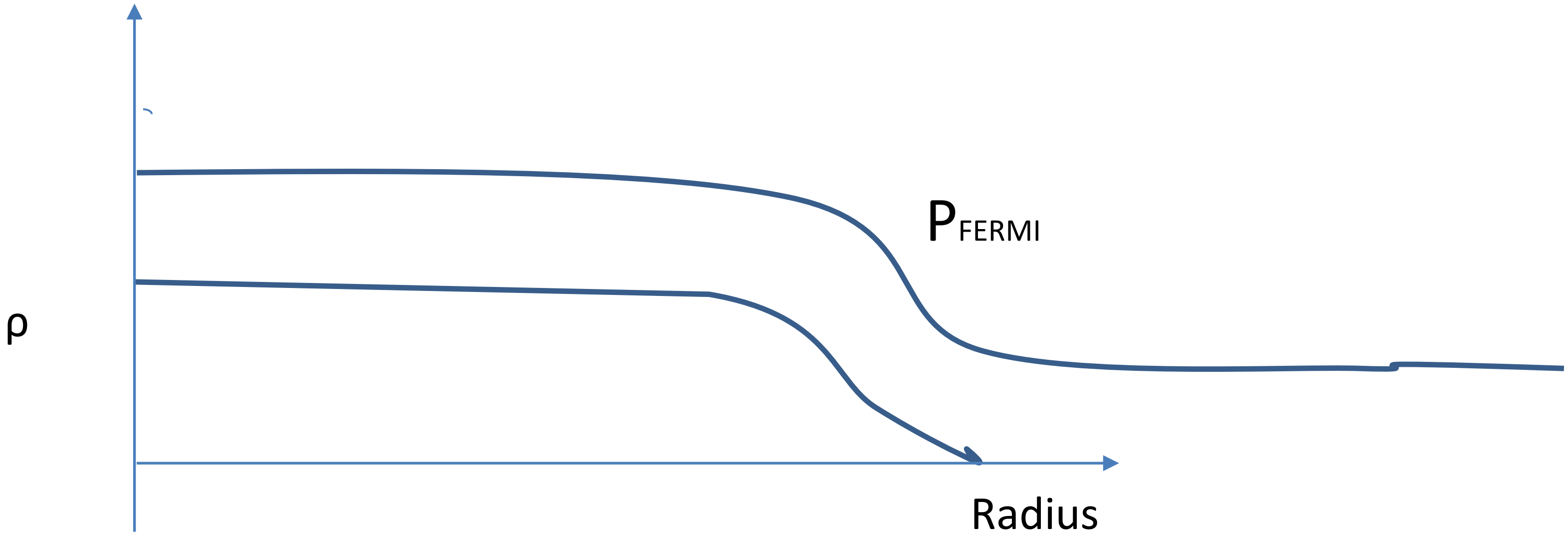
ALPHA PARTICLE TYPE ?

Seen in nuclear α decays

May be covenient energetically

Carbon nucleus ≈ α α α ?

Studied (inconclusively) with Kaonic atoms ( D. Wilkinson 1968)




$$\Psi(R\,,r\,) = \Sigma \quad \phi(R+r/2\,)\,\phi(R-r/2\,)^* \quad = \rho(R)\;\; j_1(P_{FERMI}\,r)$$

Campi , Bouyssy

Shell model

R.Schmidt PRC58

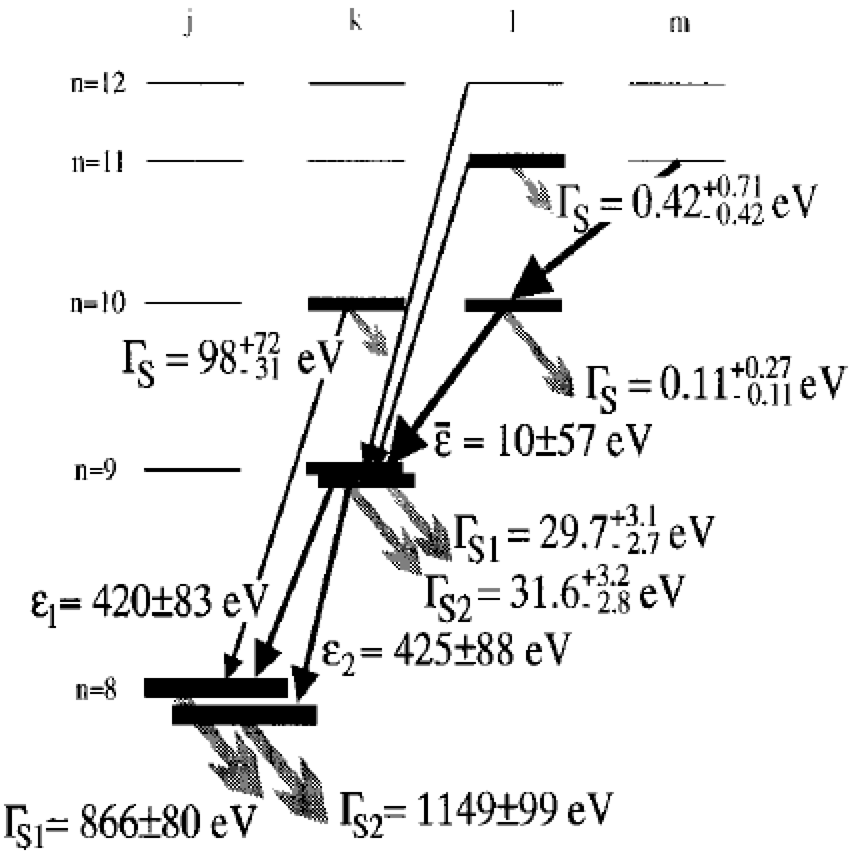



FIG. 9. Energy shifts of the transitions and widths for the levels ntiprotonic $^{172}$Yb which are sizably influenced by the strong

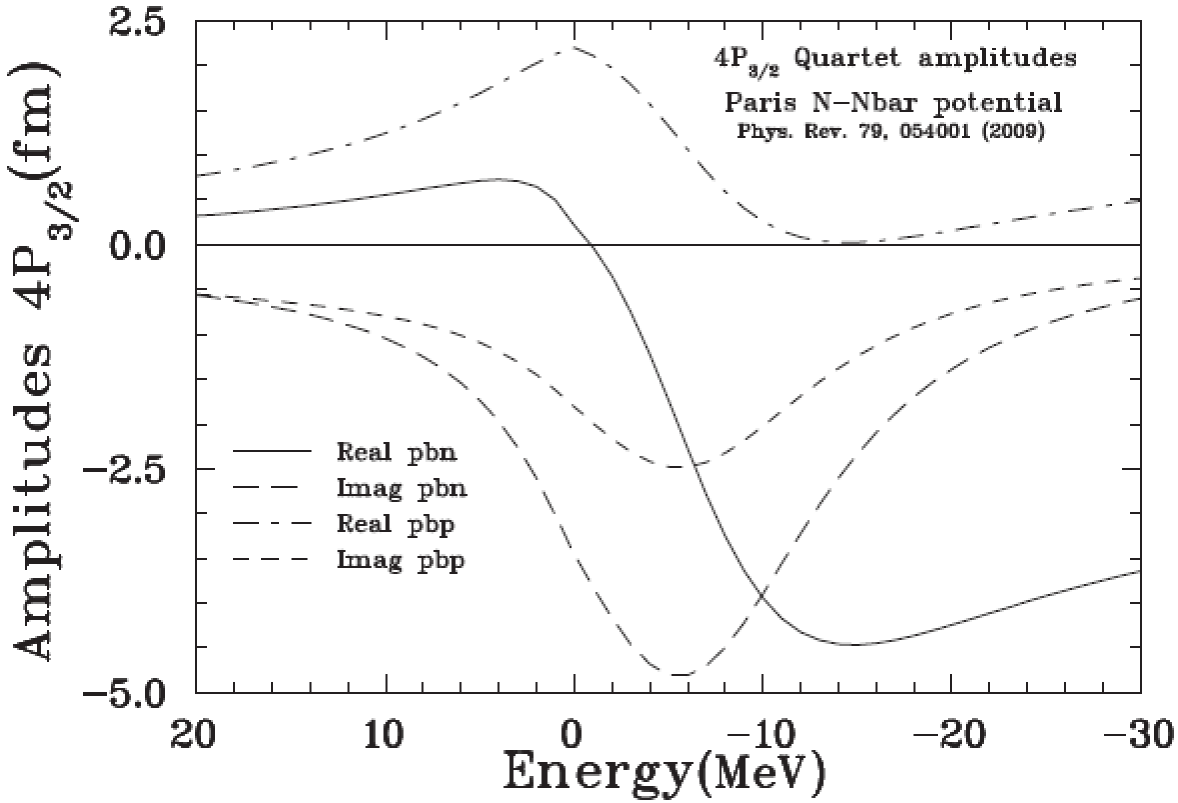



FIG. 2. Subthreshold amplitudes generating the $4P_{3/2}$ hyperfine structure component in deuterium. With the Paris 09 solution this amplitude is strongly dominated by the resonant $a(^{33}P_1)$ amplitude.

Not under full controll

ADVANTAGES OF X - RAYS :
ATOMIC STATE OF ANTIPROTON CAPTURE IS KNOWN
FEW DATA

ADVANTAGE OF PIONISATION : MUCH DATA

PROBLEM : CAPTURE ORBIT NOT KNOWN

UNCERTAINTY of ALL EXPERIMENTS :
RATIO $R_{n/p}$ = capture on neutron / capture on proton
~ 0.9 (0.1) (TO IMPROVE )

## Collaboration

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

# 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

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

## * 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

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

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

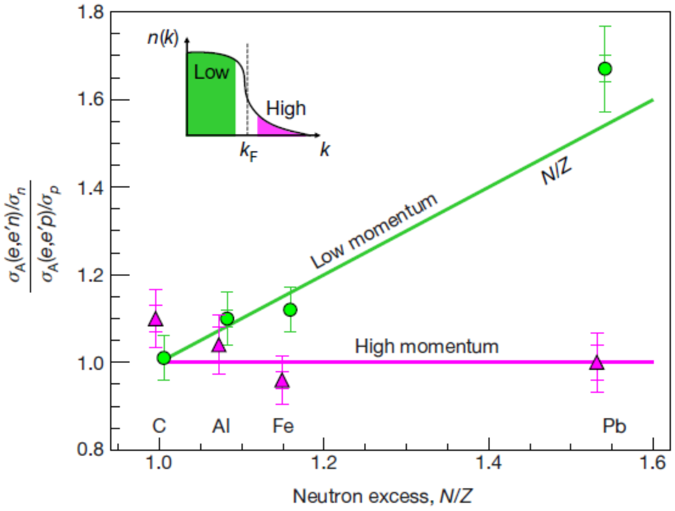



**Fig. 2 | Relative abundances of high- and low-initial-momentum neutrons and protons.** Reduced cross-section ratio, $[\sigma_A(e,e'n)/\sigma_n]/[\sigma_A(e,e'p)/\sigma_p]$, for low-momentum (green circles) and high-momentum (purple triangles) events. The inset illustrates a typical nuclear momentum

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