ANTIPROTONIC ATOM - A TOOL TO STUDY NUCLEI HADRONISATION, ANALYSIS OF OLD EXPERIMENTS

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Three different – related measurements

ATOMIC LEVELS via X RAYS 3

DETECTION OF FINAL COLD NUCLEI 2

DETECTION OF FINAL PIONS 8

ADVANTAGES OF X - RAYS

ATOMIC STATE OF ANTIPROTON IS KNOWN

HIGH PRECISION REACHED

PROBLEMS

NUCLEAR INTERACTIONS OF ANTIPROTONS ARE KNOWN CRUDELY

UPPER PART OF X-RAY CASCADE IS UNCERTAIN

ANTIPROTON OPTICAL POTENTIAL IS NOT WELL UNDERSTOOD

I

ANTIPROTONIC ATOMIC LEVELS

EXAMPLE END OF CASCADE IN Ca J.Hartmann P.Rev C 65

ADVANTAGE

INDICATION OF CAPTURE ORBIT

TEST OF P-N STATES BELOW THRESHOLD

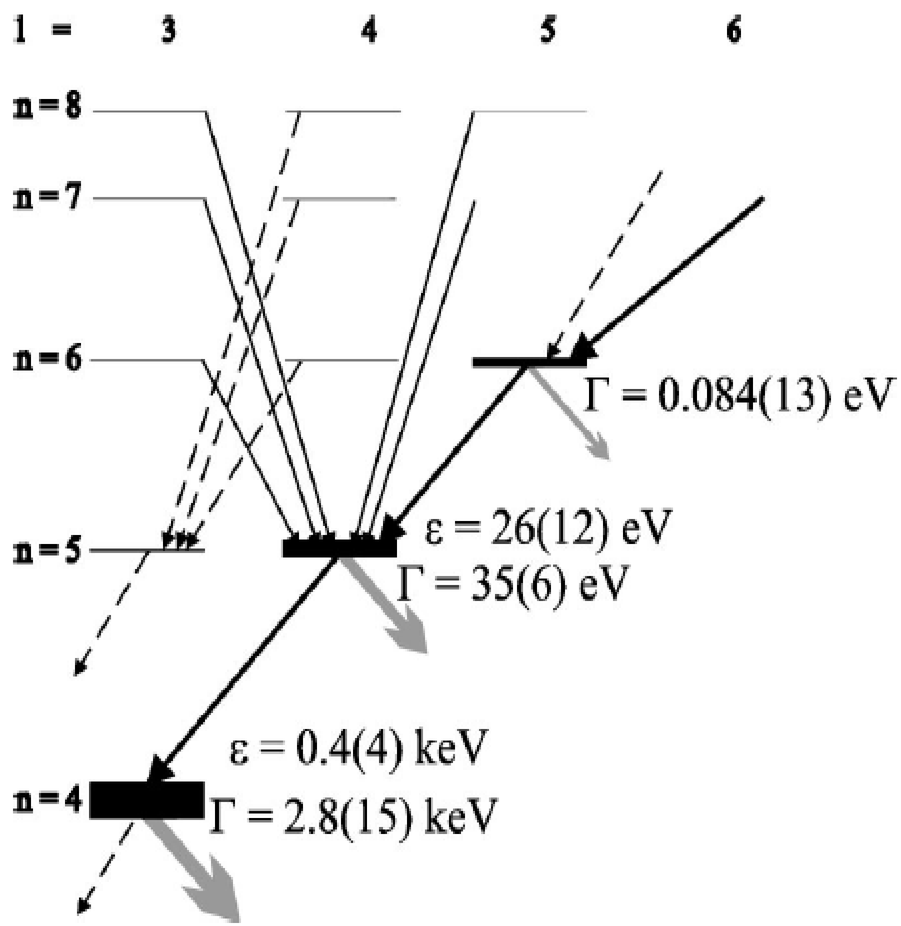

FIG. 3. Mean widths and shifts of all levels with measurable strong interaction effects. The weight of the different calcium iso-

WHY SUBTHRESHOLD STATES

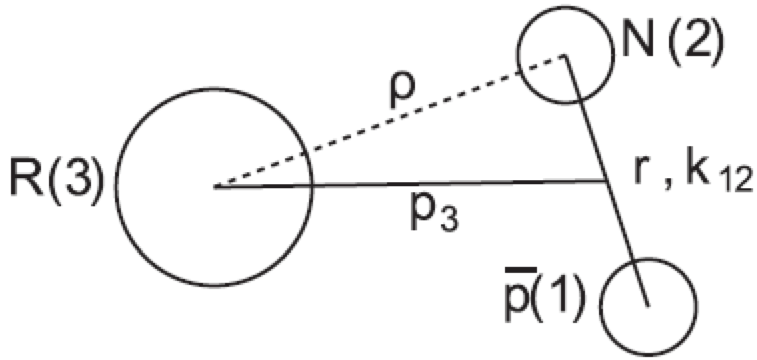

FIG. 1. Quasi-three-body system: (1) antiproton, (2) nucleon, and (3) residual system. Jacobi coordinates: momentum $\boldsymbol{p}_3, \boldsymbol{k}_{12}$ and space $\boldsymbol{\rho}, \boldsymbol{r}$.

In atoms

N-pbar ENERGY in CM system IS BELOW NN THRESHOLD

E_{CM} = 2 M - Binding - Recoil

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

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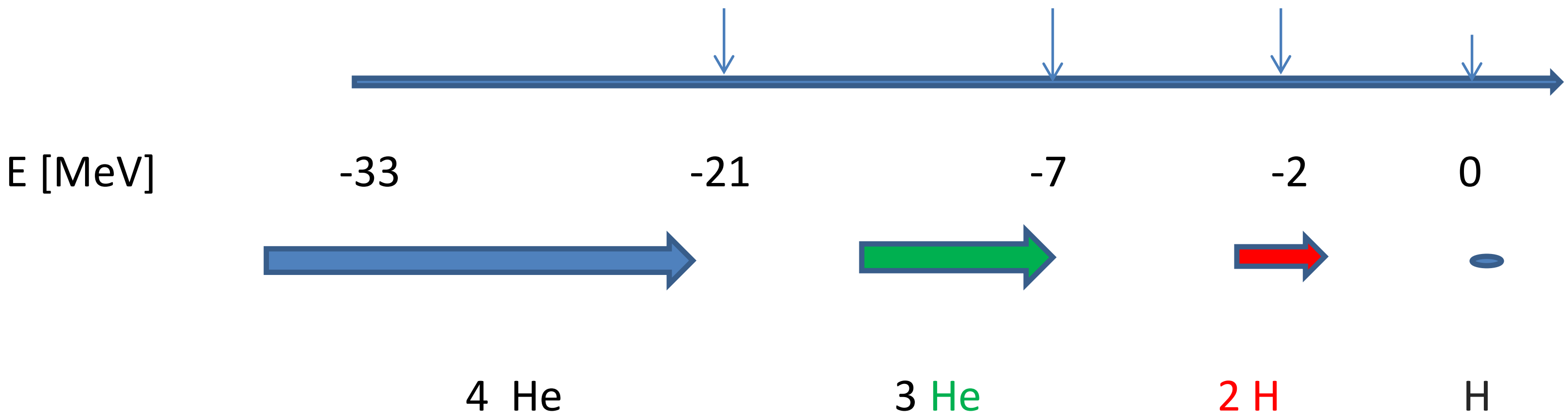
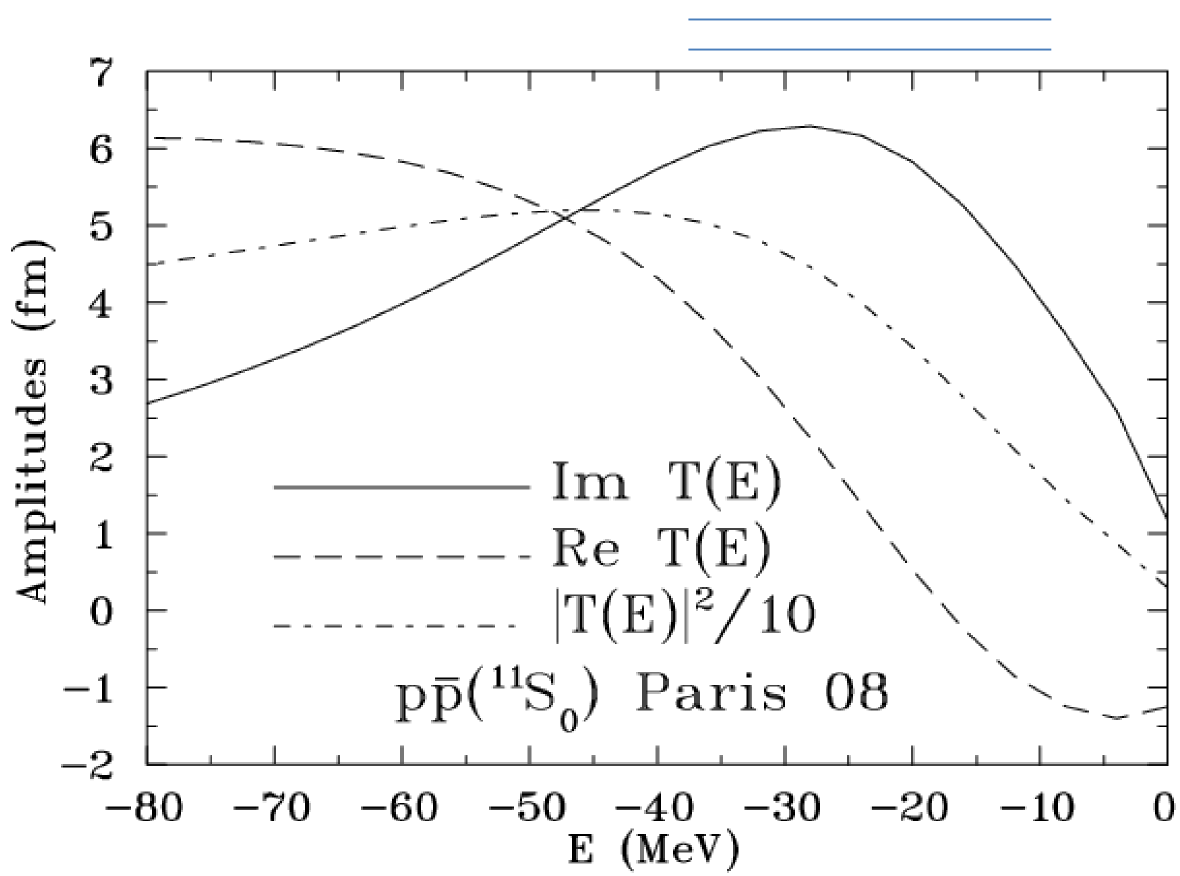
P-bar N SUBTHRESHOLD ENERGIES INVOLVED IN ATOMIC STATES
SEPARATE REGIONS IN LIGHT NUCLEI ALOW TO TEST T (E)
BELOW THRESHOLD



$T(E, r) = V(r)\,\psi(r)/\phi(r)$; $\psi = \phi + G(+)\,V\,\psi$

^{11}S AMPLITUDE   tested in J/ψ decays

Region of energies
involved in atomic
states



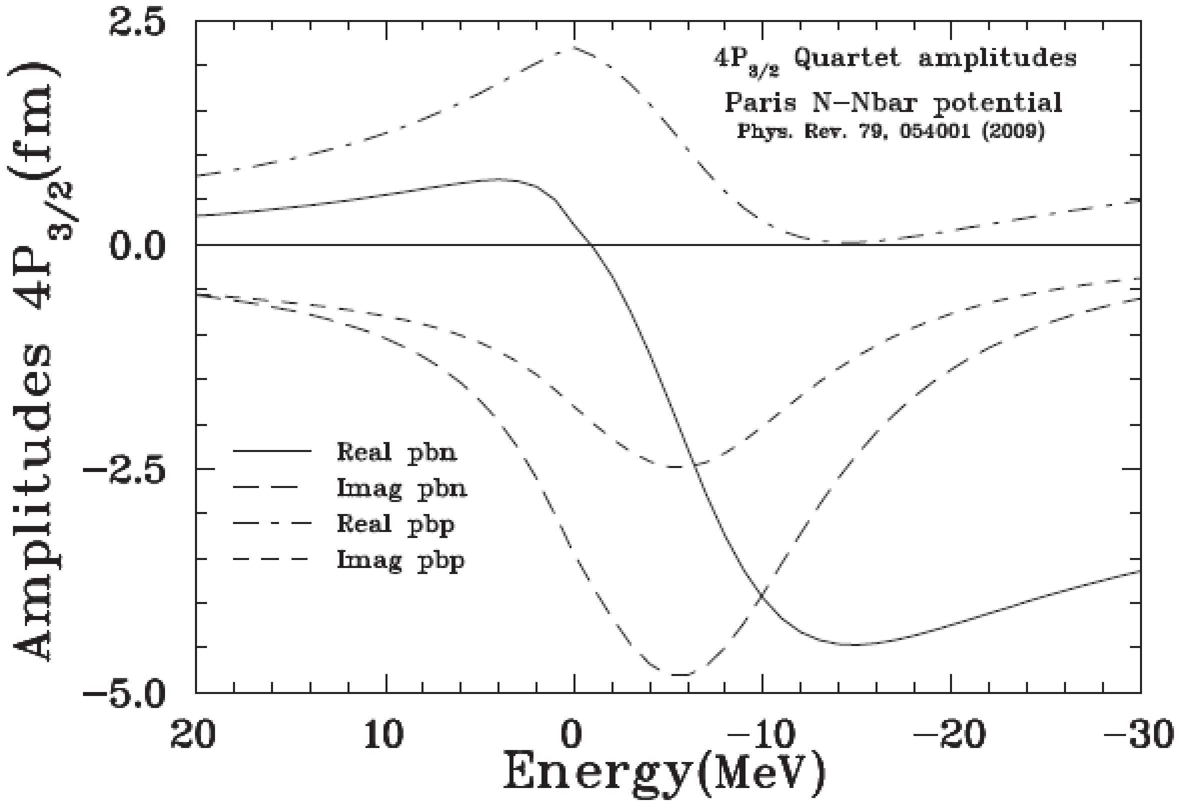
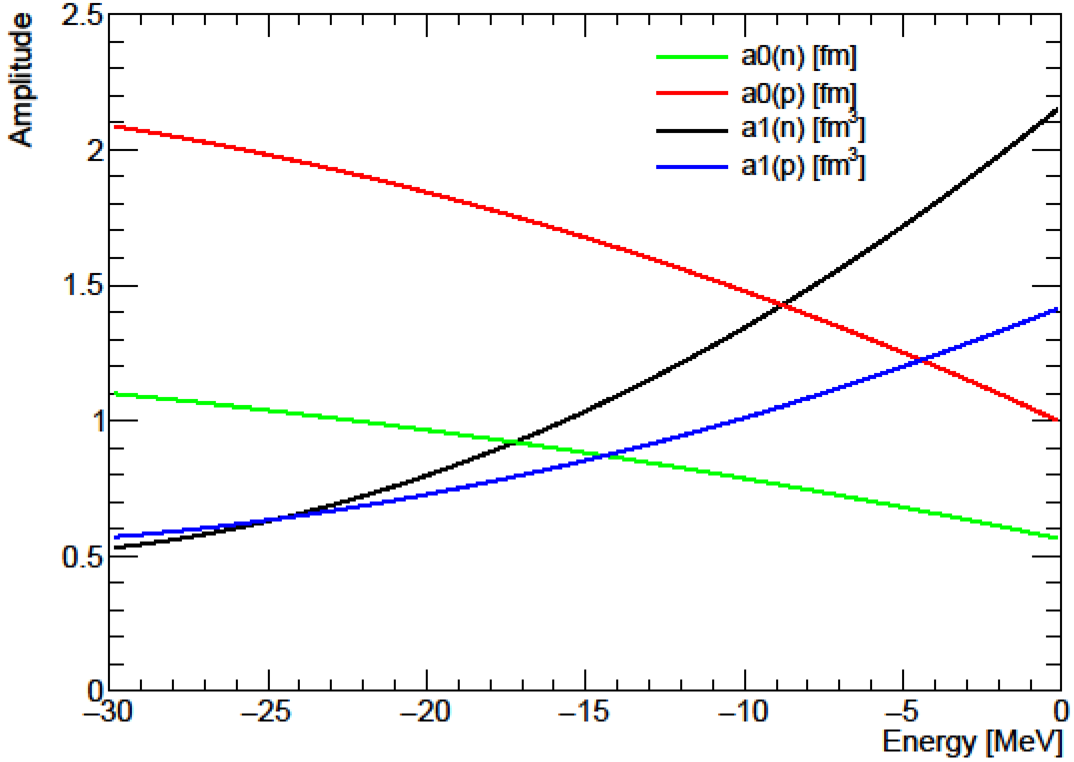


FIG. 2. Subthreshold amplitudes generating the $4P_{3/2}$ hyperfine structure component in deuterium. With the Paris 09 solution this amplitude is strongly dominated by the resonant $a(^{33}P_1)$ amplitude.

Quartet f.s. state   dominated by 33P1 baryonium state

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

Neutron/proton capture rate is energy (state) dependent



Paris 09 , B.Loiseau, J.Carbonell, S.W.

IMPORTANT PARAMETER IN HALO STUDIES

Ratio of annihilation rates

$R_{n/p}$ = σ(p-bar, n) / σ (p-bar, p) =

= < Im T (P-barn) > / < Im T (P-barn) > spin averaged

CALCULATED with Paris 09 : in He Rn/p ~ 0.48 : in D Rn/p ~ 0.80
consistent with experiments

CALCULATIONS FOR PIONISATION EXPERIMENTS

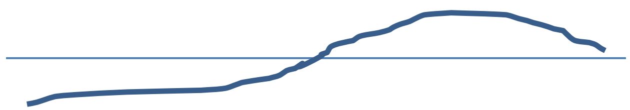
The $R_{n/p}$ calculated with Paris 09 potential, [?], for the dominant capture states.

	C	N	Ti	Ta	Pb
$R_{n/p}$	0.698	0.780	0.774	0.889	0.920
$L_{dominant}$	2	2	4	9	8

Problems for theorists

1) NUCLEAR OPTICAL POTENTIAL $V \sim \rho(r)\ T_0 \quad +3\ \mathrm{grad}\ \rho(r)\ \ \mathrm{grad}\ T_1$

CONFLICT Re T_0 IS REPULSIVE , BUT POTENTIAL FITTED TO ATOMS IS ATTRACTIVE
Re T CHANGES SIGN AT QUASI-BOUND STATE



NUCLEAR EFFECTS : PAULI PRINCIPLE , EXTERNAL NUCLEAR FIELD
PUSH THE ZERO UPWARD

(usefull Saclay work on K_{FERMI} (r) in surface region , X. Campi)

2) GOOD NUCLEAR CALCULATION of

$$A_p =< L, valence|[a_0(p) + 3\nabla a_1(p)\nabla]|L, valence >$$

II

STUDIES OF COLD FINAL NUCLEI

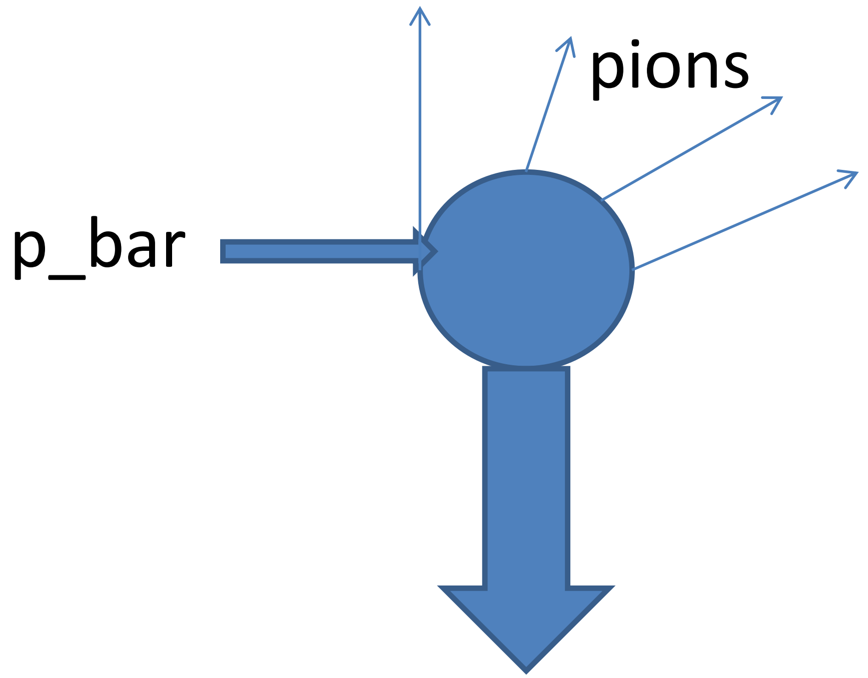
Munich –Warsaw collaboration (T. von Egidy , J. Jastrzebski)

Antiproton + Nucleus (Z , N) → Nucleus (Z-1 , N)
→ Nucleus (Z ,N-1)
→ 90 % rubbish

Radiochemical detection of residual nulei

PROBLEM - what is the capture orbital ?

Studies of final non excited nuclei
Munich – Warsaw /CERN PS



FINAL A-1 NUCLEI OF LOW < 8 MeV excitation (Radiochmical limit)
RATIO (N-1)/(Z-1) measured

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

MEASURED

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

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

$P_{emission}$ probability that residual A-1 nucleus is cold
(below neutron emission thteshold , must be calculated)

f_{HALO} local excess of neutrons in the capture region
a phenomenological quantity

ESSENTIAL POINT : COLD CAPTURE and HADRONISATION
DETERMINE PRODUCT R f

ESSENTIAL PARAMETER To STUDY NEUTRON HALO

$R_{n/p}$ relative rate of absorptions

σ(p-bar n) / σ (p-bar p)

from other experiments
0.48 in He : 0.82 in D : 0.63 in C :
1 in global optical p-bar nucleus potential

ABOUT 10% of residuals are A-1 nuclei

fixes orbitals of capture

mostly „upper” levels

deformed nucleus

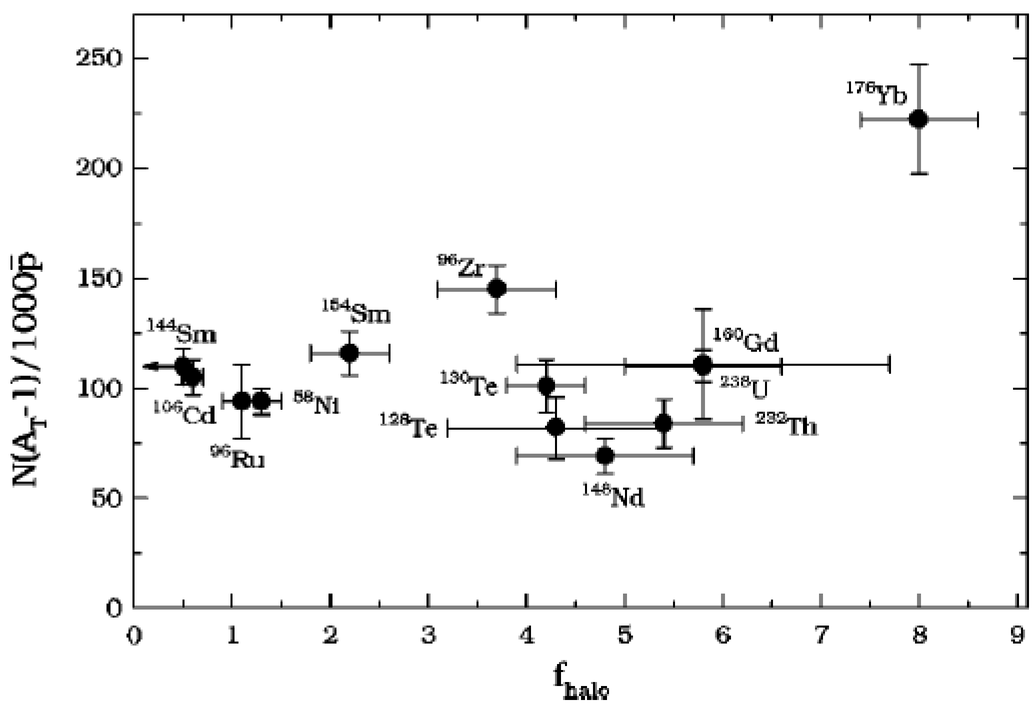


FIG. 5. Correlation between halo factor and absolute production yield for A_t-1 nuclei.

Excess of neutrons over protons
Reduced by N/Z

Lubinski PRC 57
Munich Warsaw

With known capture orbit

Rms(n) –Rms(p) Extracted

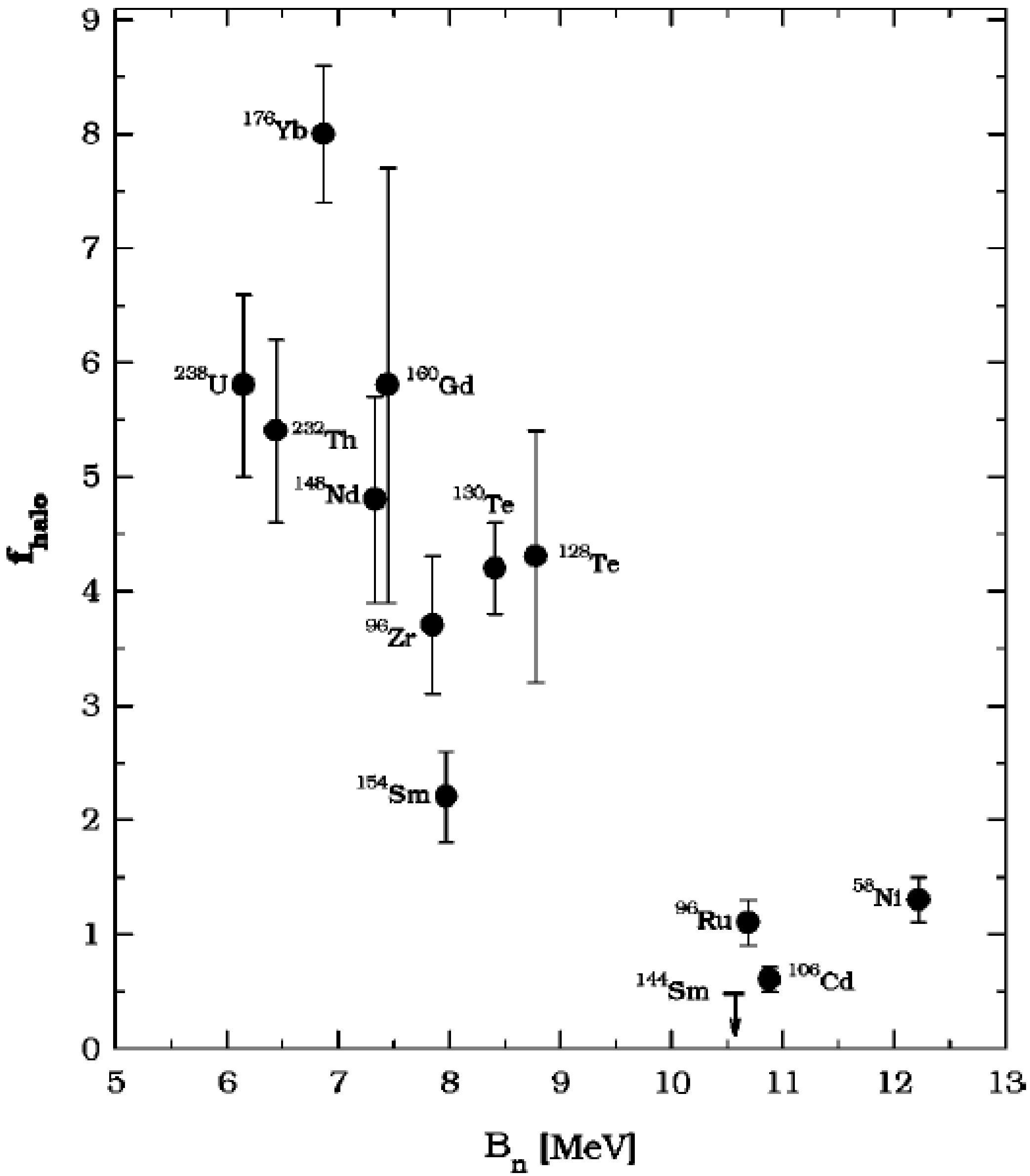


FIG. 3. Neutron halo factor (defined in the text) as a function of the target neutron separation energy B_n .

HADRONISATION (PIONISATION) EXPERIMENTS

P-bar , N → π ,π, π, π, π FROM ATOMIC STATES

MENU :

1) Old experiments : analysis , difficulties

2) Uncertainties of calculations

3) Job for theorists in PUMA era

OLD 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

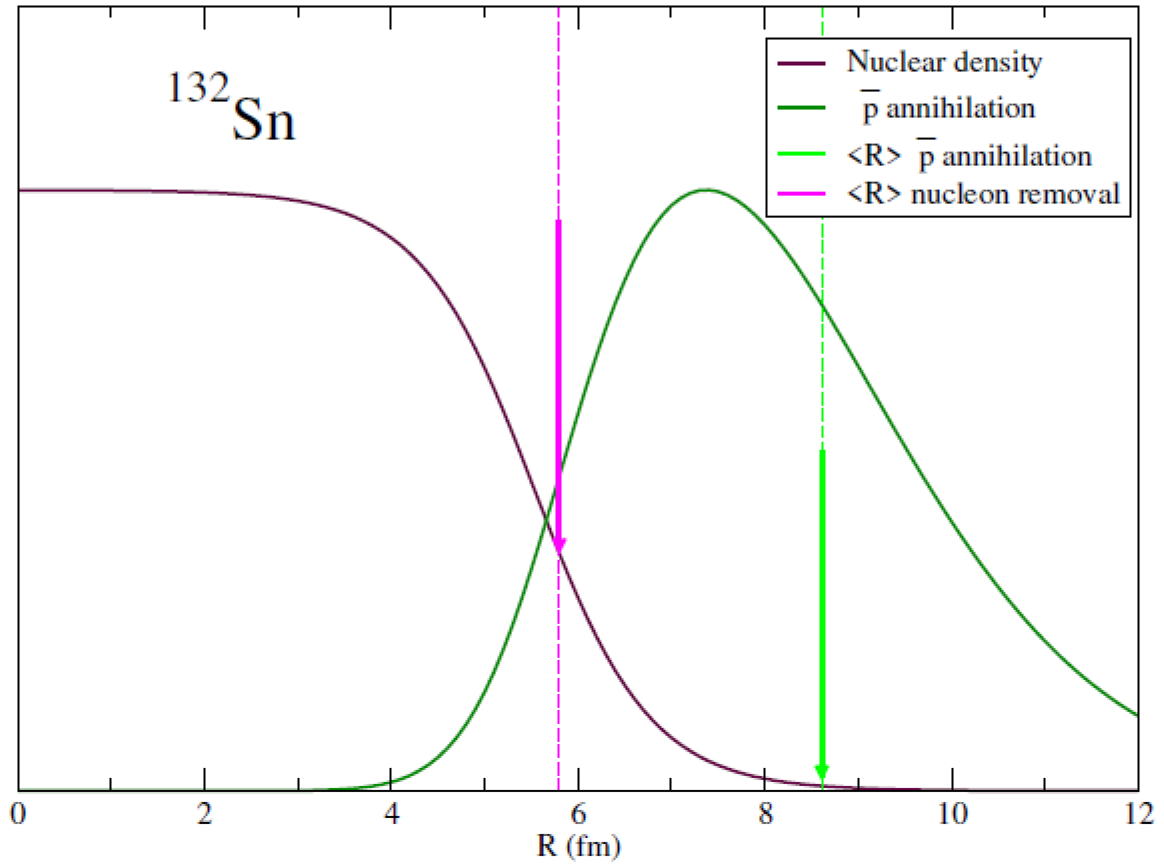
J. Riedlberger et al Phys Rev C40 (1989) 2717

N magnetic spectrometer

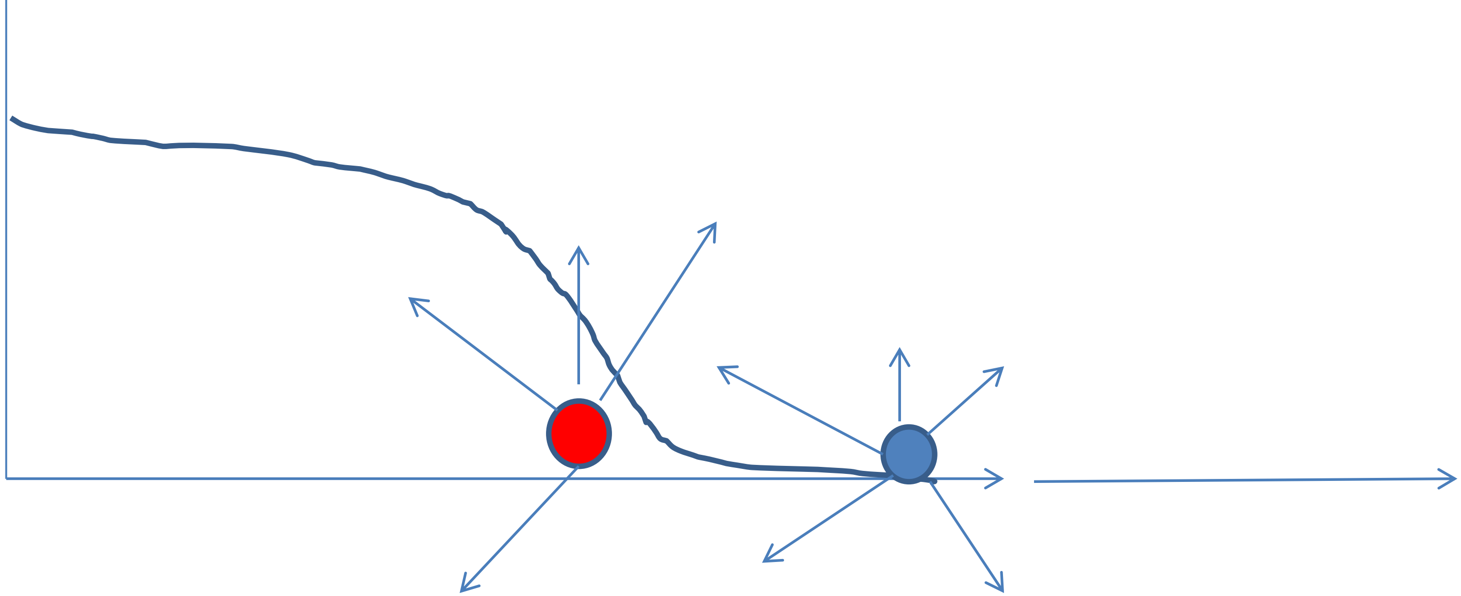
Not analyzed fully , N-Nbar data was poor

NOW ANALYSIS IS EASIER => LESSONS FOR PUMA

Z= 50 , N = 88 : a fancy nucleus to study



Antiproton makes a 2000 MeV bomb on the side of nucleus



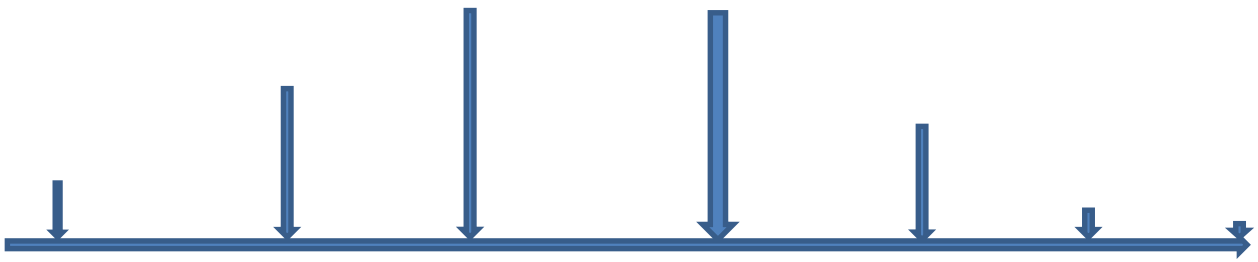
Mesons from
NN-bar → π π π

Nucleus destroyed , pions detected , less peripheral

Cold residual nuclei detectable , more peripheral

PIONISATION EXPERIMENTS

ANTIPROTON + NUCLEUS → π π π π π + rubbish



TOTAL PION CHARGE -2 -1 0 1 2 3

Very rich experiment 8 numbers : P(Q) , average meson loss = ω

EXAMPLE Pb experiment (W. Bugg)

Results : f_{HALO} = 2.34(0.50) , ω = 0.221(0.014)

SIMPLE ANALYSIS

Calculate average charge meson loss ω (L)

from π NN – NN , π (+/-)N → π (0) N'

Compare $\omega(L+1) < \omega < \omega(L)$

=> capture orbital probability : : 0.5 (upper L=9) + 0.5 (lower L=8)

agreement with cascade X

Take $R_{n/p}$ = 0.63 (from Carbon, BUGG)

f_{HALO} , $R_{n/p}$ → halo radius Rn - Rp = 0.168 (0.045) PERFECT

BUT $R_{n/p}$ = 0.63 IS NOT ACCEPABLE by other experiments

A more complete analysis including
full information

P(Q) channel probabilities
<n(+/-)> total number of charge mesons emitted in single capture

Explicit calculations of absorptive and charge exchange pionic final state interactions

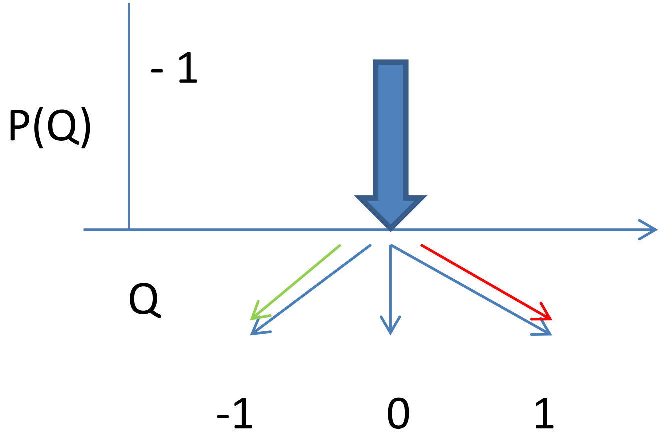
DATA : P(Q) , <n± >

extraction of average meson absorption - ω

average meson charge exchange - λ

f_{HALO} · R n/p

P-bar P capture



ω (+) ω(-)

absorption

λ(+)

π(0) -> π(+)

λ(-)

π(0) -> π(-}

Parameters λ ω f_{HALO} · R n/p

obtained by best fit to data

DATA : $P(Q)$, $< n\pm >$

extraction of average meson absorption - ω

average meson charge exchange - λ

f_{HALO} · $R\ n/p$

FOR a GIVEN CAPTURE ORBIT – L

CALCULATE

$\omega(L)$, $\lambda(L)$, $R\ n/p\ (L)$

COMPARISON $\omega(L)$ ~ ω

EXTRACTION OF L

From L , $R_{n/p}$

R_{ms} (neutrons) - R_{ms} (protons)

Next iteration : corrections for nucleon correlations at surface

N - Riedlberger PR C40 (1989) High statistics , No hydrogen contamination, magnetic spectrometer , ASTERIX

: 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

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

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

These are values averaged over two pionic charges.

	$L = 2$	$L = 3$	best fit
ω	0.218	0.158	0.165
λ	0.147	0.103	.13

CONCLUSIONS from N experiment

the best fit $R_{n/p} \cdot f^h = 0.77(.04)$ and $R_{n/p} = .80$ calculated from Paris potential (
Capture happens half from „upper"(L=3) , half from „ lower"(L=2) orbitals.

factor $f^h = .96(.05)$ that is a weak preference for an enhanced proton tail

Consistent with separations $S(n) = 10.5$ MeV and $S(p) = 7.5$ MeV

NNNN Correlations are indicated
in Q =3, -3

CONCLUSIONS from N experiment

OBSERVATION

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

Large difference between π(+) and π(-) exchange probabilities in a symmetric nucleus . Related to different single nucleon spectra. Possible byproduct for PUMA

NICE SO FAR , BUT NO LONGER SO

DIFFICULTUES WITH ANALYSIS OF OLD HYDROGEN CHAMBER DATA

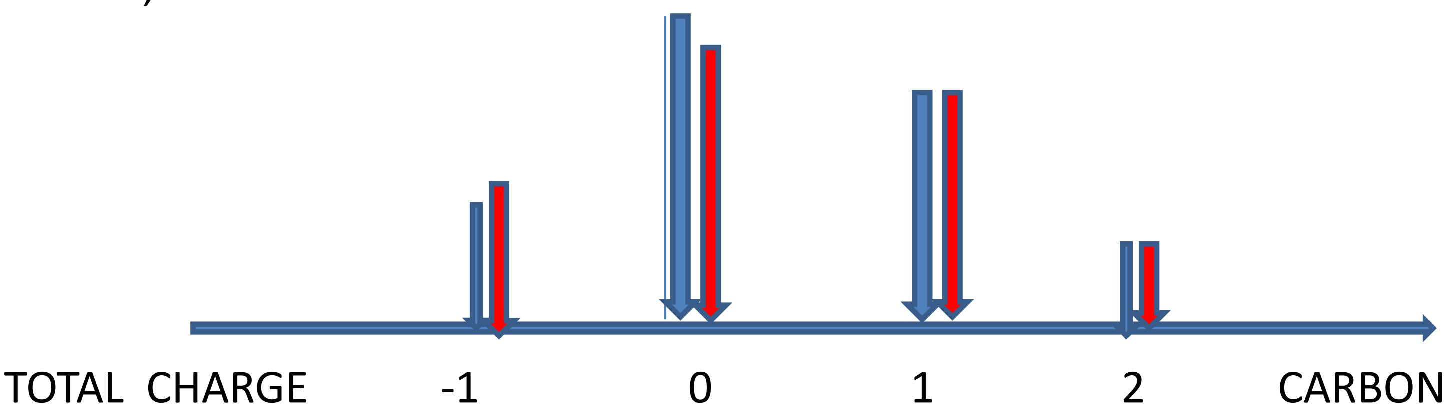
HYDROGEN BACKGROUND UNCERTAIN

TWO EXPERIMENTS DIFFERING BY HYDROGEN CONTAMINATION
(BUUG - hydrogen chamber vs WADE propane chamber)
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

WADE FREON FOUR STANDARD DEVIATION DIFFERENCE in Q =0

BUGG , HYDROGEN



Rn - Rp = 1.01 (0.03) FREON CHAMBER
= 1.10 (0.03) HYDROGEN CHAMBER

Δ R - 10 % PROBLEM IN ALL BUGG’S EXPERIMENTS

BUT STATE OF CAPTURE IS STABLE

AN ALTERNATIVE for ALL HYDROGEN CHAMBER C, Ti, Ta , Pb analysis

With hydrogen contamination as given ~ 10 % (NO ERRORS GIVEN)

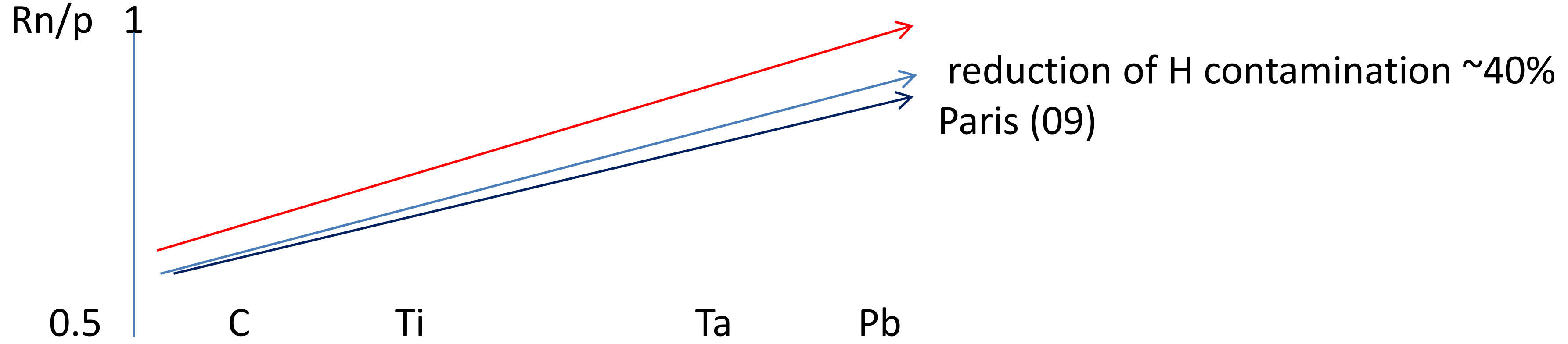
1) Either Rn/p larger by 10 -20 % than calculated by PARIS 09

2) Or hydrogen contamination reduced to about 5 %

Hydrogen chamber data

Rn/p

enhancement needed to get Rp-Rn
as in other antiorotonic expeeriments



CAPTURE STATES AS EXPECTED ~ 50% „upper” L , ~ 50 „ lower” L

BUT WHAT IS THE NEUTRON HALO IN LEAD NUCLEUS ?

STRANGE CORRELATION OF EXPERIMENTAL NEUTRON RADII IN Pb

Rn-Rp [fm]	~ 28	parity violation
	~ 22	pionisation
	~ 20	proton scattering
	~ 16 -18	antiproton levels, cold capture

These follow increasing peripherality of interaction region

? Possibly due to differences in assumed nuclear profiles

STATUS REPORT

PIONISATION EXPERIMENTS YIELD REASONABLE ESTIMATES OF HALO THICKNESS.

CAPTURE STATES ARE WELL EXTRACTED FROM CHANNEL P(Q) SPECTRA

THERE IS A LARGE UNCERTAINTY DUE TO HYDROGEN BACKGROUND IN OLD HYDROGEN CHAMBER EXPERIMENTS

SOME CHALLENGING PROBLEMS FOR THEORISTS

1) Understanding P-bar N interactions below threshold, bound states there

2) Pauli blocking in pion charge exchange scattering on nuclei
Controll of exclusion principle in the nuclear surface region
This question is of significance for antiproton – nucleus potential.

3) Good calculation of Rn/p ratio at nuclear surface

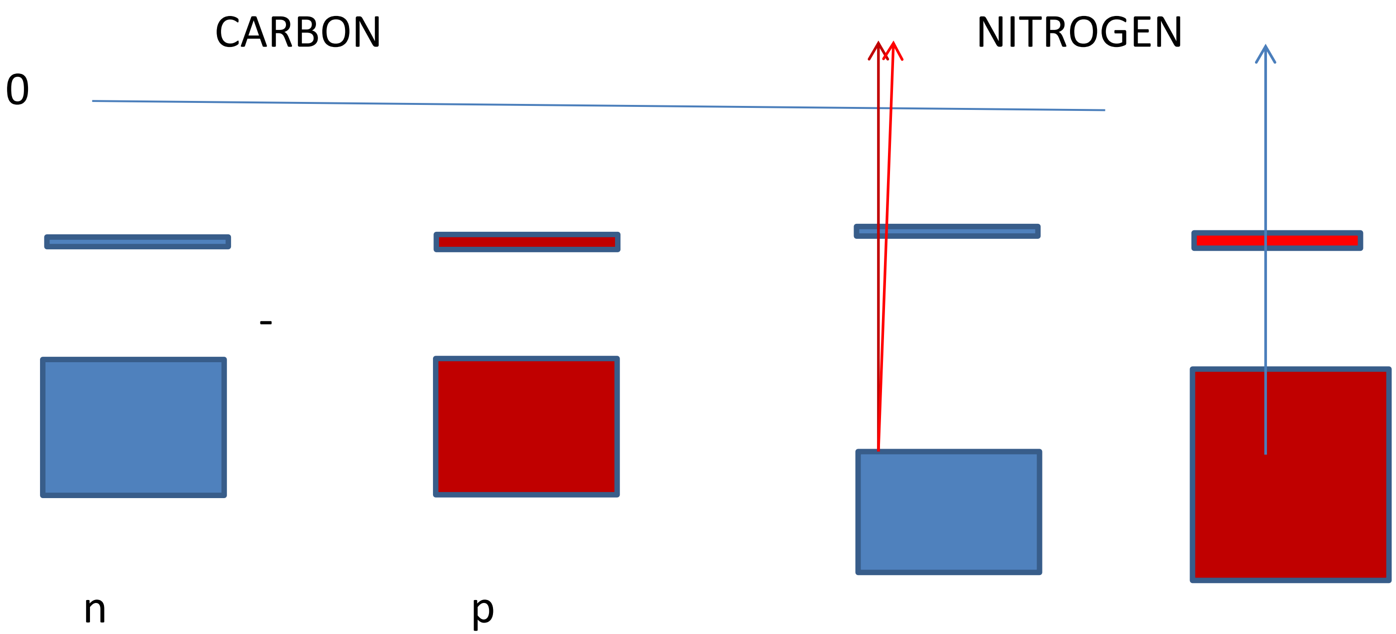
4) Analysis of future data in terms of neutron density distributions

5) Inclusion of nuclear correlations into analysis of PUMA data

Symmetric nuclei nonsymmetric effect : Pauli bloking

Pion is fast ~ 400 Me V /c But Nucleon is heavy and slow

λ(+) > λ(-) in light nuclei N



π(0) n → π(-) p

λ(-) < λ (+)

FINAL STATE INTERACTIONS OF PIONS

π NN – NN absorption

cross sections known, poor accuracy Ashery , P R C 23(1881)

calculations W Gibbs PR C 66 (2002)

Johnson Satchler optical potential Ann Phys 238 (1996)

consistent in predicting ω to 10 %

π (+/-) → π(0) and inverse based on π p charge exchange

Gibbs , Kaufman found Pauli blocking significant

** ARE THERE STRONG CORRELATIONS ON NUCLEAR SURFACES

ALPHA PARTICLE TYPE ?

Seen in nuclear α decays

May be covenient energetically

Carbon nucleus ≈ α α α ?

Traces in Nitrogen (3 α + valence n,p) pionisation experiment

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

THANK YOU

APPENDIX

R.Schmidt PRC58
CASCADE IN A DEFORMED NUCLEUS

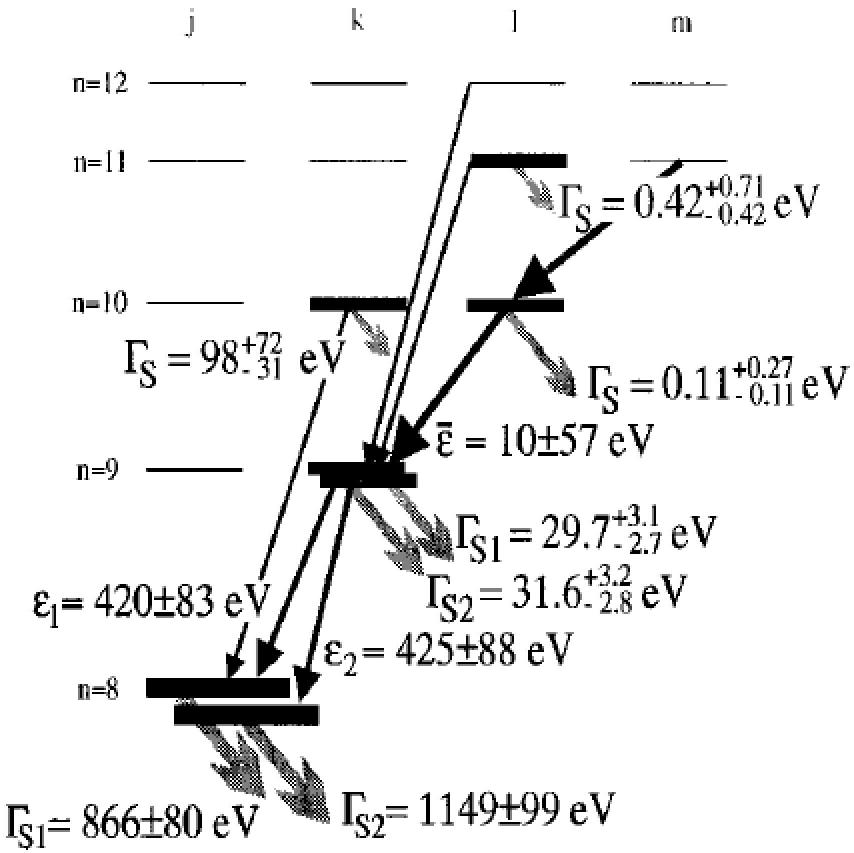


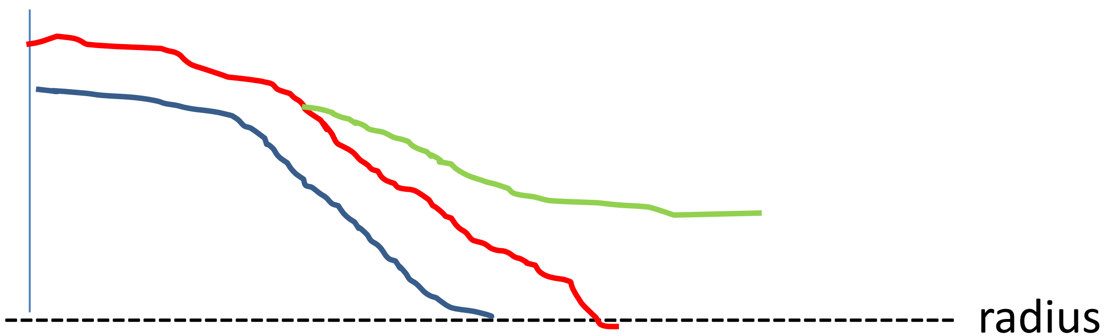
FIG. 9. Energy shifts of the transitions and widths for the levels antiprotonic ^{172}Yb which are sizably influenced by the strong

FERMI MOMENTUM AT NUCLEAR SURFACE ?

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

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

$= \rho\ j_1(K_{FERM}|x-x'|) / (K_{FERMI} |x-x'|)$ correlation function



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

WHY STUDY NUCLEAR SURFACE ?

* 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

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

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.

THE ORIGIN OF SYMMETRY ENERGY