Nuclear structure studies with low energy $\bar{p}$

S. Wycech

Atomic X-rays

- atomic level widths measured

Reactions

$$\bar{p} + (N, Z) \longrightarrow (N, Z-1) + mesons \quad (1)$$

$$\bar{p} + (N, Z) \longrightarrow (N-1, Z) + mesons \quad (2)$$

- Stopped $\bar{p}$. Charged mesons detected.
- Trapped $\bar{p}$. Charged mesons detected.
- Cold capture, radiochemical detection of A-1 nuclei
- Capture in flight: total, $A-1$

ATOMIC X - RAYS level widths measured

$$\frac{\Gamma}{2} = \int d\mathbf{R}\ \mathrm{Im}V^{opt}(\mathbf{R}) \mid \Psi_{\bar{N}}(\mathbf{R}') \mid^2$$

$$V^{opt}(\mathbf{R}) = \frac{2\pi}{\mu_{N\bar{N}}} \Sigma_s \int d\mathbf{R}'\ \rho_s(\mathbf{R}') t^s_{N\bar{p}}(\mathbf{R} - \mathbf{R}')$$

$\Psi_{\bar{p}}(\mathbf{R})$ - $\bar{p}$ atomic wave function $\sim R^l$

high $l \rightarrow$ nuclear surface

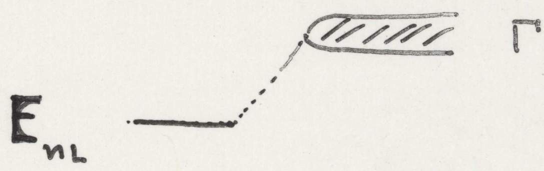
More complicated $V^{opt} = V_s + \nabla V_p \nabla$

ADVANTAGES - atomic state known

- level shifts test V^{opt}

PROBLEMS - 50 % enhancement due to force range

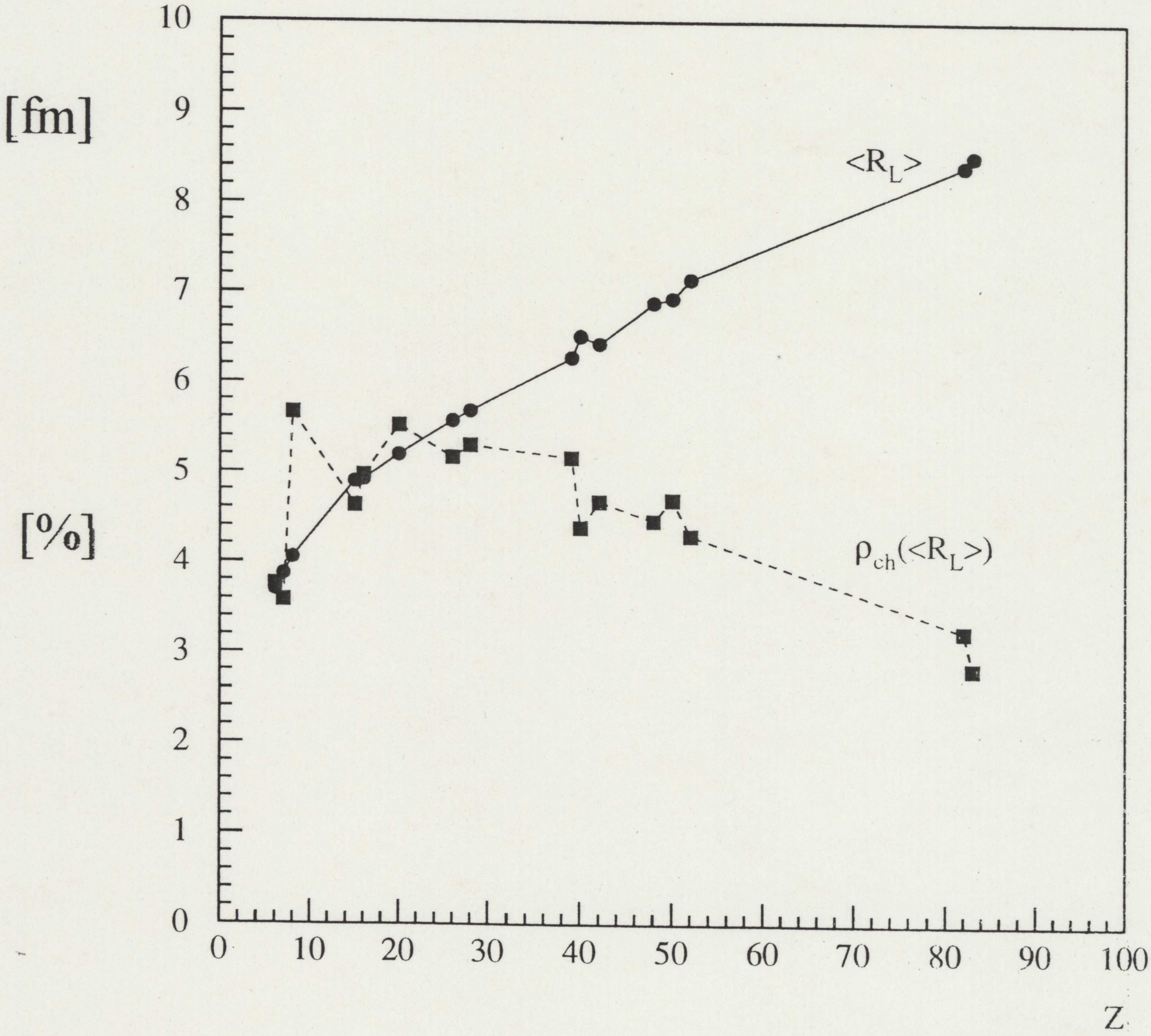
- large R tested $\rightarrow R_{ms}$ wanted



ATOM + NUCLEAR (keV)

Average radii tested in " lower " orbit <R> [fm]

Nuclear density involved ρ(<R>) / ρ(0) [%]



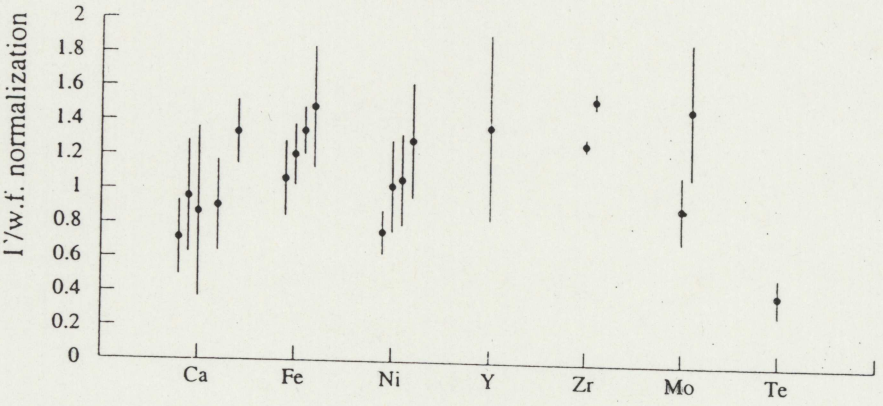


Figure 1. Experimental widths of n = 6, l =5 atomic levels, scaled by the normalization factors of the corresponding wave functions. Arbitrary units. The data: Ca,Fe,Ni,Zr,Te from [2],Fe,Y,Zr from [1] (Roberson), Mo from [14].

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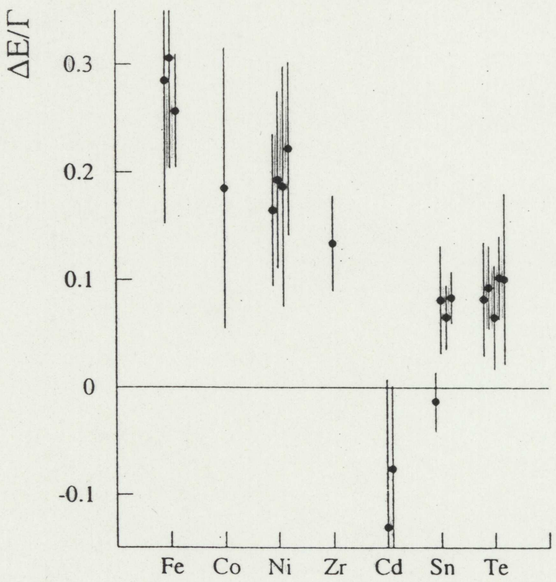
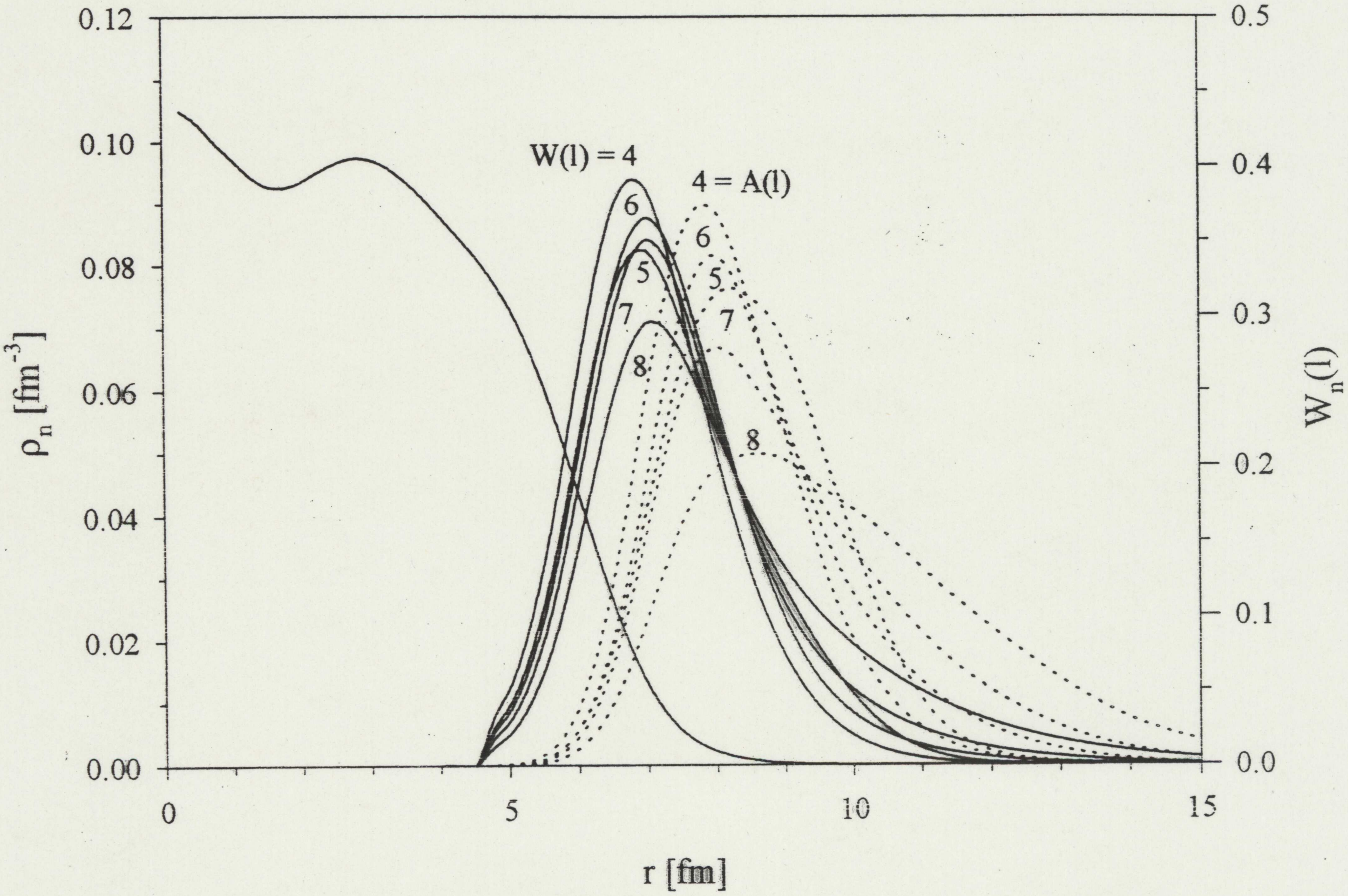


Figure 2. The ratio of experimental $\Delta E/\Gamma$. The data: Fe,Ni,Zr,Cd,Sn,Te from [2], Fe,Y,Zr from [1] (Roberson).

WHAT REGIONS IN NUCLEI ARE TESTED



SHAPES : almost L- independent . An advantage for some nuclear studies

VOLUMES : depend on L , n , nuclear interactions

COLD CAPTURE

$\bar{p}\ (A) \longrightarrow$ mesons $(A-1)_{COLD}$

Measured $\quad \frac{\Gamma_{\bar{p}n}}{\Gamma_{\bar{p}p}}, \quad \frac{\Gamma_{A-1,cold}}{\Gamma_{total}}$

Annihilation $\rightarrow$ high energy release $\rightarrow$ closure approx.

$$\frac{\Gamma_{\bar{p}n}}{2} = \frac{2\pi}{\mu}\mathrm{Im}t_{n\bar{p}} \int d\mathbf{R} \mid \Psi_{\bar{p}}(\mathbf{R}) \mid^2 \ \rho_n(\mathbf{R})\ P_{fsi}(\mathbf{R})$$

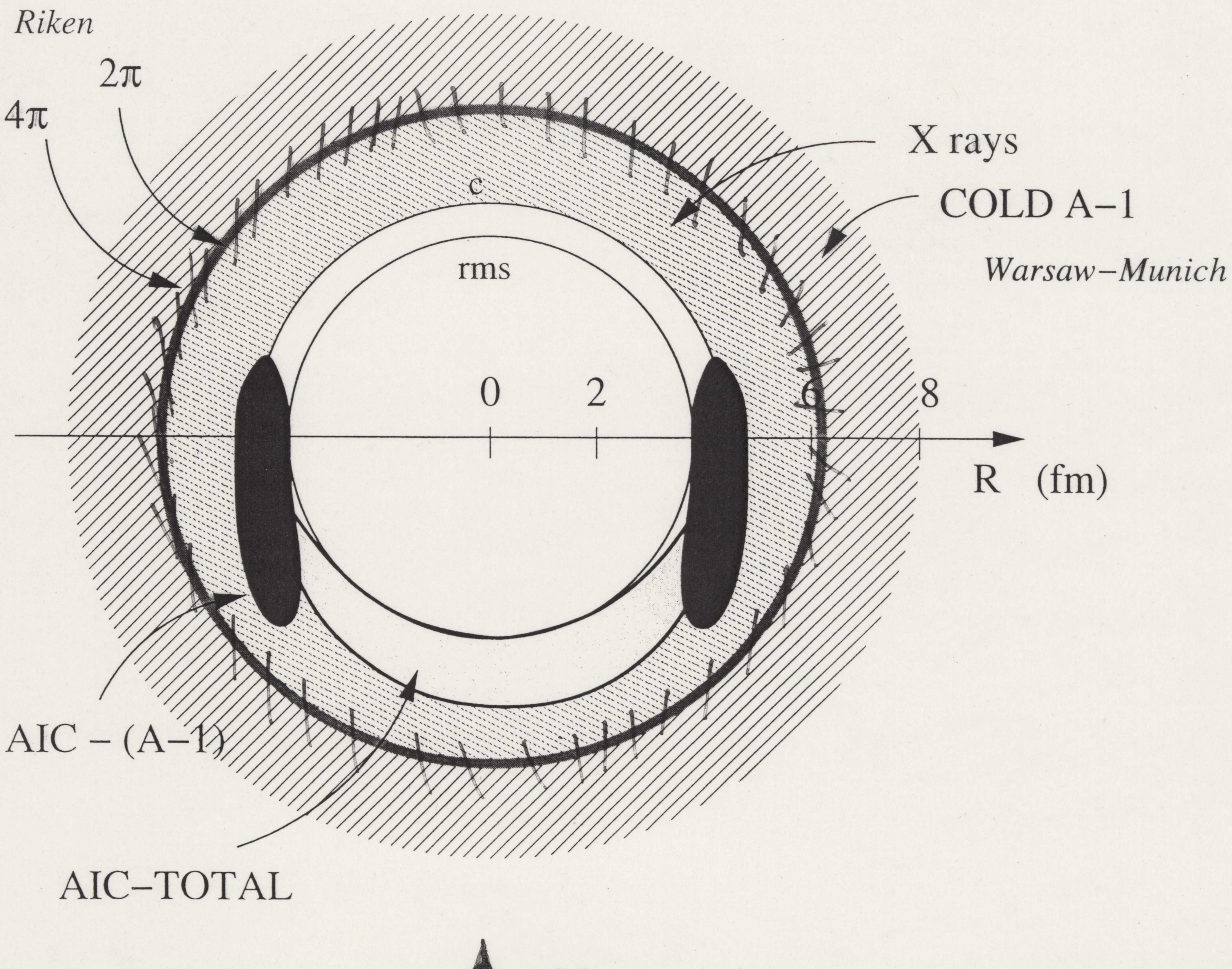
$P_{fsi} = P_{miss}(\mathbf{R})\ P_{dh}(\mathbf{R})$

P_{miss} probability for all mesons to miss the nucleus

P_{dh} correction for "hot, evaporating" A-1 nuclei

PROBLEM $\quad P_{fsi}$, initial states are *calculated*

the check is $\frac{\Gamma_{A-1,cold}}{\Gamma_{total}} \approx 0.1$

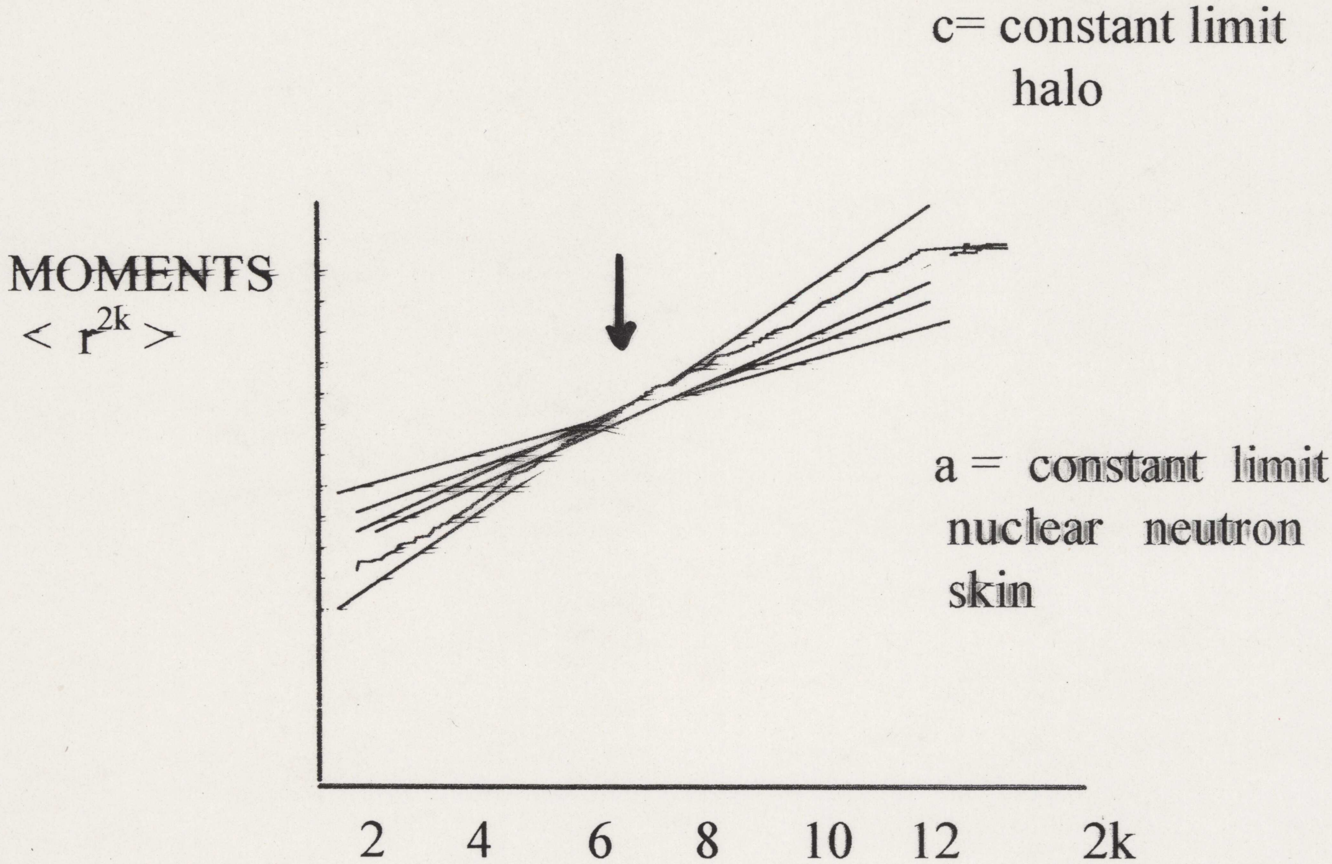


Riken
2π
4π
X rays
COLD A−1
Warsaw−Munich
c
rms
0
2
6
8
R (fm)
AIC − (A−1)
AIC−TOTAL
p̄ - AIC

NEUTRON DENSITIES TESTED

Take a reasonable density $\rho_{neutron}(r : c, t, w_i)$

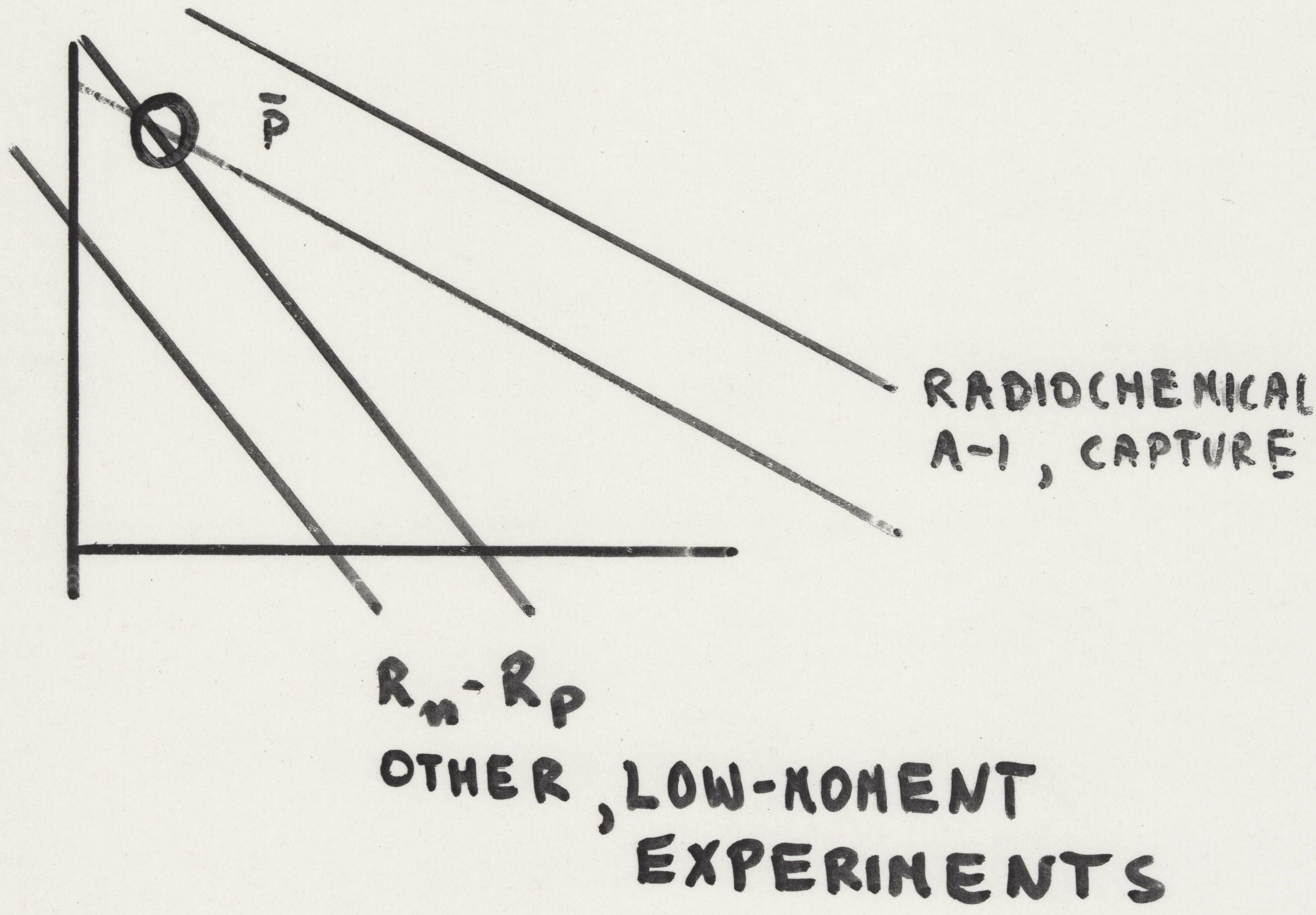
Fit the widths changing parameters c, t, w_i



THE 2L – 3 MOMENT IS BEST DETERMINED

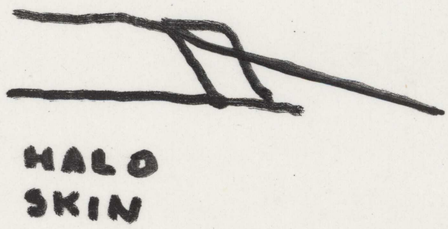
GIVEN $< r^2 >$ one can tell „ halo ” or „skin”

124 Sn



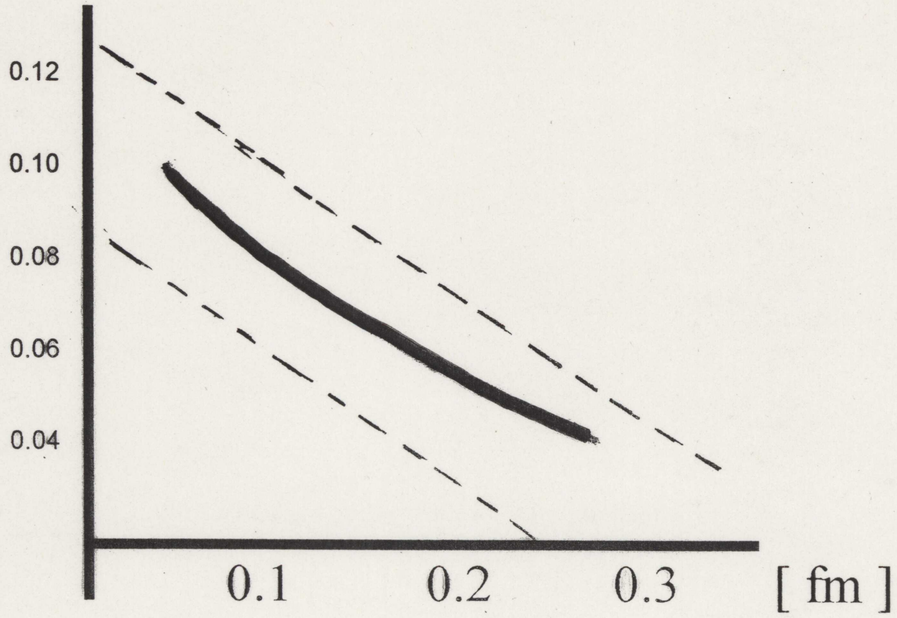
$\bar{p}$
RADIOCHEMICAL
A-1, CAPTURE
$R_n - R_p$
OTHER, LOW-MOMENT
EXPERIMENTS

124 Sn nuclear surface neutrons



surface slope : HALO

$a_n - a_p$ [fm]



c_n -c_p -half density : SKIN

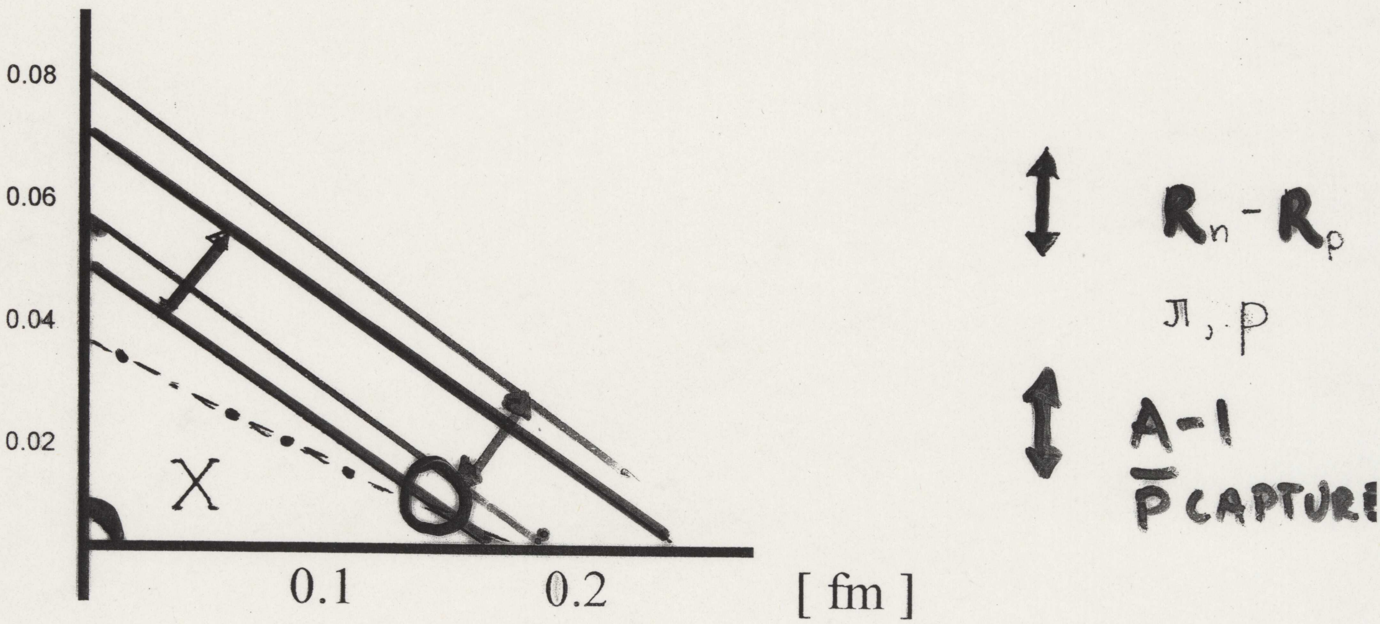
———— $\chi^2 \approx 0$

-------------- $\chi^2_{PDF} \approx 1$

Long tail - sizeable contribution from 3s shell

48 Ca - the nuclear surface
neutrons

surface slope
$a_n - a_p$ [fm]



$c_n - c_p$ -half density

X

———— $\chi^2 \approx 0$

-·-·-·-·- $\chi^2_{PDF} \approx 1$

)ATA

1+

2

2+

Table 1: The $\bar{p}$- atomic - methods to study neutron skin.

Method	measured quantity	advantages	difficulties
X-rays	level widths Γ	$\bar{p}$ state known	no p,n separation
	level shifts	check on $V_{\bar{p}}^{optical}$	
Cold capture	$\Gamma(\bar{p}n)/\Gamma(\bar{p}p)$	n,p separation	$\bar{p}$ state unknown
	$\Gamma(A-1)/\Gamma(total)$	check on $\bar{p}$ states	
Meson emission	$N(\pi^-)/N(\pi^+)$	n,p separation	$\bar{p}$ state unknown
	$N(\pi^-) - N(\pi^+)$	check on π absorption	

REQUIREMENTS

- understanding initial states of $\bar{p}$ capture
- control over $\sigma(\bar{p}n)/\sigma(\bar{p}p)$ - external
- control of final state π interactions

Table 2: THE EXPERIMENTAL CAPTURE RATIOS $R_{n/p} = \sigma(\bar{p}n)/\sigma(\bar{p}p)$ AT LOW ENERGIES

Element	R_{np}	method	state	reference	remarks
D	0.81(3)	chamber	stopped	Bizzari	
^3He	0.47(4)	chamber	stopped	Balestra	
^4He	0.48(3)	chamber	stopped	Balestra	
^{12}C	0.63	π^+, π^-	atoms	W. Bugg	$\rho_p = \rho_n$
^{58}Ni	0.8	cold A-1	atoms	W	$\rho_p = \rho_n$
Z=8-90	≈ 1	X-rays	atoms	Friedman	
Z=8-90	≤ 1	X-rays	atoms	W	
Z $\approx$ 50	≈ 1	X ,cold A-1	atoms	Trzcinska	

Different proportions of S and P waves in $\bar{p}-N$ system

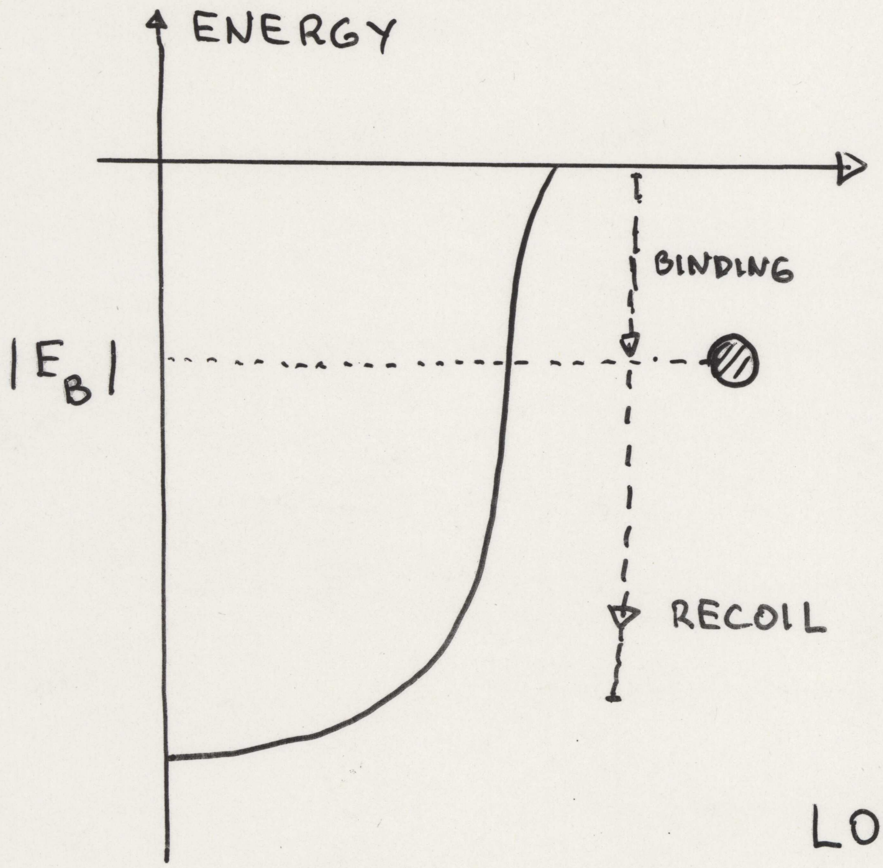
in flight He 10-50 MeV/c $\rightarrow S$

. D 200 MeV/c $\rightarrow S + P$

in atoms High l states $\rightarrow P$ dominates

Nucleon binding $\rightarrow t(E_{\bar{p}} - E_B - \frac{p^2}{2m_R})$

$\bar{p}$ K^- ATOMS



$$T_{KN}\left(-|E_B| - E^{RECOIL}\right)$$

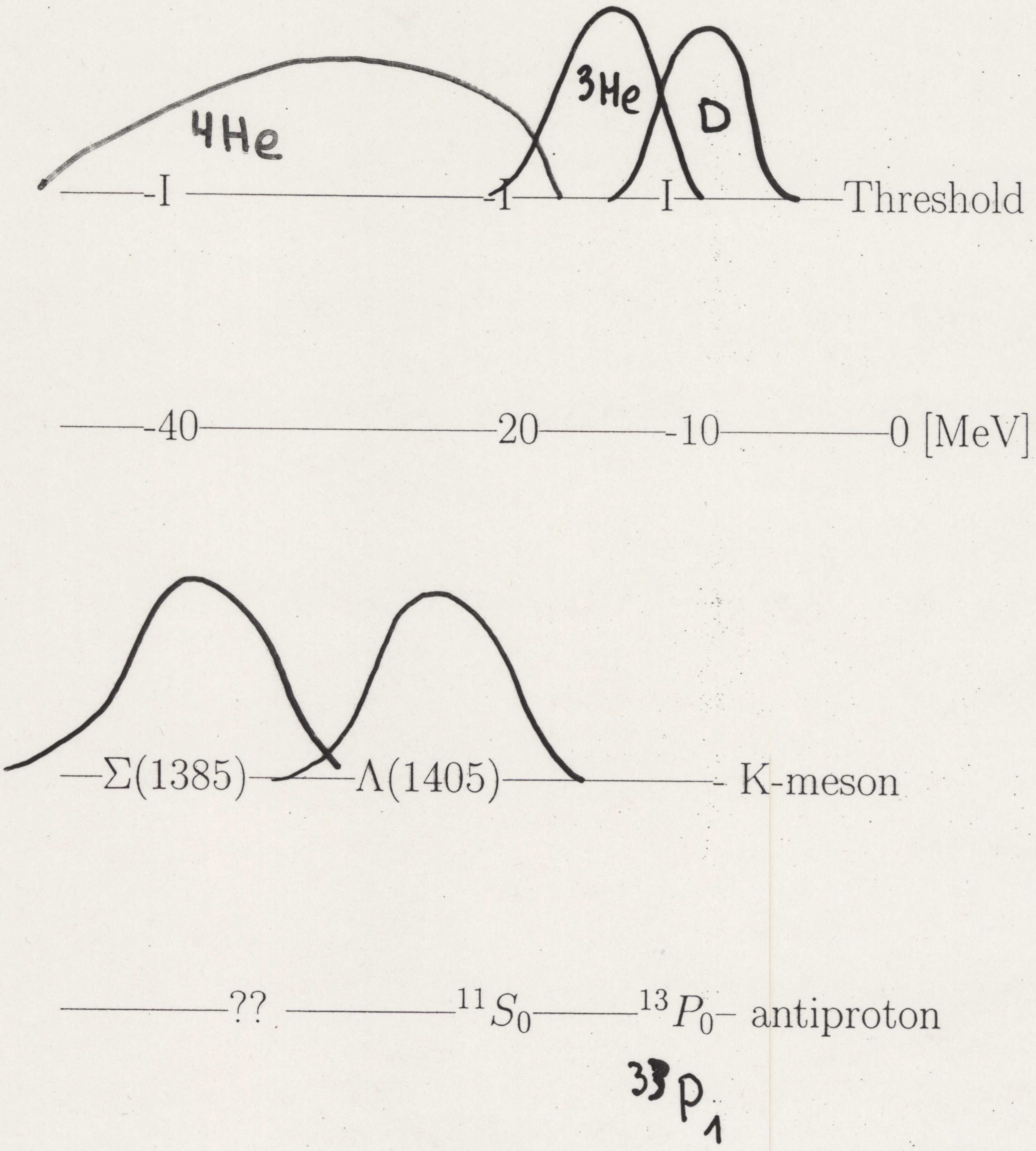
LOOK UNDER

($\bar{p}N$) K^-N THRESHOLD

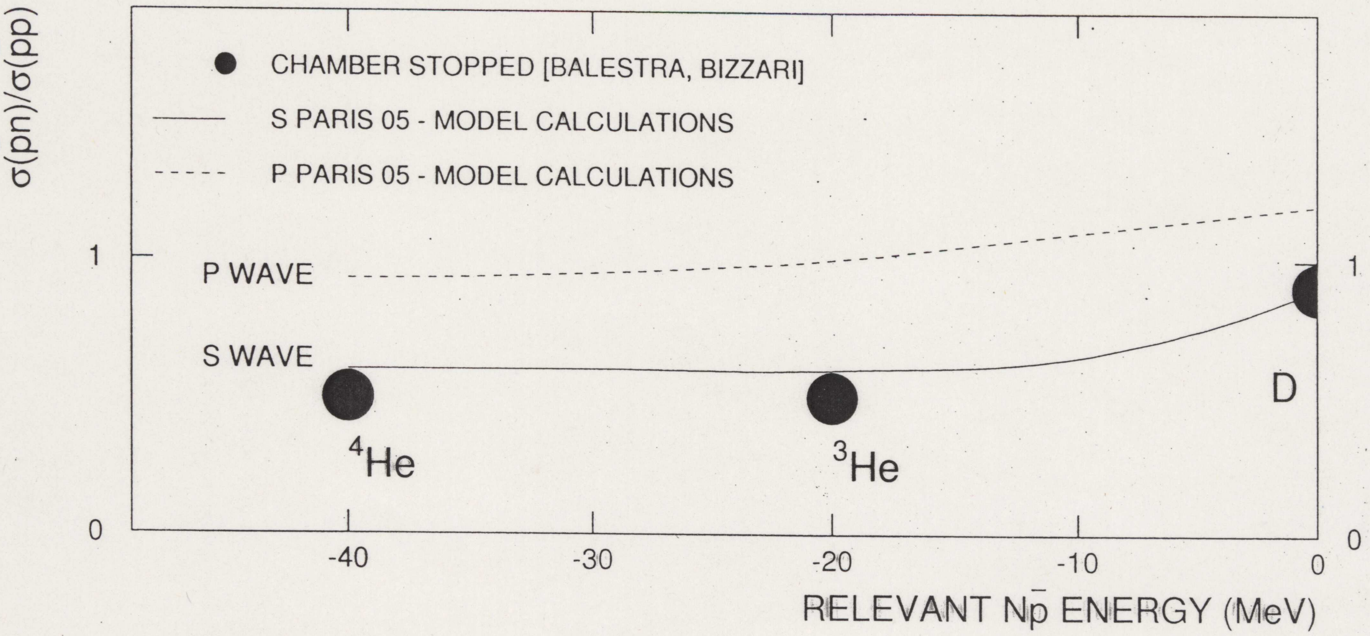
IN UPPER LEVELS

Relevant amplitudes $\quad t_{KN}(E_{atomic} - E_B - \frac{p^2}{2m_R})$

E_B binding energy, $\quad \frac{p^2}{2m_R}$ spectator recoil energy



S-WAVE



CHAMBER STOPPED [BALESTRA, BIZZARI]
S PARIS 05 - MODEL CALCULATIONS
P PARIS 05 - MODEL CALCULATIONS
σ(p̄n)/σ(p̄p)
P WAVE
S WAVE
⁴He
³He
D
1
0
-40
-30
-20
-10
0
RELEVANT Np̄ ENERGY (MeV)

CAPTURE IN ATOMS: $R_{n/p} = \sigma(\bar{p}n)/\sigma(\bar{p}p)$

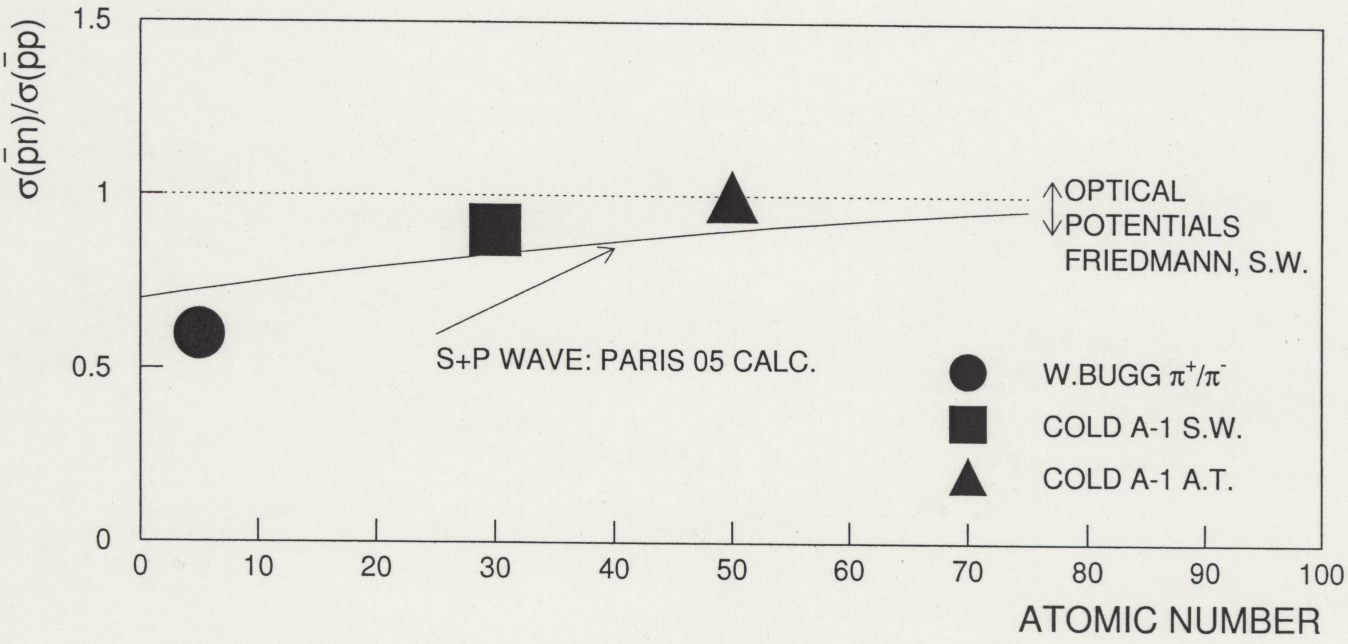
four $\bar{p} - N$ amplitudes $t_{\bar{p}N} = a_N + 3b_N \mathbf{p}\mathbf{p}'$

optical potential $V^{opt} \sim \quad a_s\rho^s + 3b_s\nabla\rho^s\nabla$

$$R_{n/p} =< n,l \mid ImV_n \mid n,l > / < n,l \mid ImV_p \mid n,l >$$

increases slowly with l and Z

$$< n,l \mid V \mid n,l > \sim < \rho(r)[a + 3b\frac{l(2l+1)}{r^2}] >_{n,l}$$



σ(p̄n)/σ(p̄p)
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
ATOMIC NUMBER
OPTICAL
POTENTIALS
FRIEDMANN, S.W.
S+P WAVE: PARIS 05 CALC.
W.BUGG π+/π-
COLD A-1 S.W.
COLD A-1 A.T.

PHENOMENOLOGICAL ANALYSIS OF $\bar{p}$ D

Basic amplitudes (12 * 2 !!)

$$t_{\bar{p}N} = a_N + 3b_N \mathbf{p}\mathbf{p}' \tag{6}$$

$N = proton, neutron \qquad a = lengths \qquad b = volumes$

averaged over the recoil

$$\bar{a} = \int a(-E_B - \frac{p^2}{2m_R}) \mid \tilde{\phi}(p) \mid^2 d\vec{p} \tag{7}$$

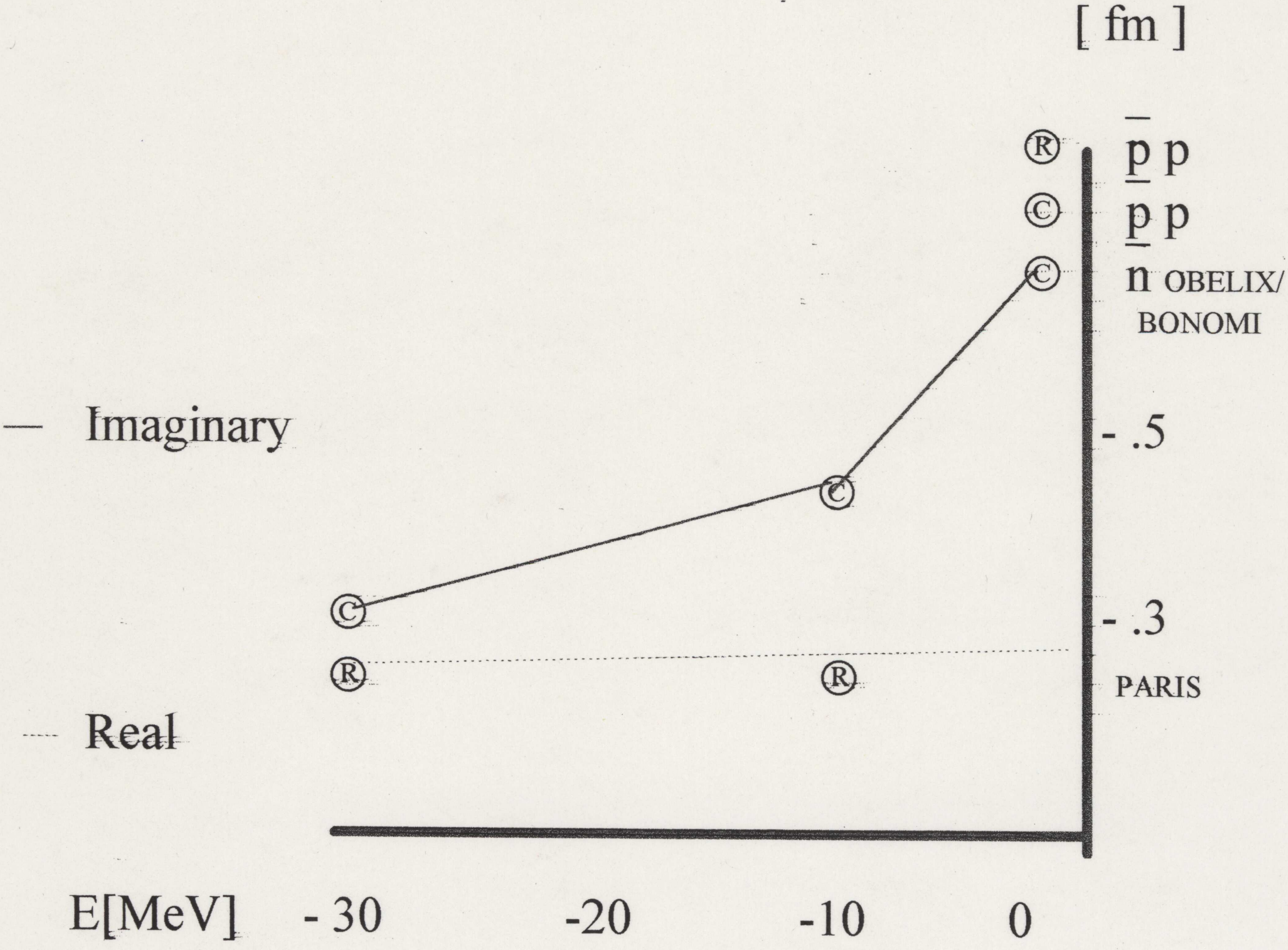
$\phi(p)$ - the Fourier transform of $\psi_N(r)\psi_{\bar{p}}(r)$

Spin, isospin averages extracted from data :
H(1S,2P) [Augsburger], $\sigma(\bar{n}p)$ [Mutchler]
D(1S,2P) [Gotta] 3 data - 4 parameters
^{3}He(2P,3D) [Schneider] 3 data - 4 parameters
^{4}He(2P,3D) [Schneider] 3 data - 4 parameters

AVERAGED $\bar{p}N$ AMPLITUDES
EXTRACTED from D, 4He

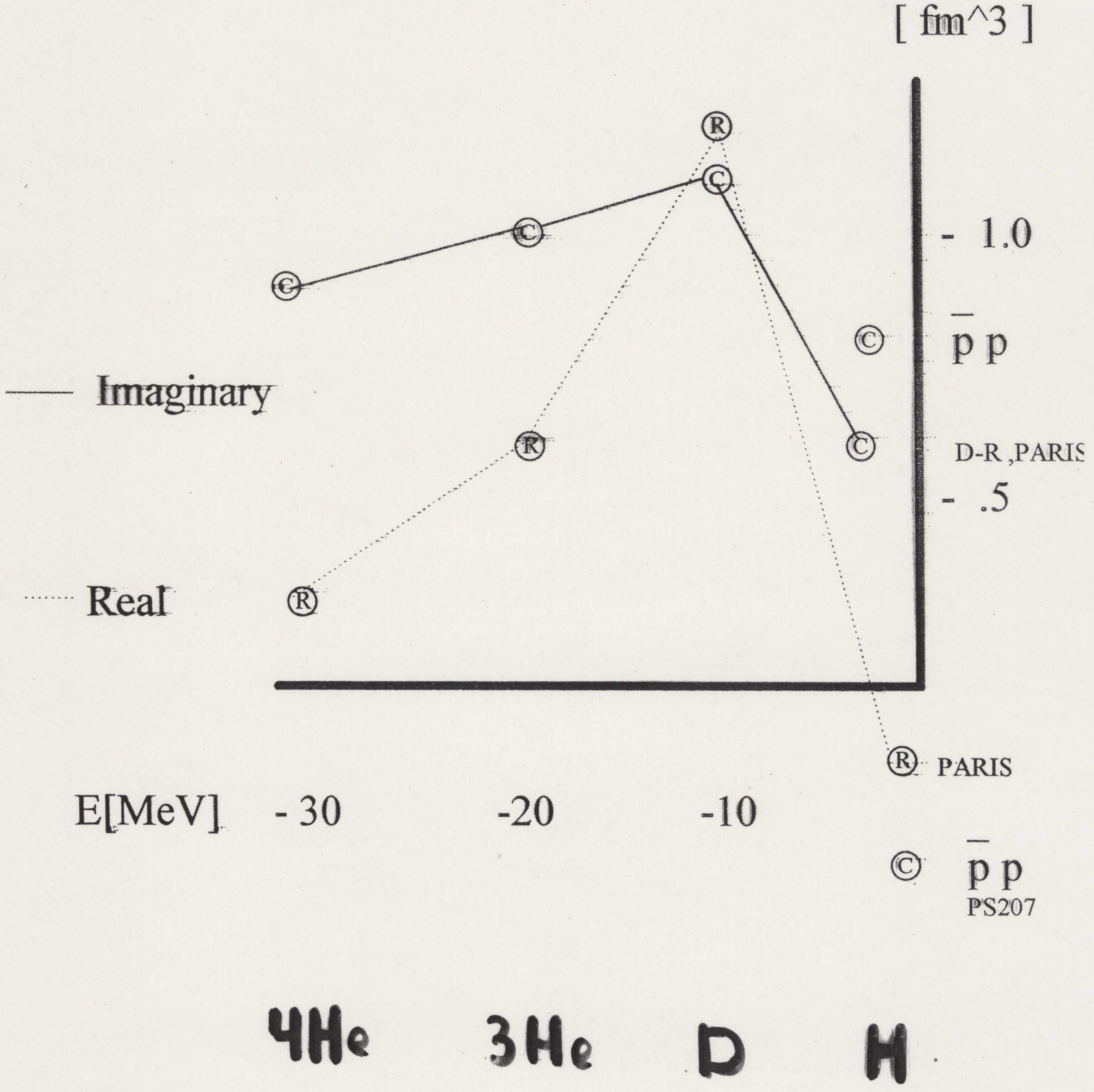
S-waves

$a_s(E)$



AVERAGED $\bar{p}N$ AMPLITUDES
EXTRACTED from D, 3He, 4He

P-waves $a_p(E)$



MEASUREMENTS of π^+ and π^-

Trapped unstable nuclei + $\bar{p}$ M.Wada, Y.Yamazaki

$$\bar{p} + n \to n(\pi^- + \pi^+) + m\pi^0 + \pi^-$$
$$\bar{p} + p \to n(\pi^- + \pi^+) + m\pi^0$$

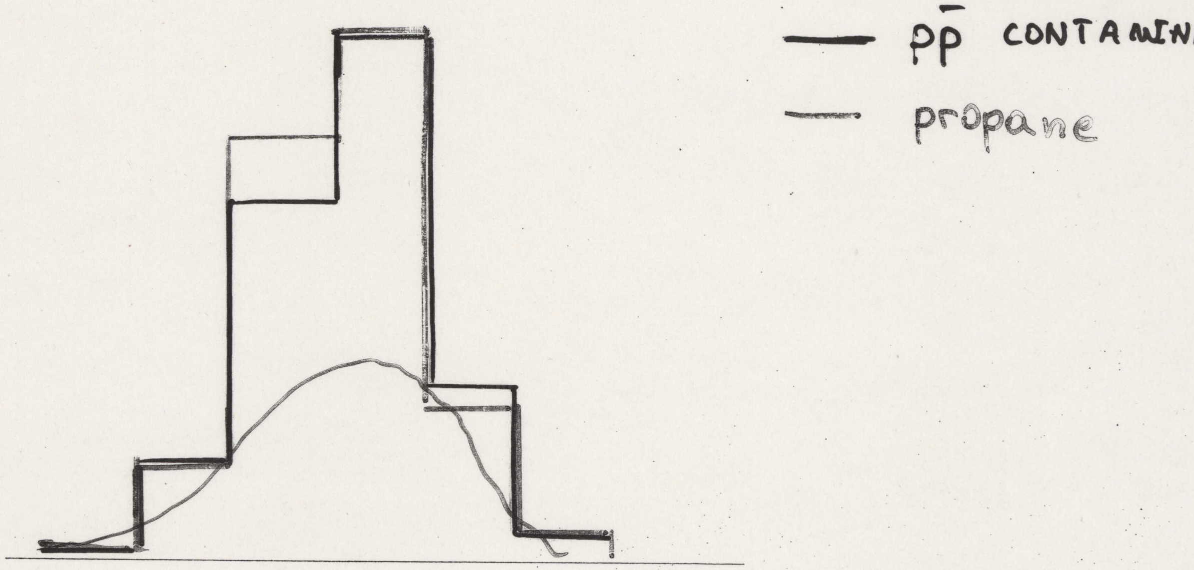
W.Bugg et al	hydrogen chamber :	C.....Pb
W. Wade, V. Lind	propane chamber :	C

Bugg - total charges : 8 numbers measured

Wade - charges, fast p : 12 numbers

Other capture studies : 2 numbers

CHARGE MULTIPLICITIES



-4 -3 -2 -1 0 +1 +2 +3 total charge

($n\bar{p}$) ($p\bar{p}$)

problems $\pi^+, \pi^- \rightarrow absorbed$

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

$R_{n/p}$, initial $\bar{p}$ state → neutron excess

OLD ANALYSIS

$N(\pi^-) - N(\pi^+)$ $\rightarrow \bar{p}n$ capture

$(N(\pi^-) + N(\pi^+))/N_{\bar{p}}$ $\rightarrow \pi$ absorption

$N[-1]/N[0]$ $\rightarrow$ neutron halo

problems $\pi^0 \rightarrow \pi^+$, $\pi^0 \rightarrow \pi^-$
. hydrogen background
. only 2-3 numbers used effectively

full data: $\pi^0 \rightarrow \pi^\pm$ checked by the experiment
free parameters ω- absorption probability
. λ ch.exchange probability

Input

multiplicities: $\bar{p}$ stopped in H, ^{2}H [Riedlberger]
$p\bar{p} \to k\pi^{\pm}$ $n\bar{p} \to k(\pi^{\pm})\pi^{-}$
one π^0 data + statistical $m(\pi^0)$ [Zemany]

Output

ω : capture region

$$P = \frac{1}{4\pi}\int d\Omega \, \exp\left[- \int_0^\infty dz' \frac{\sigma'}{\rho_c} [\rho(z')]^2 \right], \quad (3)$$

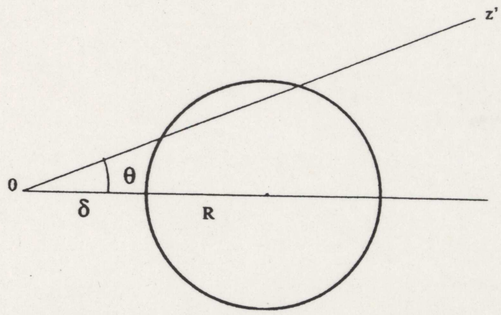
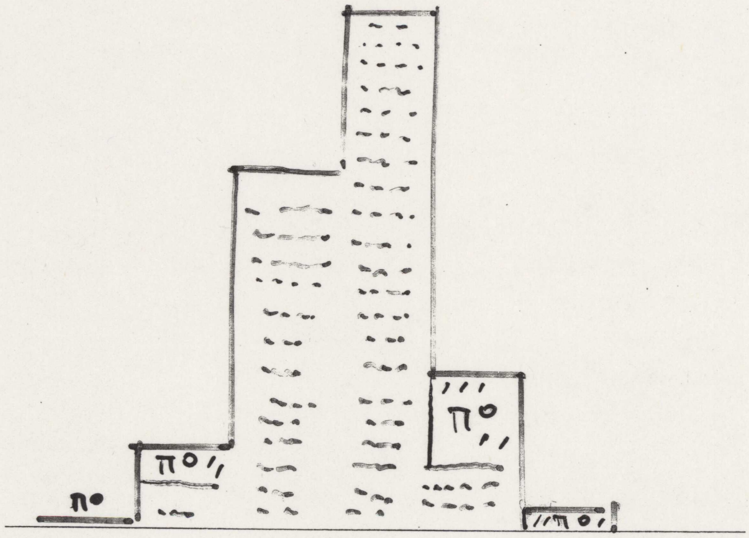


FIG. 1. Definition of the geometrical variables used in this paper. R is the half-density nuclear radius.

λ : $\pi^0 p \to \Delta(1233) \to \pi^+ n$

- an experimental control of crucial parameters

Two parameter fit to $\bar{p} + C$



-4 -3 -2 -1 0 +1 +2 +3 total charge

$\pi^0 \to \pi^\pm$

Multiplicities $p\bar{p}$ $\quad W[m(\pi^0), k(\pi^\pm)]$

$N[0] = \Sigma_{m,k} W[m,k](1-\omega)^k(1-\omega)^k$
$N[1] = \Sigma_{m,k} W[m,k](1-\omega)^{k-1}\omega(1-\omega)^k$
one π^- absorbed ....
$\Delta N[1] = \Sigma_{m,k} W[m,k](1-\omega)^k \lambda (1-\omega)^k$
one $\pi^0 \to \pi^+$ ....
best fit $\omega = 0.13, \lambda = 0.18$

NEXT → Neutron excess

CONCLUSIONS: $\bar{p}$ *nucleus* $\rightarrow$ *mesons*

- a full multiplicity measurement gives neutron
  halo, π absorption and π charge exchange.

- the reduction of hydrogen background is important

- parallel calculations of π absorption,
  charge exchange (Z-N asymmetries) are profitable

CONCLUSIONS:

- nuclear studies with $\bar{p}$ require subthreshold $\bar{p} - nucleon$ interactions.

- consistency of: a $\bar{p} - nucleon$ model, averaged absorption strengh in atoms, in flight is reached. The $\bar{p} - nucleus$ potential needs polishing. Fine structure, real potentials are not well controlled.

- several old and planned experiments give interesting complementary information on the nuclear surface properties.