How it all started

- What is Radioactive Ion Beams (RIB)

1. Bevalac
2. Anomalon
3. Nuclear radii from heavy-ion collisions
4. Fragmentation of radioactive beam
5. Surface excess neutron
6. Shell and other change in structure

The Radioactive Nuclear Beams

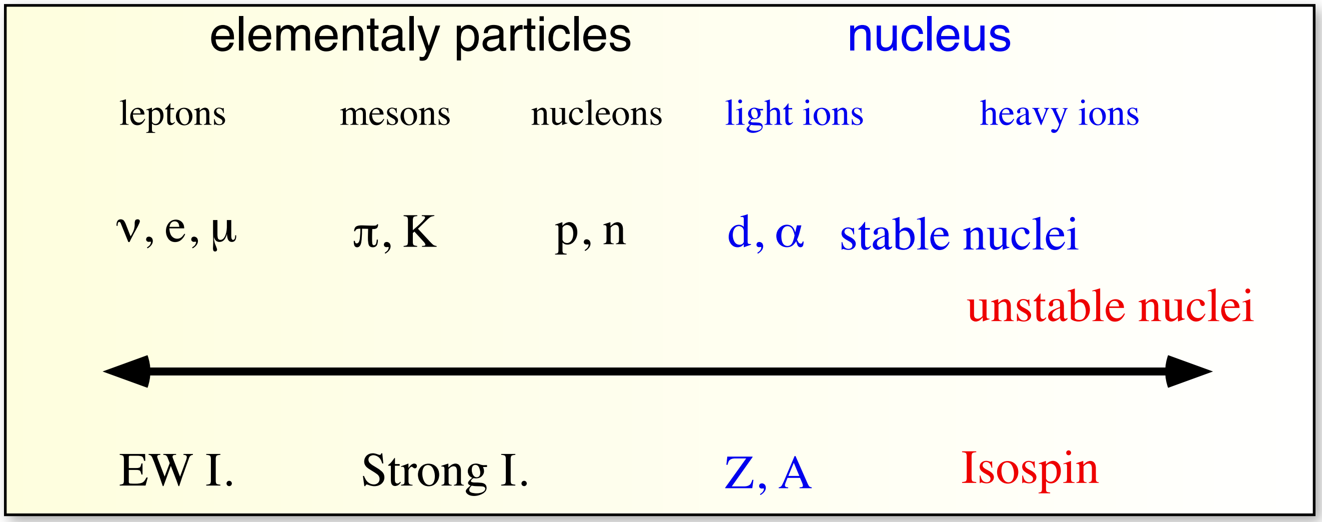

Fig. from “What is RNB”

Restrictions We Had

- **Scattering could be made only between stable nuclei and elementary particles.**
  - *Accelerated beams of electrons, protons, and heavy ions (stable nuclei).*
- **Unstable nuclei were produced by these scattering (reactions). But a scattering of unstable nucleus was impossible until RIB.**

- **Therefore restricted observations gave restricted knowledge.**

Stable --> Unstable

Special --> General

In 1970th at Berkeley

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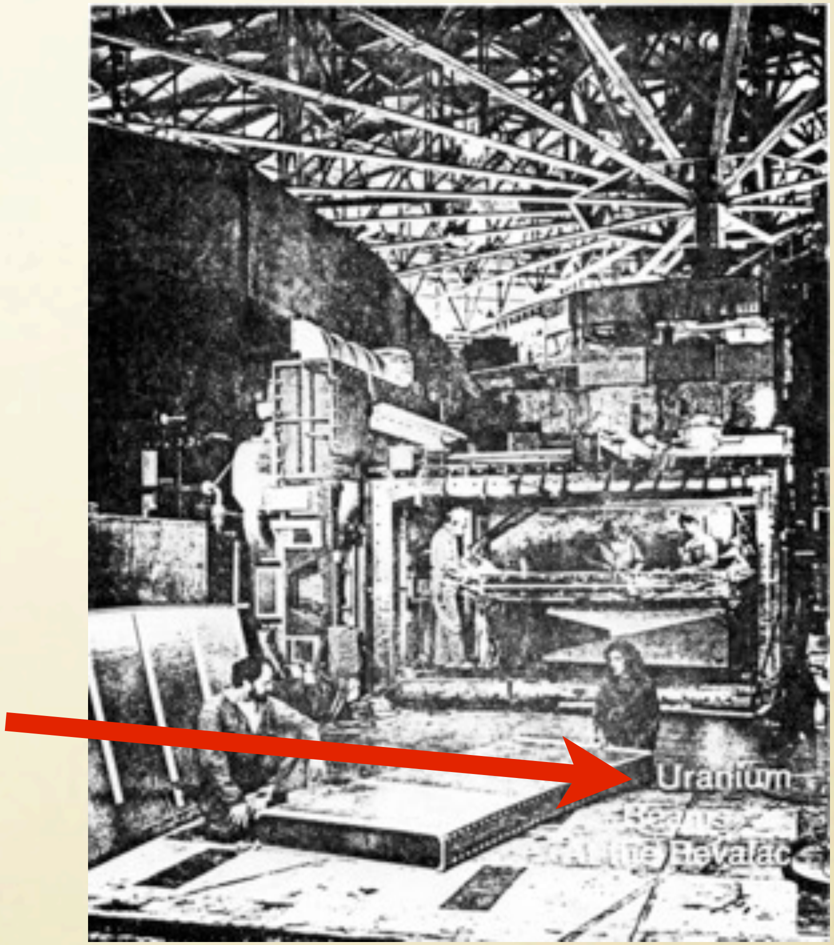
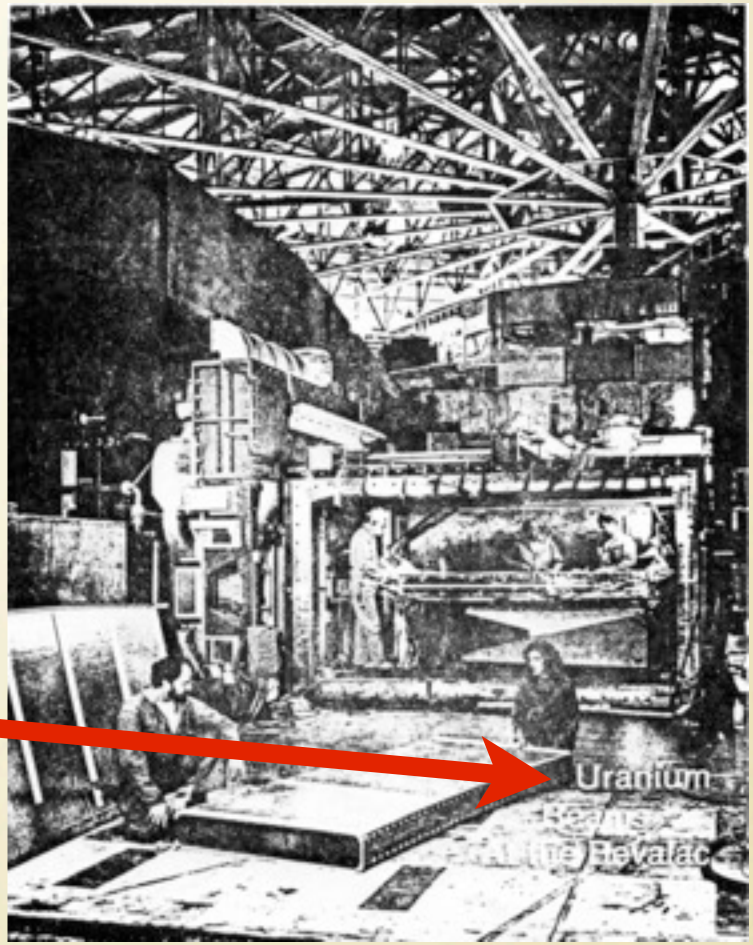
- **BEVATRON/BEVALAC**
  - *The first high-energy heavy-ion facility.*

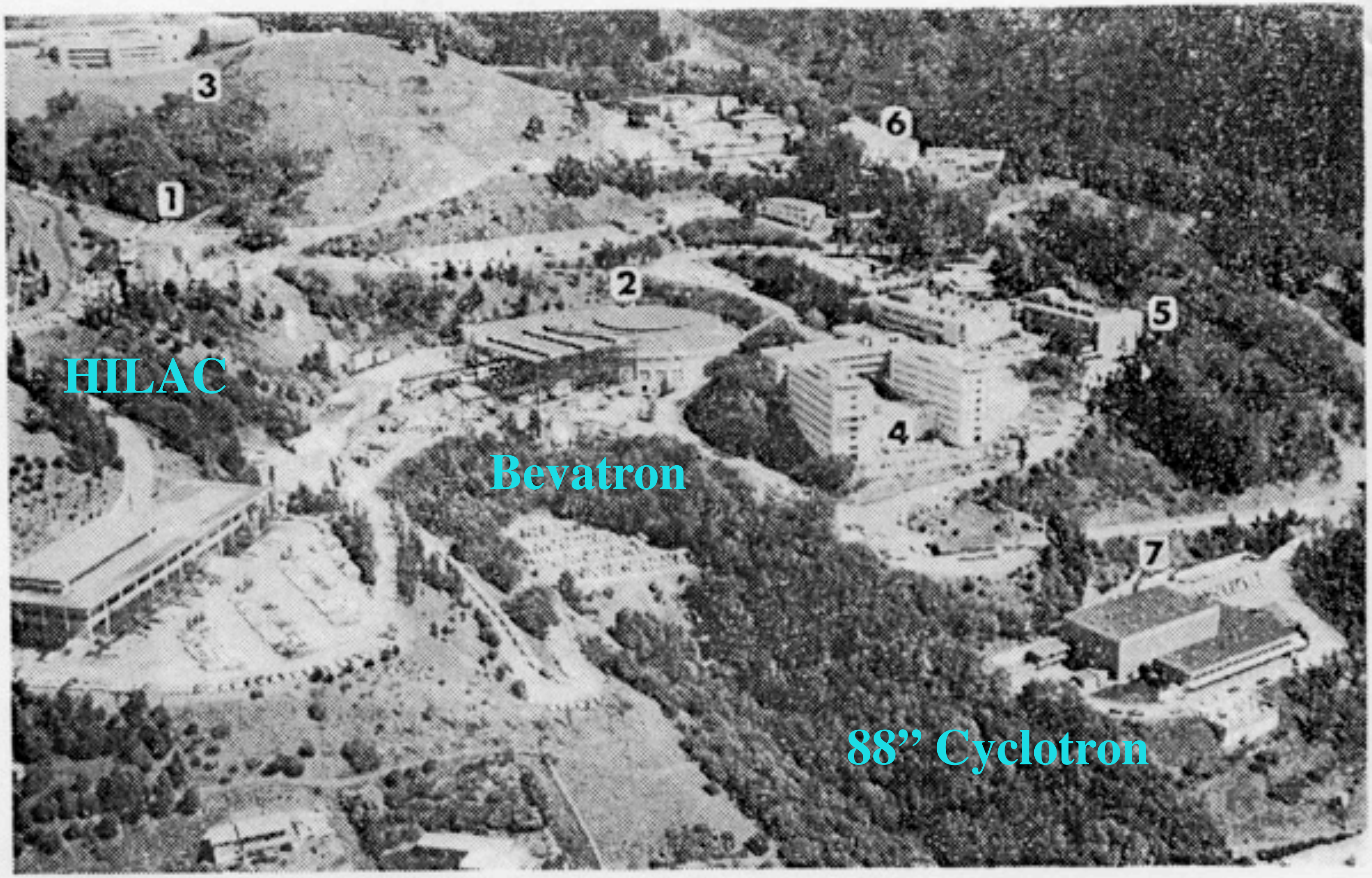


In 1970th at Berkeley

- **BEVATRON:After completing the goal of discovering anti-proton and also to determine precise kaon mass.**
- **BEVATRON/BEVALAC**
  - ***The first high-energy heavy-ion facility.***
- **The main aim was to study central collisions and produce new types of nuclear matters!**



Lawrence Berkeley (National) Laboratory



第7図　ローレンス・バークレー研究所の全景とベバラック（スーパ・ハイラック＋ベバトロン）配置図．スーパ・ハイラック

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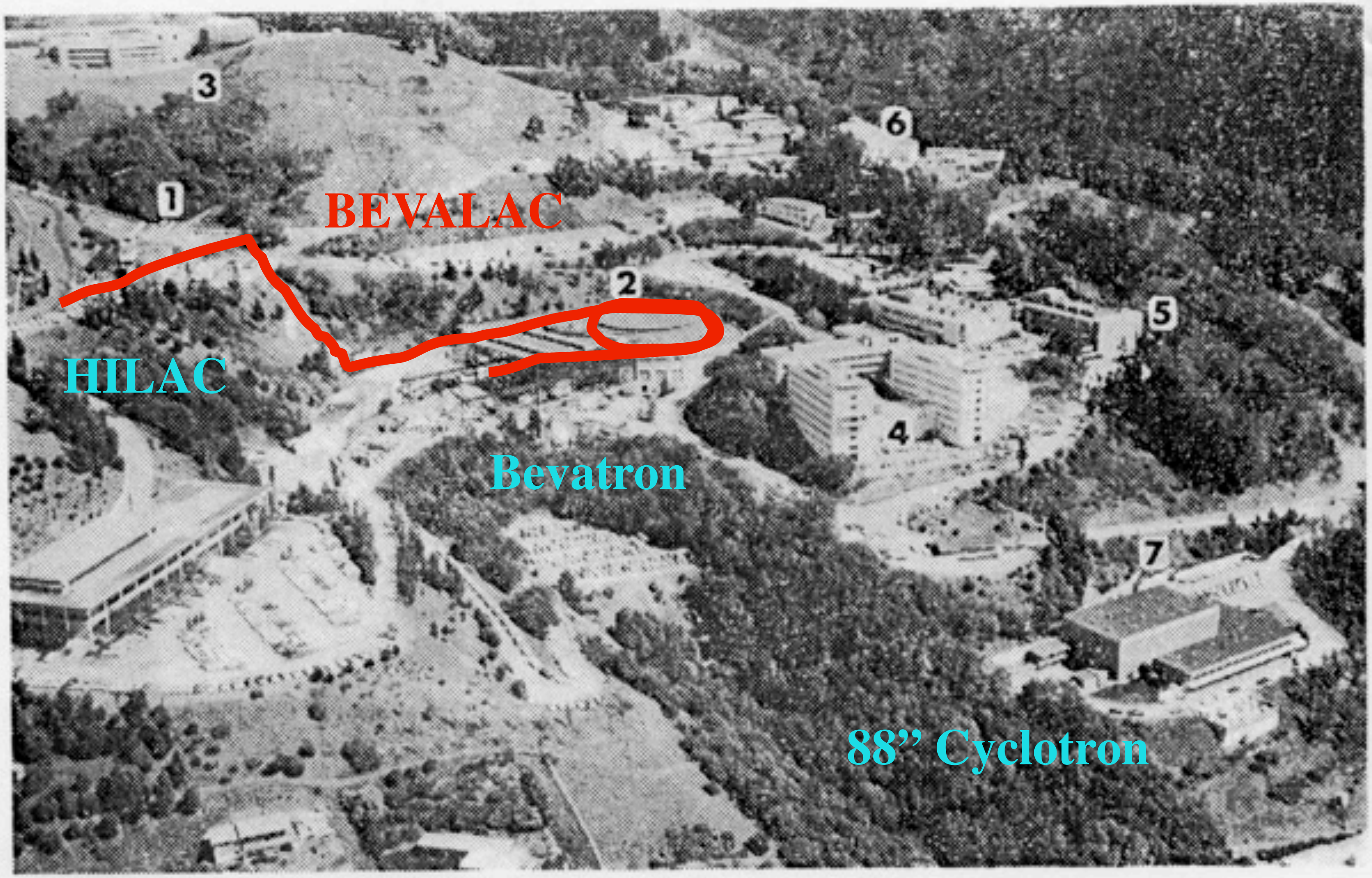

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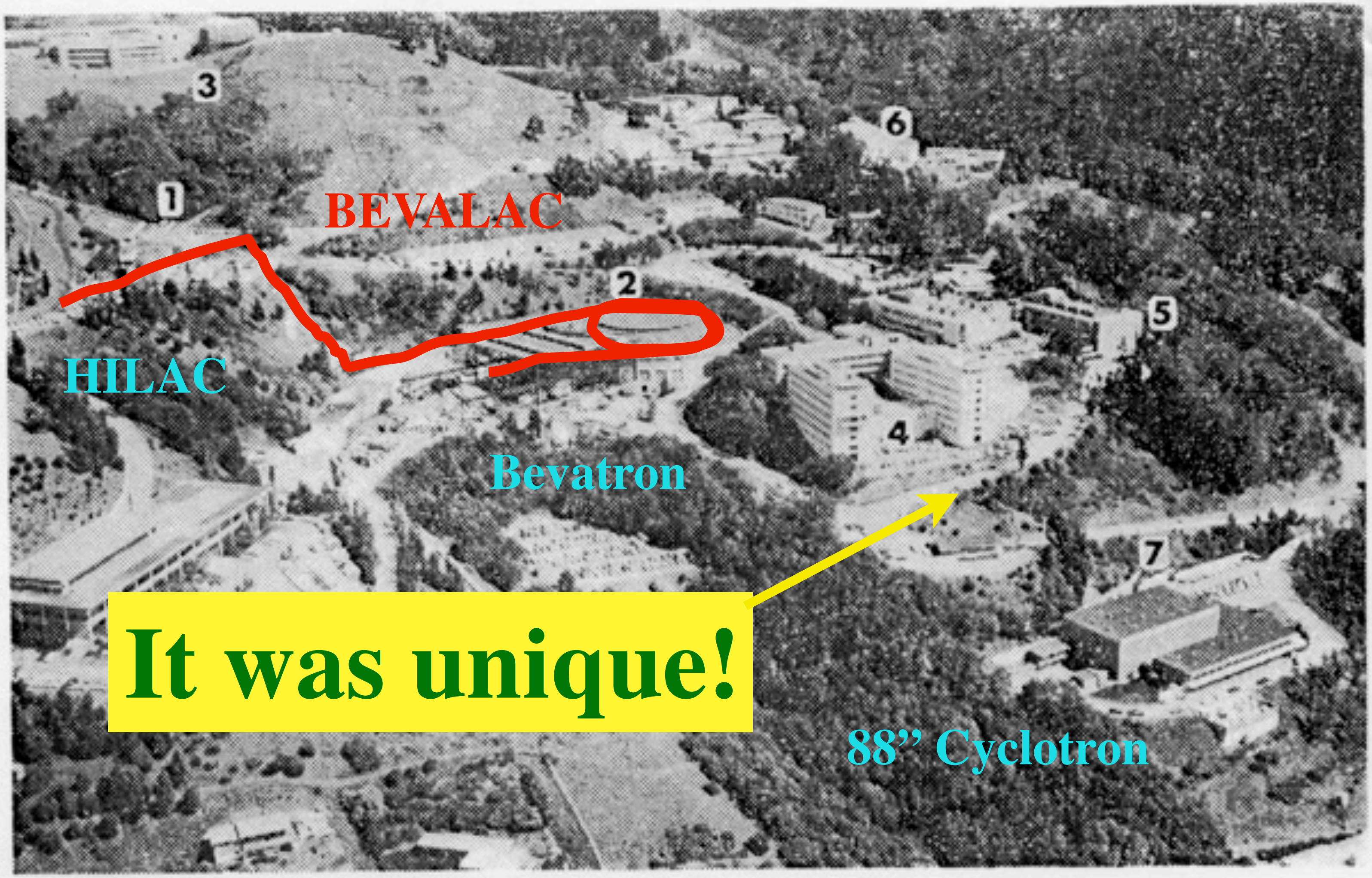

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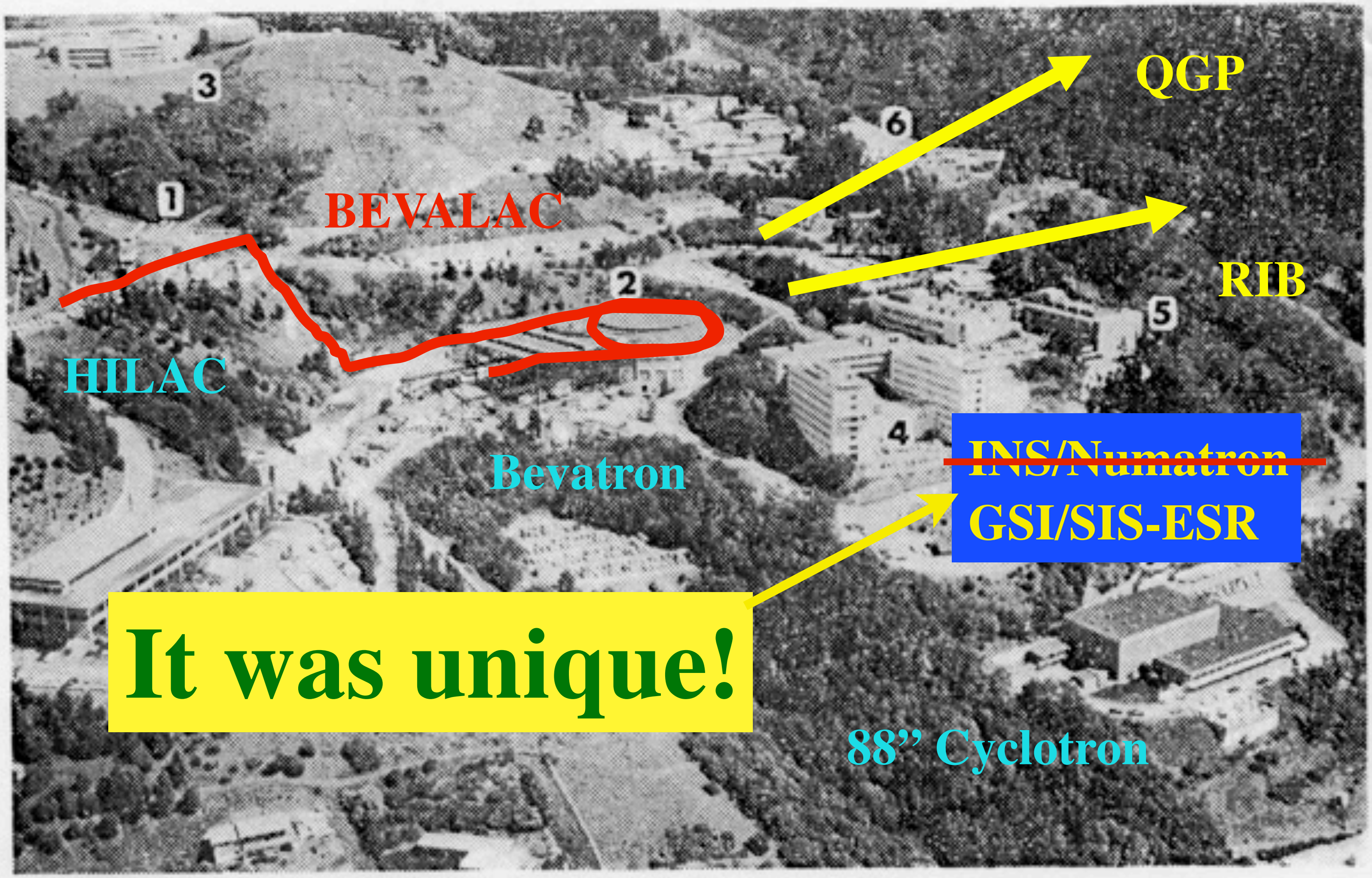

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Discovery I

Projectile fragmentation (somewhat expected)

- H. H. Heckman, D. E. Greiner, P. J. Lindstrom, and F. S. Bieser, Physical review Letters 28 (1972) 296.

Fragmentation of ^{14}N nuclei at 29 GeV

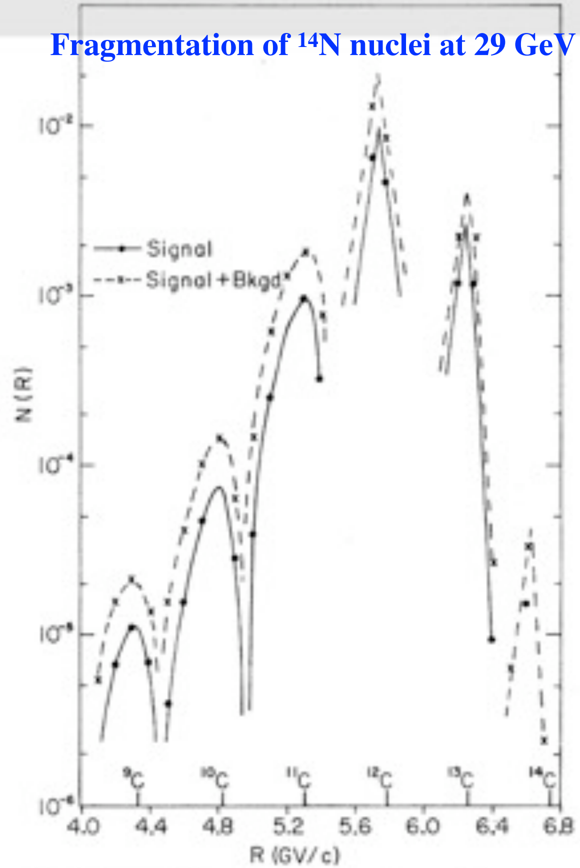

FIG. 1. Rigidity spectrum of carbon isotopes produced by the fragmentation of 29-GeV ^{14}N nuclei. The differential intensity has been normalized to give the observed count-rate per incident ^{14}N beam particle on the carbon target (4.36 g cm^{-2}).

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to) the ^{14}N beam. Second, and most important, was the background of beam fragments produced in the vicinity of the target and in the walls of the evacuated beam pipe.

To determine the signal-to-background ratios, we measured at each rigidity setting the Z (i.e., dE/dx) and time-of-flight (TOF) spectra, with and without the target in place. The shape of the observed Z spectra at any given rigidity was independent of target, whether C, CH_2, or background target material. The target-in, target-

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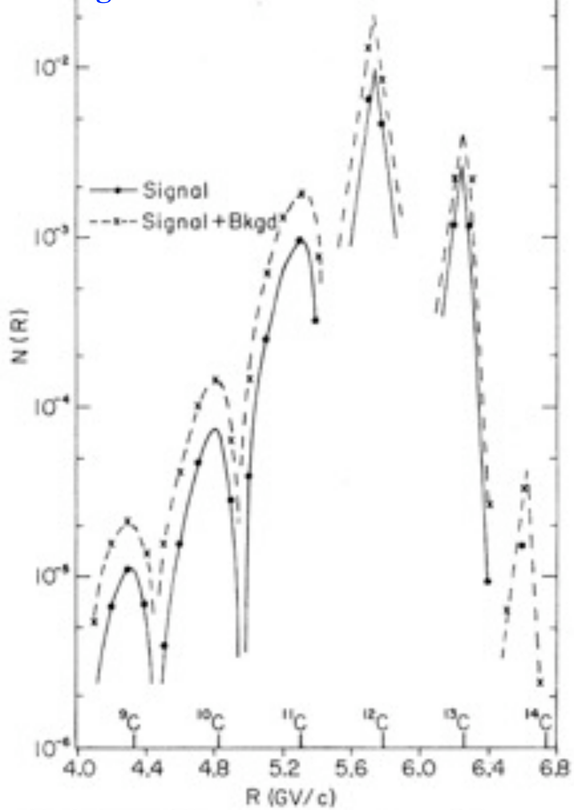

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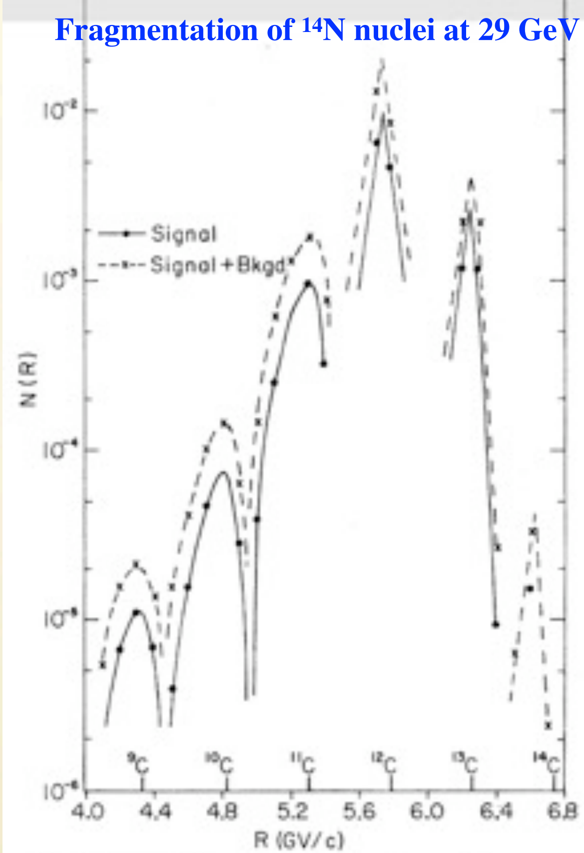

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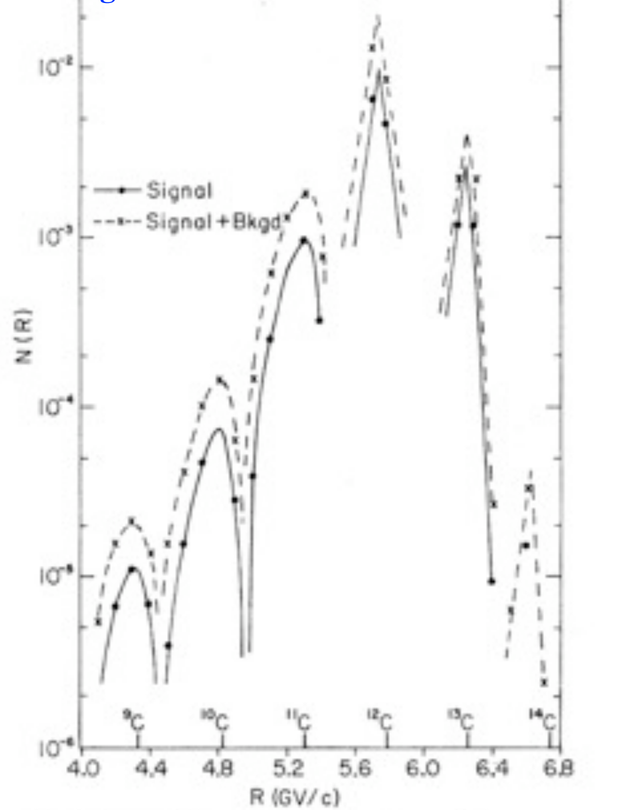

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The large yield of exotic nuclei (surprise)

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Production of neutron-rich nuclides by fragmentation of 212-MeV/amu ^{48}Ca

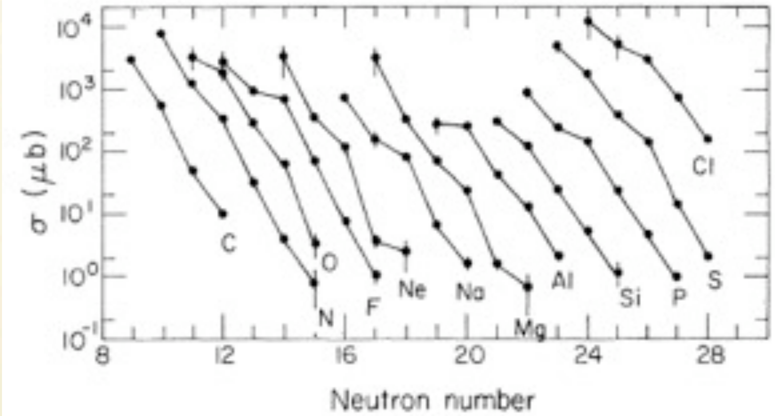

FIG. 2. Production cross sections for the elements observed in the fragmentation of 212-MeV/amu ^{218}Ca by a beryllium target. Lines are to guide the eye.

^{20}Ne -> ^{14}Be

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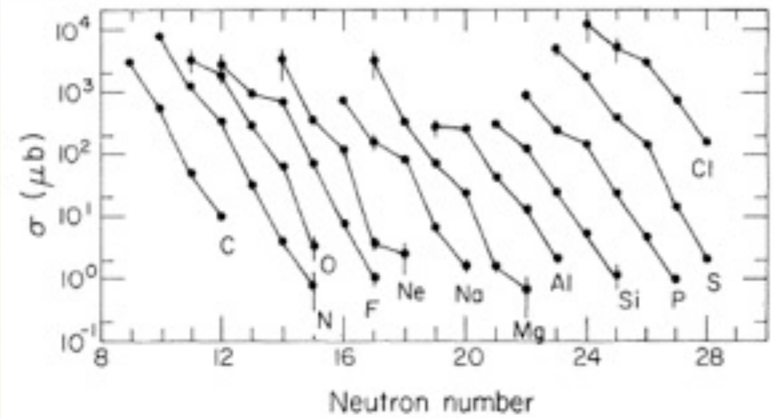

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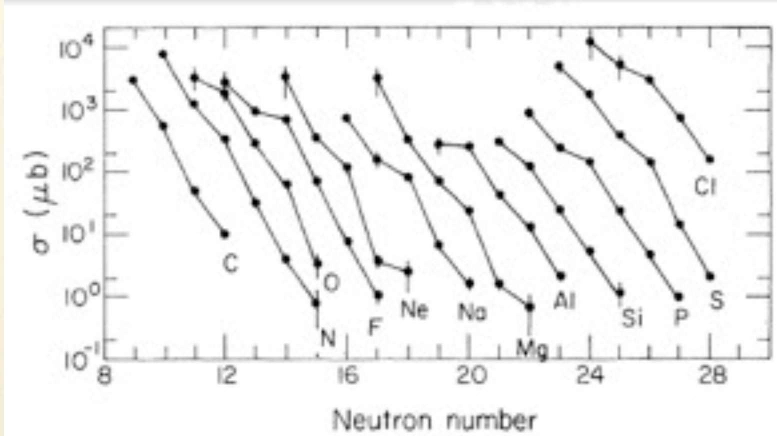

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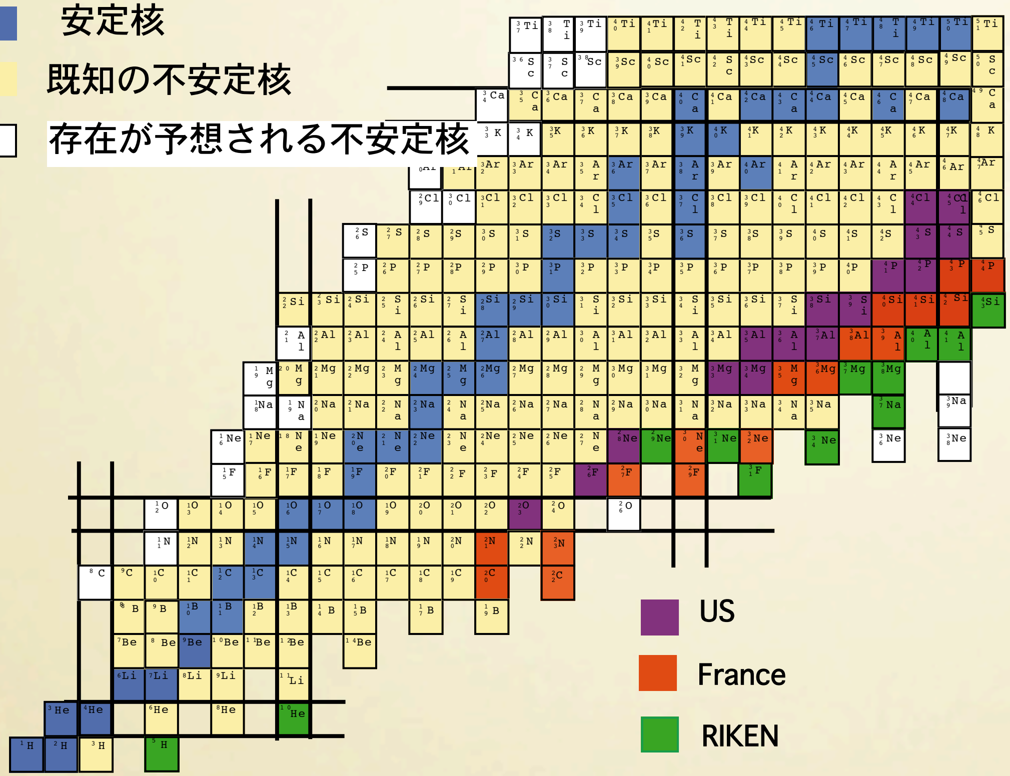
Certainly provided a new method

安定核

既知の不安定核

存在が予想される不安定核



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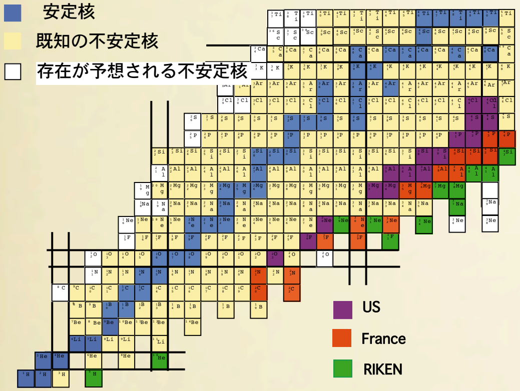
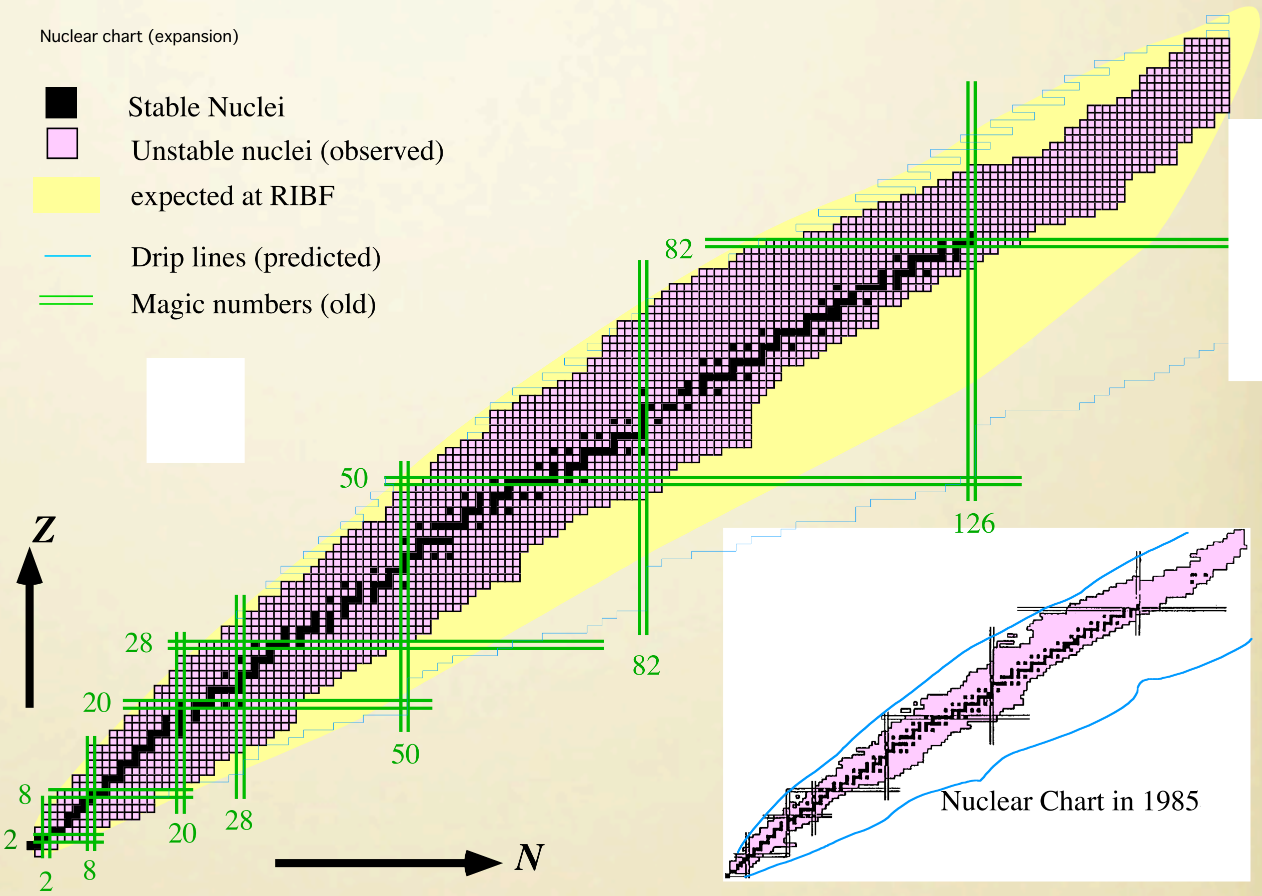
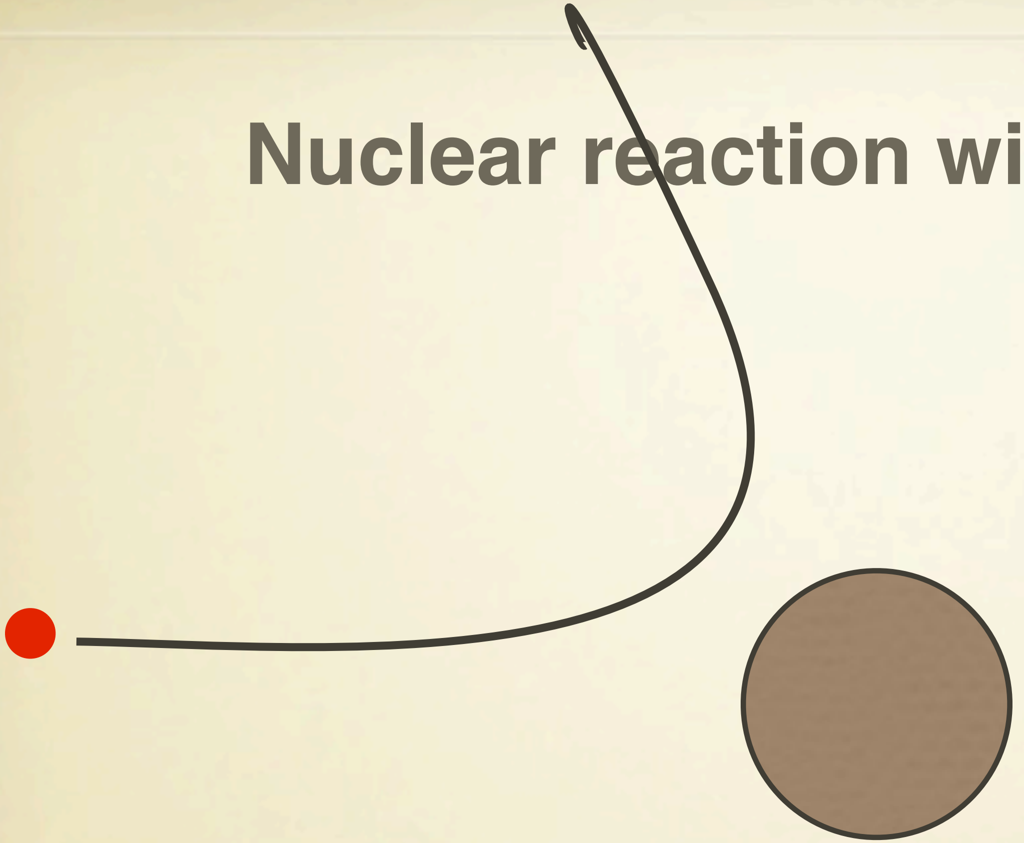
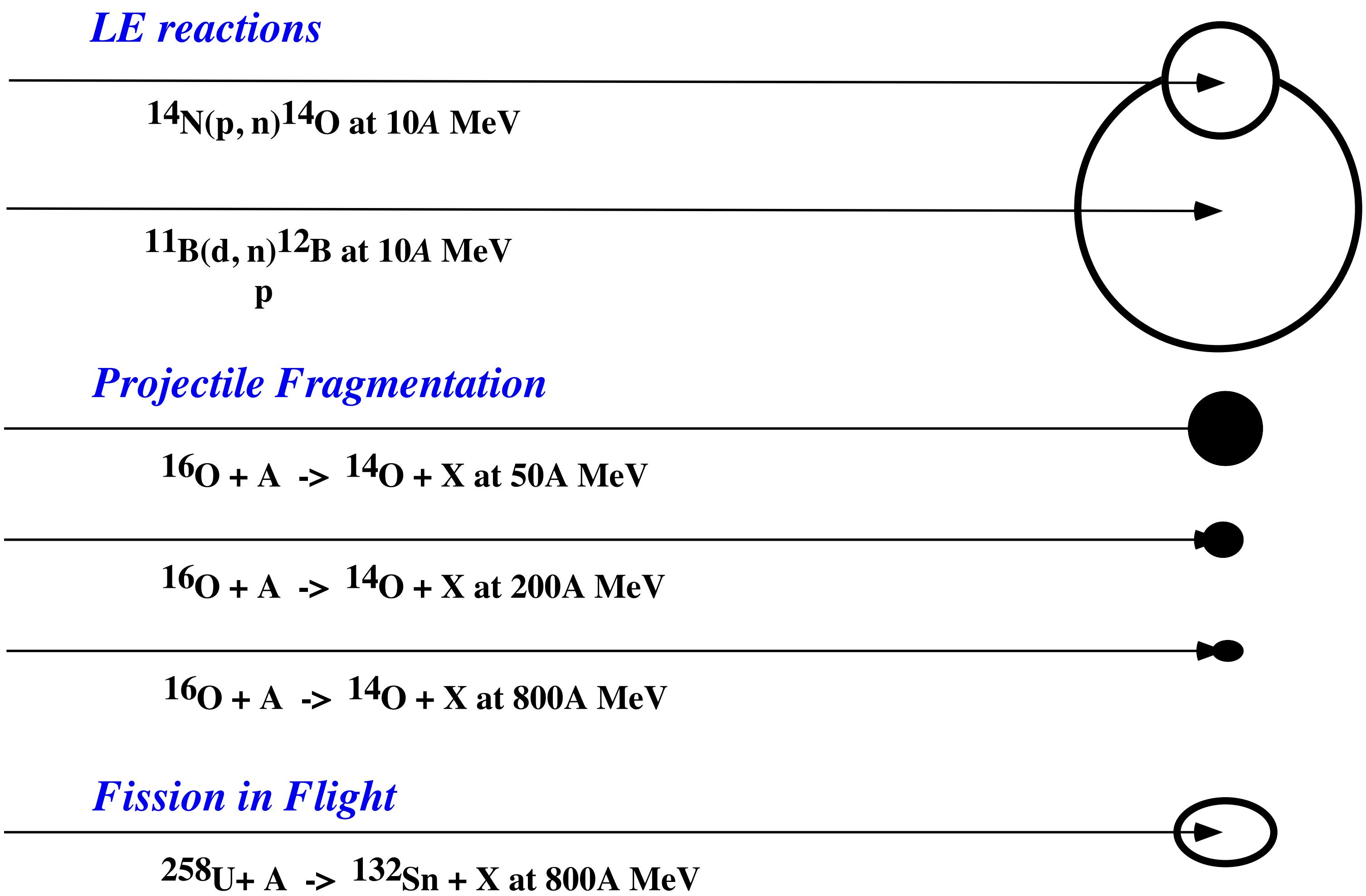




Nuclear reaction with light ions



Momentum Broadening of Reaction Products

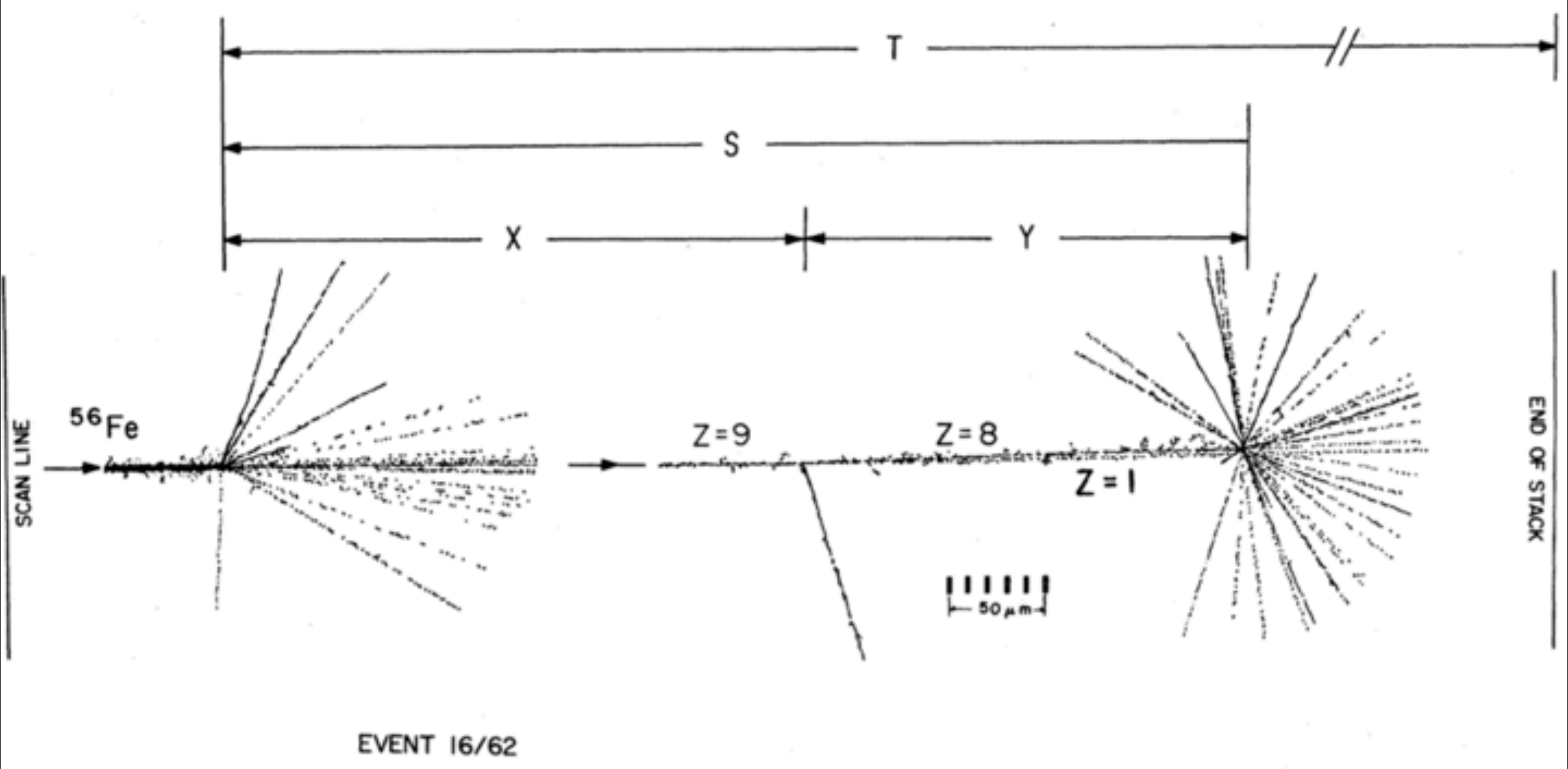


It was obvious that projectile fragments can be good secondary beam.

Now some mistake happened!

An example

E. M. Friedlander et al., Phys. Rev. C 27 (1983) 1489.
Other many Phys. Rev. Letters papers



Anomalon?

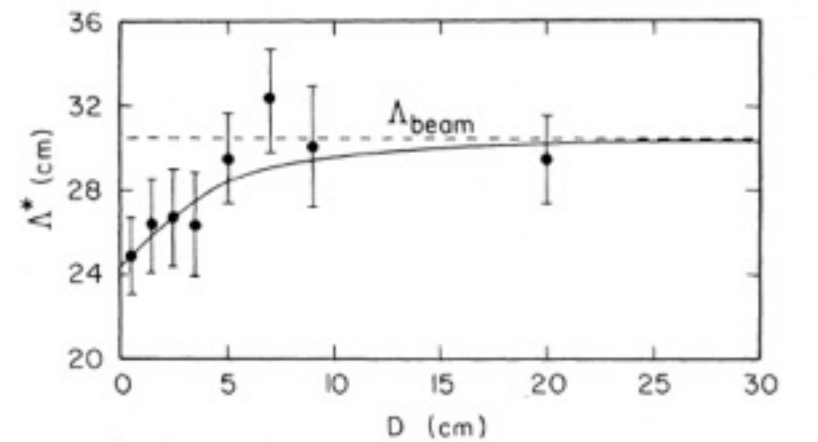


FIG. 1. Estimates Λ^* for the parameter Λ [Eq. (2)] at different distances D from the origins of PF's: full circles, experiment; dashed line, prediction from Λ_{beam}; solid line, prediction assuming a 6% admixture of PF's with $\lambda_a = 2.5$ cm.

Reaction mean-free path of different charged particles are parameterized by $\lambda_z = \Lambda Z^{-b}$ and plotted against the distance from the first reaction point.

Particles produced by the fragmentation showed the extremely short mean free path.

Secondary particles have short mean free paths or short life?

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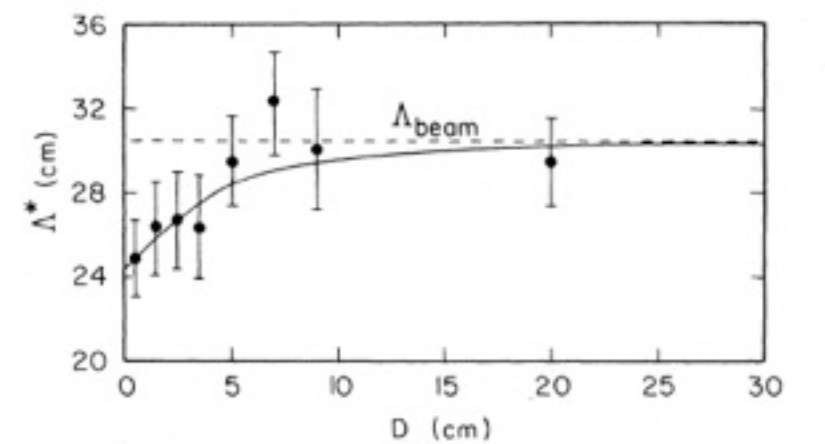

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Need high statistic “counter experiments”!

Anomalon?

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An anomalously short mean free path observed recently from relativistic heavy-ion collisions with ^{12}C at 4.2 A GeV/c is interpreted to be due to the existence of a new multiquark compound resonance. Several experiments are suggested to verify our interpretation. “1985 Lettere Al Nouvo Cimento”

Someone else has done (a personal statement)

- **T. J. M. Symons, M. Baumgarner, J. P. Dufour, J. Girard, D. E. Greiner, P. J. Lindstrom, and D. L. Olson and H. J. Crawford,**

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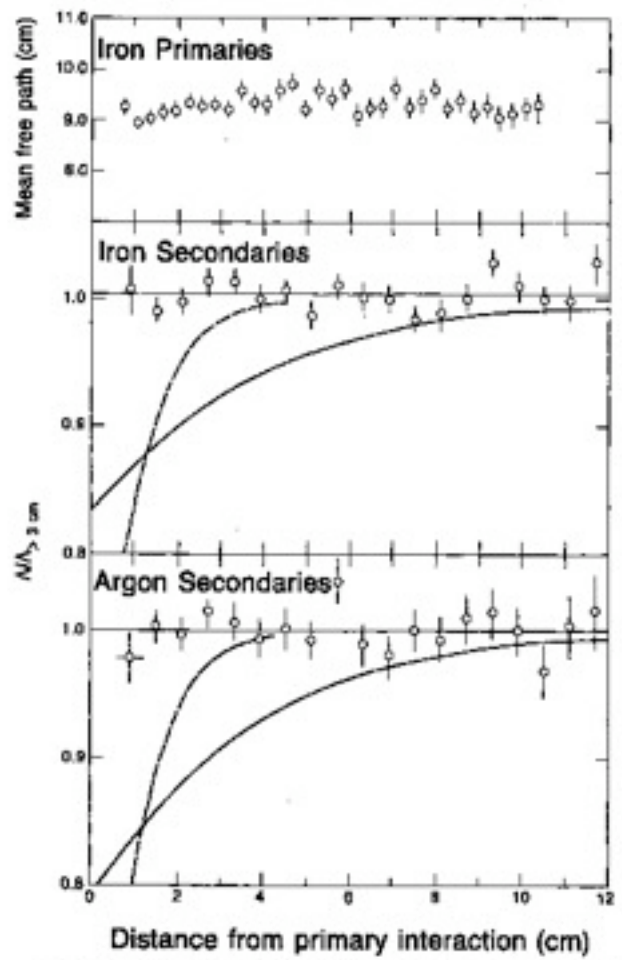

FIG. 3. Ratios of estimated to average mean free paths as a function of distance from the primary interaction point for ^{40}Ar and ^{56}Fe beams. For explanation of curves, see text.

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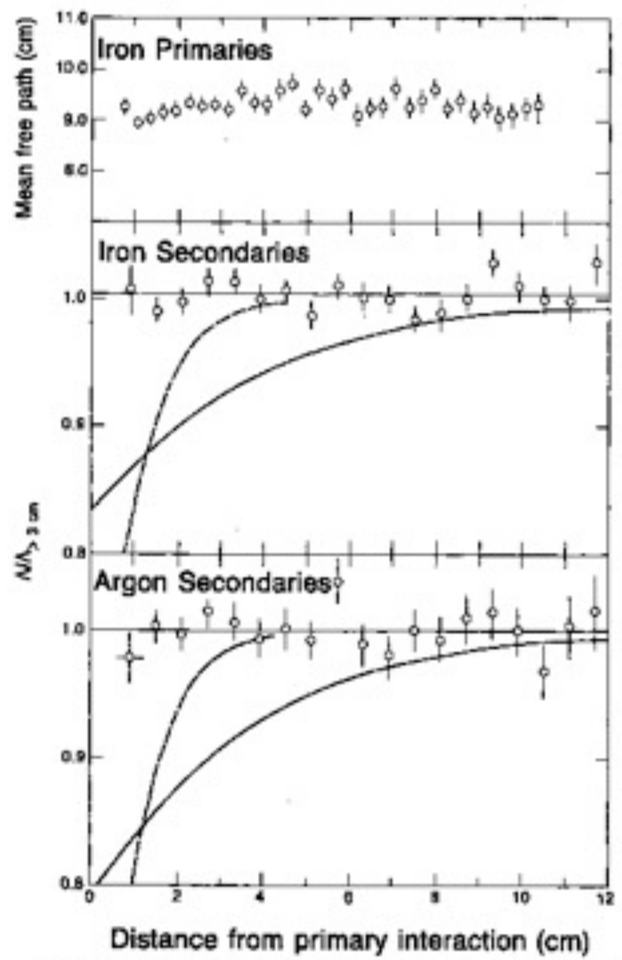

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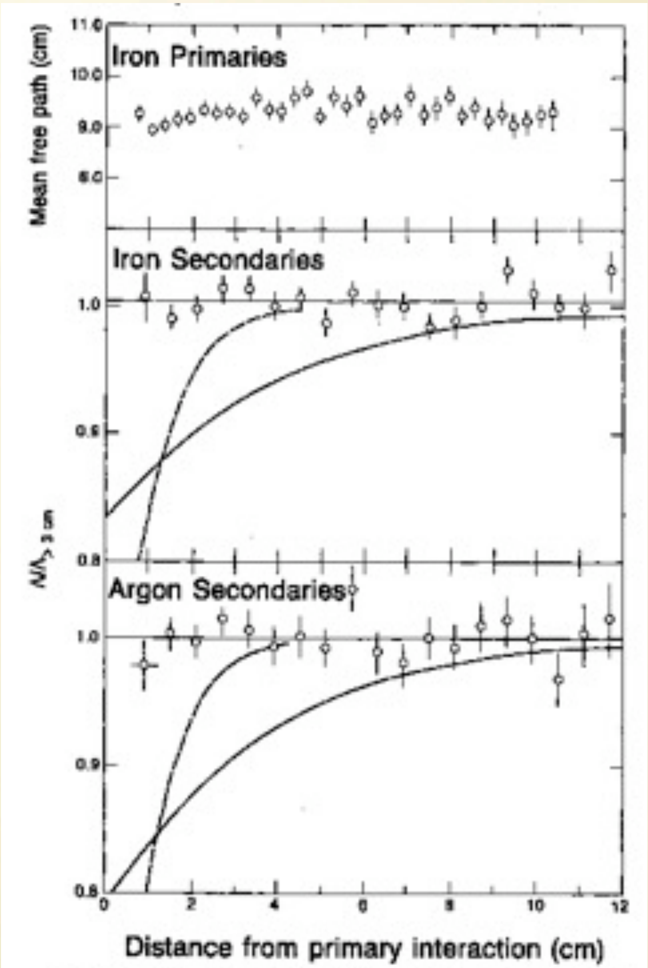

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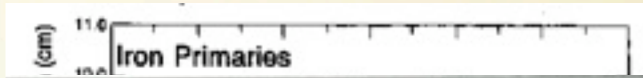

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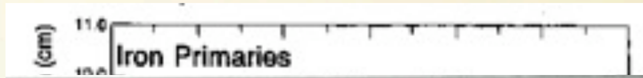

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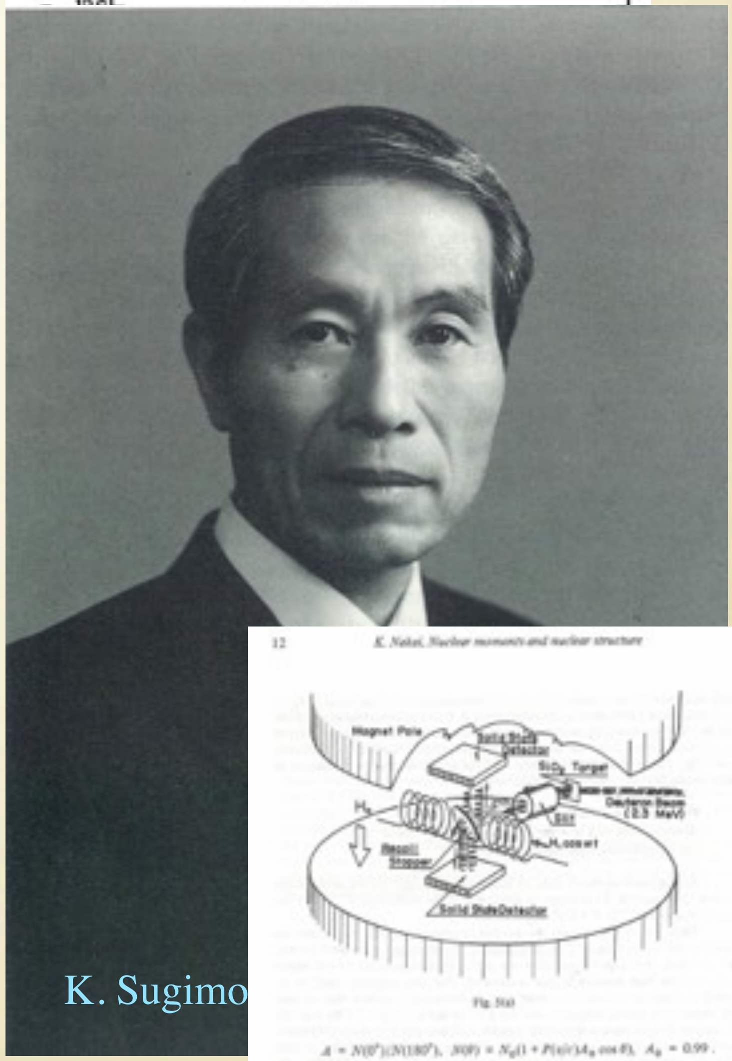

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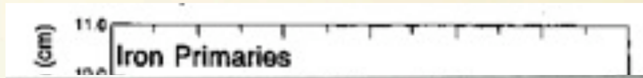

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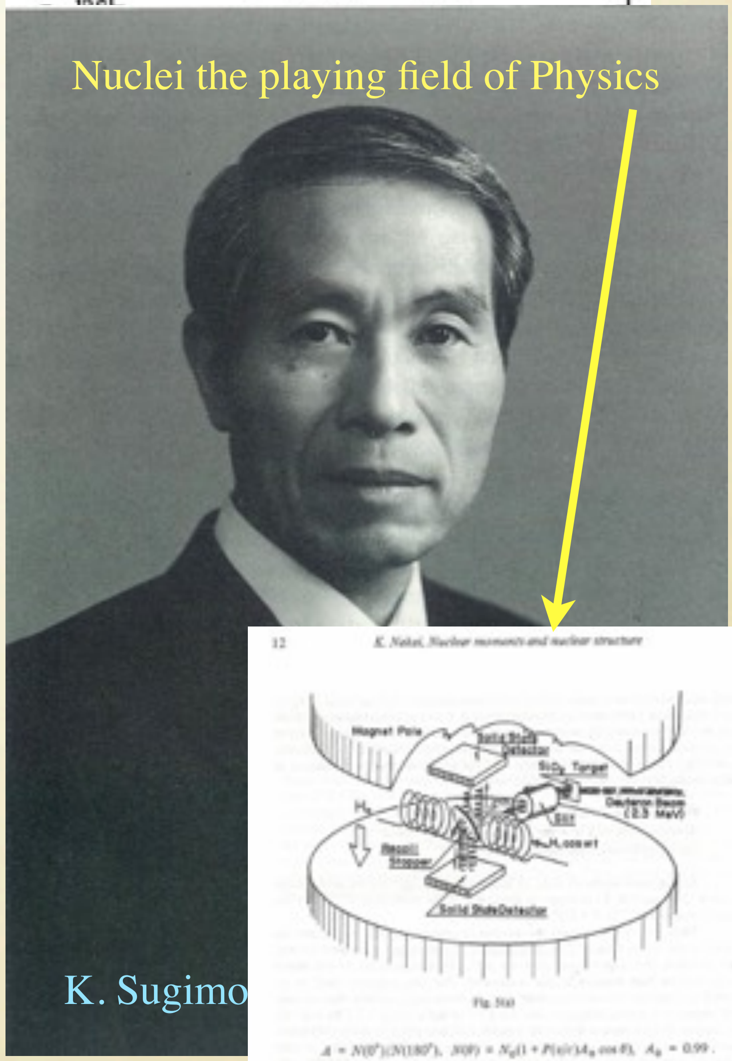

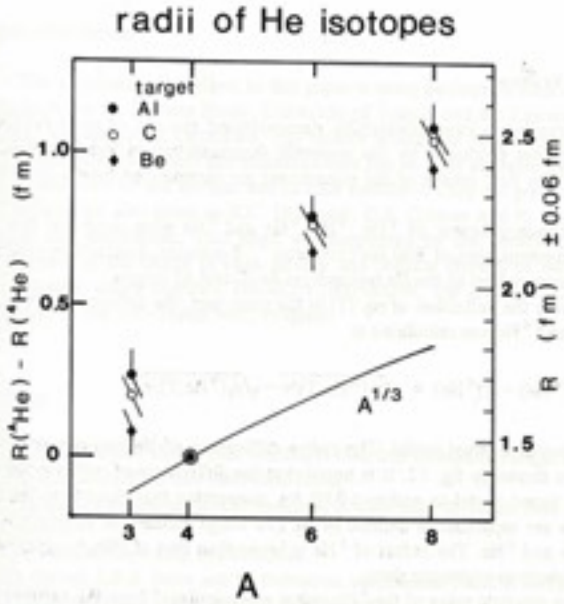

Fig. 12. Radius differences of the He isotopes from ^{4}He are plotted. The absolute value of the radius is also shown on the right-hand side ordinate scale. A solid curve shows an $A^{1/3}$ dependence of nuclear radii.

Hyperfine Interactions 21(1985)265–273

ANOMALONS?

Denys WILKINSON

Department of Physics, University of Sussex, Brighton, UK

1. Introduction

Kenzo Sugimoto's interests in the fields of nuclear and atomic physics are very widespread and he has been involved in many novel advances. When, therefore, I wondered how I might most appropriately respond to the happy invitation to help honour him in this volume, my thoughts naturally turned to those matters of my own concern that touch upon wide ranges of physical concepts and novel ideas.

The matter that I have chosen to discuss here indeed involves concepts and speculations both directly derivative of traditional nuclear physics and remote from it. It is the so-called phenomenon of the anomalons. It is a matter of some contention, into which I do not intend to go, as to whether or not the phenomenon has actually been discovered yet, but that should not inhibit discussion of it: many wild geese have had high heuristic value as both Kenzo Sugimoto and I know full well in relation to second-class currents, but that is another story.

2. Anomalons?

It has been rumoured for many years [1] that nuclear collisions of relativistic heavy ions give rise to a class of multiply-charged nuclear fragments that display anomalously-short mean free paths against their own subsequent nuclear interactions. It has also been suggested that these anomalons' can pass on this property after their first or even subsequent collisions so that there are sometimes several generically-related anomalously short free paths. These early reports were derived from cosmic-ray studies using nuclear emulsions. More recently [2] there have been extensive studies, still using nuclear emulsions but with incident heavy ions (^{16}O, ^{40}Ar and ^{56}Fe of energy about 2A GeV) from the Berkeley Bevalac. These experiments appear to establish the phenomenon with high statistical likelihood. The phenomenon is consistent with the production of the anomalons in a few percent of the primary collisions and with the anomalons having a mean free path a few times shorter than that to be expected of a normal nucleus of the same value of Z. Alternatively, the proportion of anomalons produced might be some tens of percent and the mean free path shortened by a factor

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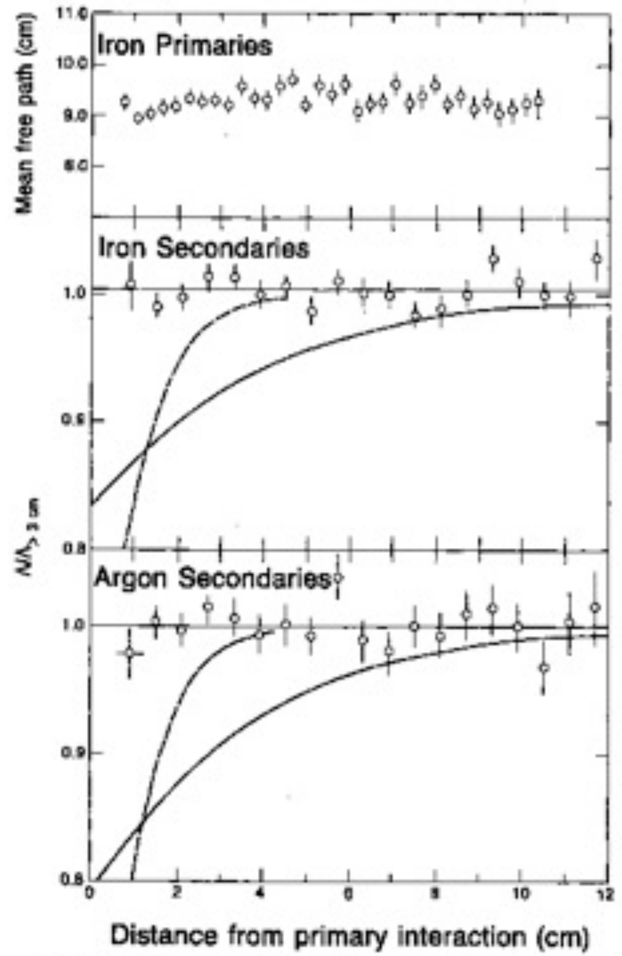

FIG. 3. Ratios of estimated to average mean free paths as a function of distance from the primary interaction point for ^{40}Ar and ^{56}Fe beams. For explanation of curves, see text.

Someone else has done (a personal statement)

- T. J. M. Symons, M. Baumgarner, J. P. Dufour, J. Girard, D. E. Greiner, P. J. Lindstrom, and D. L. Olson and H. J. Crawford,

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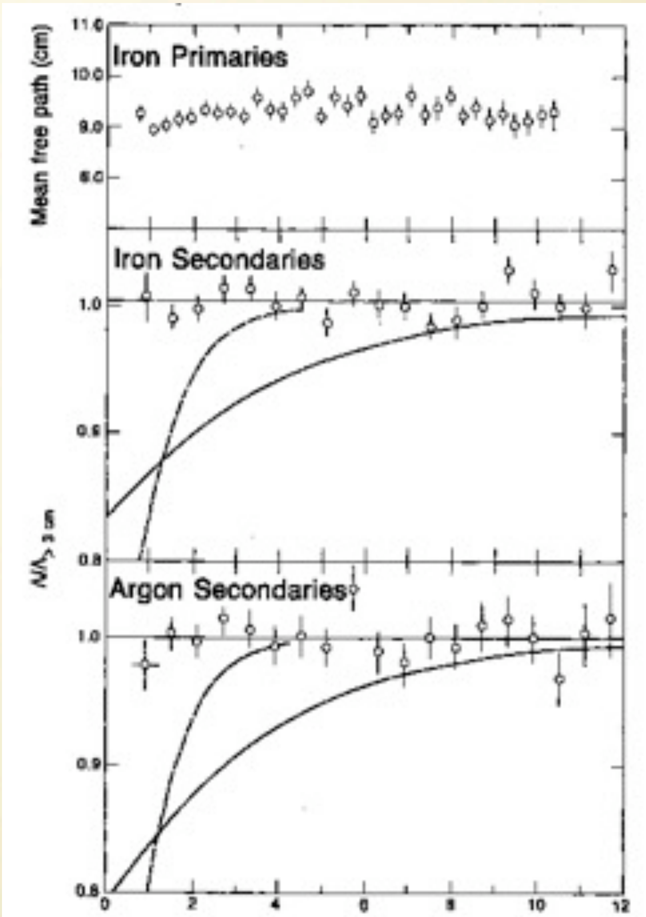

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Starting of RI beam experiments

Collabortors

H. HAMAGAKI, O. HASHIMOTO, S. NAGAMIYA, Y. SHIDA, N. YOSHIKAWA, O. YAMAKAWA, K. SUGIMOTO, T. KOBAYASHI, D.E. GREINER, N. TAKAHASHI and Y. NOJIRI

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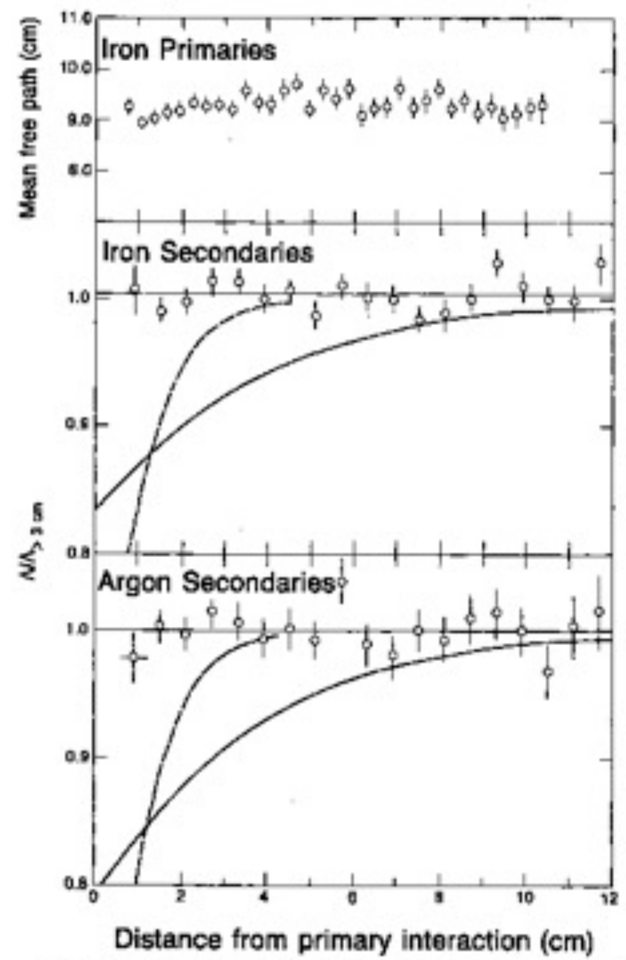

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付録 1

The first proposal

LAWRENCE BERKELEY LABORATORY

Proposal for Bevalac Nuclear Science Experiment

Office Use Only

Twenty (20) copies required - a separate set for each experiment, sent to the Accelerator Research Coordination Office, Building 51, Room 208, Lawrence Berkeley Laboratory, Berkeley CA., 94720.

Date: April 15, 1983

Group: INS/LBL

Institution: LBL, INS Univ. Tokyo, Osaka univ

Person in charge (name, institution, address, telephone number):
Isao Tanihata
INS Univ. of Tokyo
3-2-1 Midori-cho, Tanashi
Tokyo 188, JAPAN
(0424) 61-4131

Experimenters - complete list (name, institution, title or position, address, and telephone number):

H. Hamagaki	INS Univ. of Tokyo
O. Hashimoto	(0424) 61-4131
T. Kobayashi	/LBL EX. 6812
Y. Shida	.
K. Sugimoto	.
I. Tanihata	.
N. Yoshikawa	.
S. Nagamiya	Univ. of Tokyo (03)812-2111
N. Takahashi	Osaka Univ. (06)872-1151
O. Yamakawa	Nagoya Univ.
H. Crawford	LBL EX. 5235
D. Greiner	. EX. 4885
P. Lindstrom	. EX. 4885

(office use only)

TIME REQUEST SUMMARY — Beam line:

Particle	Energy	Hours requested (Data-taking & tuneup)
^{11}B(or ^{12}C)	800 MeV/A	56^h
^{19}F(or ^{16}O)	800 MeV/A	56^h
beam line test		24^h
^{7}Li	800 MeV/A	24^h
		/ total// 160^h

Title of Experiment (60 characters or fewer):

Nuclear Radii

Summary of Experiment (for circulation; do not exceed space provided)

A Systematic study of the nuclear radii for a wide range of isotopes is planned by measuring the isotopic and isobaric dependence of the interaction cross sections. In the present experiment, as the first step of a series of planned experiments, the isotopes of He(3-8), Li(6-11) and some of Be, B and C isotopes produced through the projectile fragmentation at a primary target will be used as secondary beams. The interaction cross sections will be measured by the transmission method using a secondary target. An analysing magnet, plastic counter telescopes, and MWPCs will be used to identify the incident and the out going nuclei. Some of the fragmentation cross sections in the secondary reactions will also be measured simultaneously.

A secondary beam lines with a capability of isotopic mass separation up to $M/\Delta M \sim 20$ is expected to be available for the experiment.

The remaining pages of the proposal should provide additional information in the order listed on the reverse side of this page.

Date revised: February, 1983

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
Telephone 415/486-4000

ARC Office
Building 51 Room 208
Telephone 486-5185

February 10, 1983

Dr. Isao Tanihata
Institute for Nuclear Study
University of Tokyo
3-2-1 Midori-cho Tanashi-shi
Tokyo 188 Japan

Dear Isao:

Thank you for your letter of February 1, asking about secondary beam facilities here at the Bevalac. Answers to your questions will be sent soon; I wanted you to know that your letter has arrived and has been read and is being studied! Your experiment, plus several others now in the planning stage, could make good use of a secondary beam line, and we are now thinking about how to implement one. Within a very few weeks you will receive a much longer letter answering your questions in detail.

I hope 1983 is doing well for you.

Sincerely,

Fred H.G. Lothrop

FHGL:kw

cc: J. Alonso
M. Zisman

^{9}Li	5×10^6	sec^{-1}	^{16}O
^{11}Li	250	sec^{-1}	^{16}O

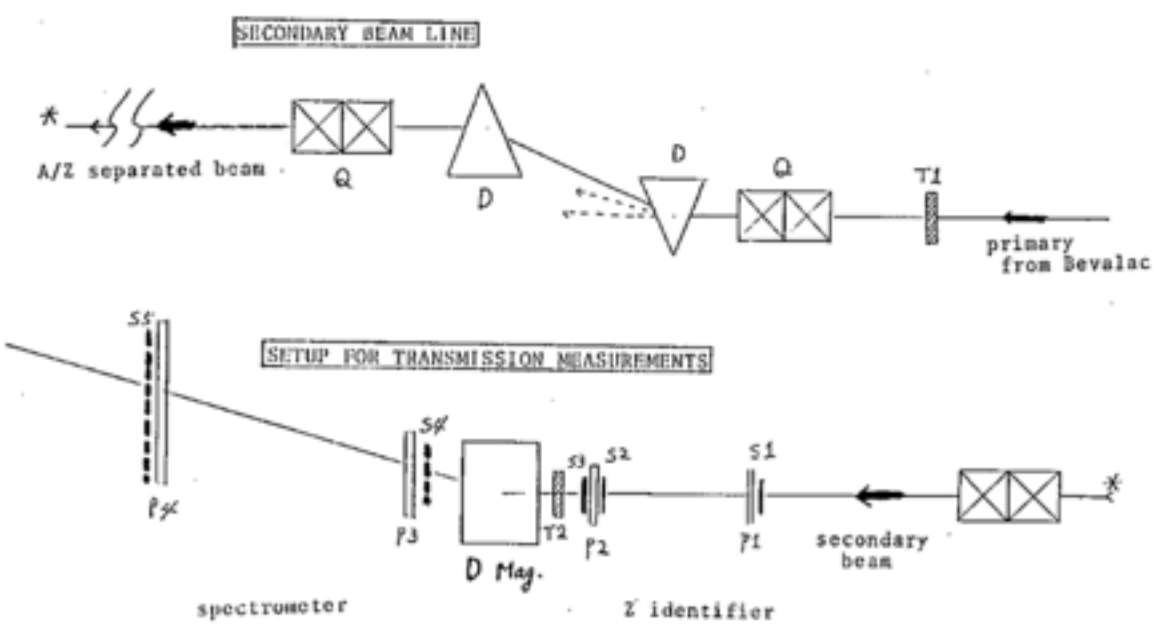
The momentum broadening of the secondary beam is about 3% when 800 MeV/A primary is used. Therefore a secondary beam line which accepts a momentum spread of $\Delta P/P < 3$ % is ideal. In the present experiment, however, a beam line with a smaller acceptance can be used, because we require only a low intensity beam of a few thousands particles per pulse on the reaction target in order to identify the nuclear species individually (see sec. e).

The interaction cross section is determined by the transmission method. Intensities of the nuclei before(I_0) and after(I) a reaction target will be measured. The interaction cross section σ_I is obtained by,

$$I = I_0 \exp(-\sigma_I t),$$

where t is the thickness of the secondary target.

The experimental set up is shown in Fig. 1. Th



15年7月21日火曜日

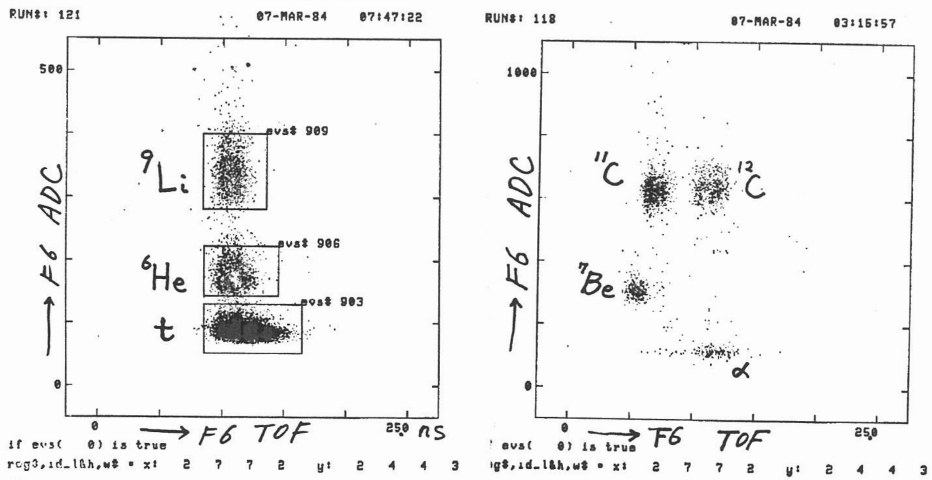
March 7, 1984

HOT!!

News from LBL.

We have got unstable nuclear Beams.

^{12}C Beam. of ~ 800 A·MeV



木村. Isao Tanihata 藤, O. Hashimoto, 山川

小林

INTERACTION CROSS SECTION

In the present experiment, we define effective radii in nucleus-nucleus collisions as,

$$\sigma_I = \pi(R_p + R_T)^2.$$

Systematic change of R_p can be obtained by a series of σ_I measurements with the same target.

Measurement of Reaction Cross Section of Heavy-Ion Collisions

- **Jaros et al. PR C18 (1978) 2273**
  - *The best method of total and reaction cross sections: The good geometry attenuation method*

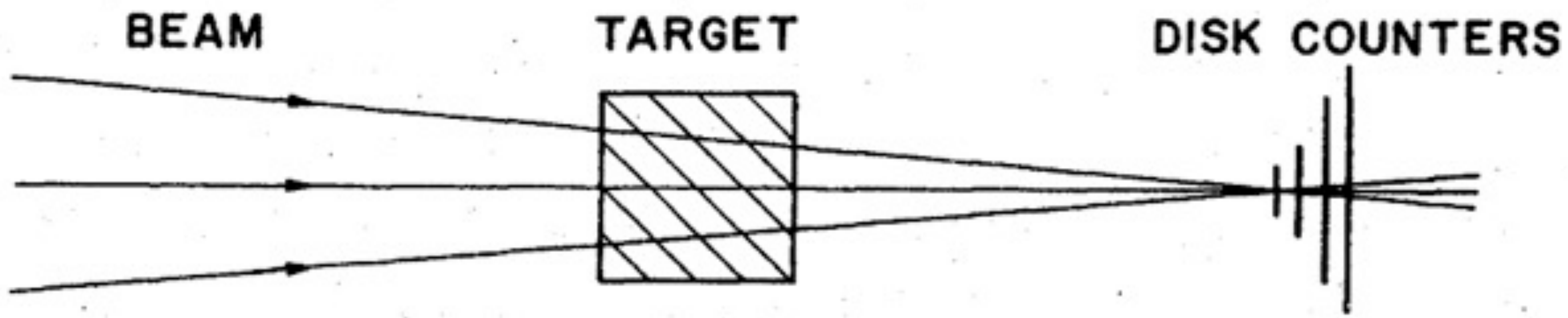


FIG. 2. Schematic diagram of the attenuation method used in this experiment.

- **At high energy, it is impossible to measure reaction cross section due to the Coulomb interactions.**

Why it has to be the interaction cross section not the reaction or the total cross section

PHYSICAL REVIEW C VOLUME 18, NUMBER 5 NOVEMBER 1978

Nucleus-nucleus total cross sections for light nuclei at 1.55 and 2.89 GeV/c per nucleon*

J. Jaros,† A. Wagner,‡ L. Anderson, O. Chamberlain, R. Z. Fuzesy, J. Gallup, W. Gorn,§ L. Schroeder, S. Shannon, G. Shapiro, and H. Steiner

The foregoing should warn us that total nuclear cross section is a concept useful in a limited domain of atomic number. It is our view that we can only get a good experimental determination of the nuclear total cross section if most of the elastic scattering occurs at angles where it is not dominated by the Coulomb scattering. We feel the situation is manageable for $Z=6$, but we would hesitate to try measurements for $Z \geq 12$.

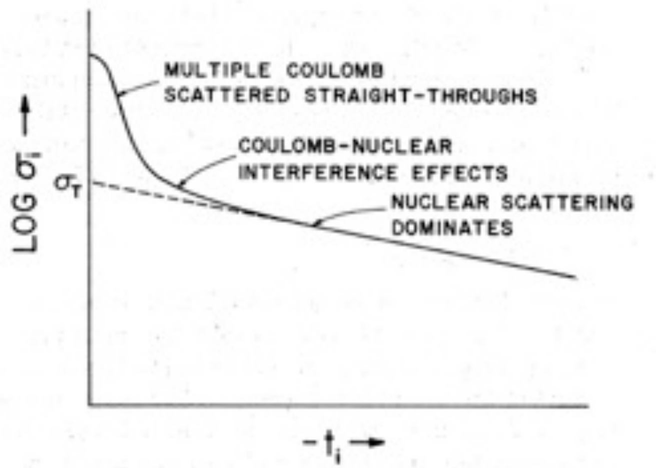
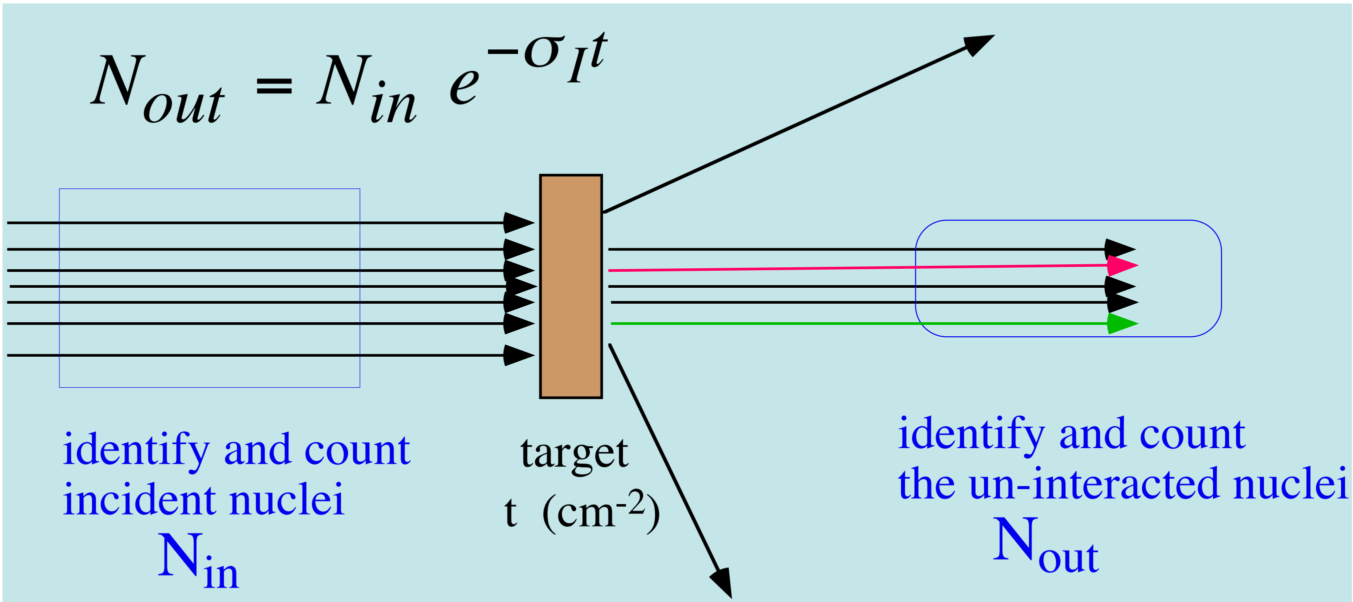


FIG. 3. Partial cross-section plot.

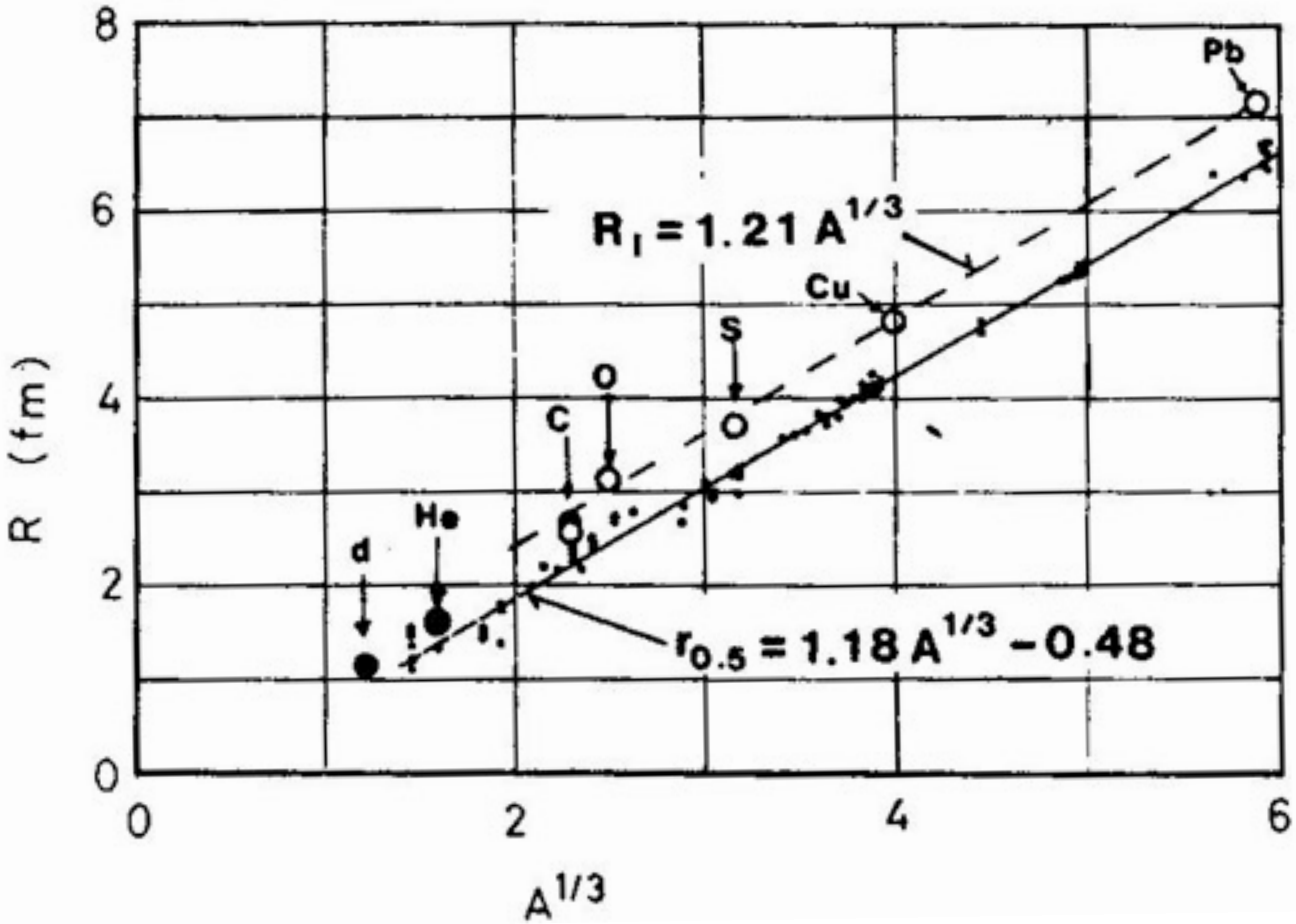
Interaction Cross sections can be Measured
in High Precision

- **Transmission method**



Interaction Radii

- Yes, we are measuring radii of nuclei!

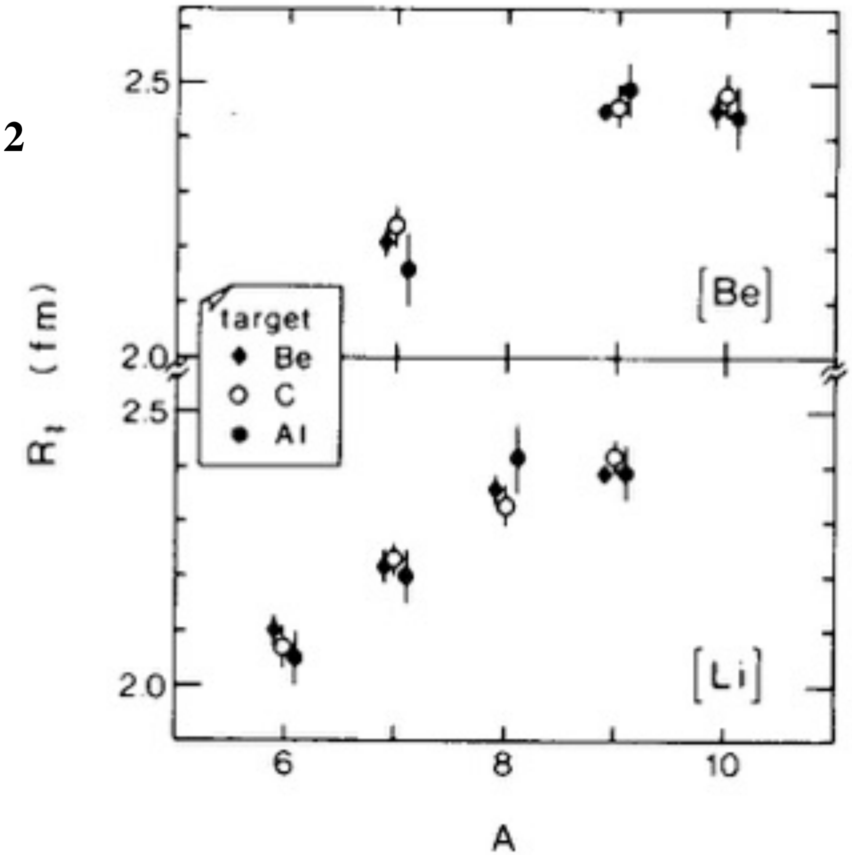


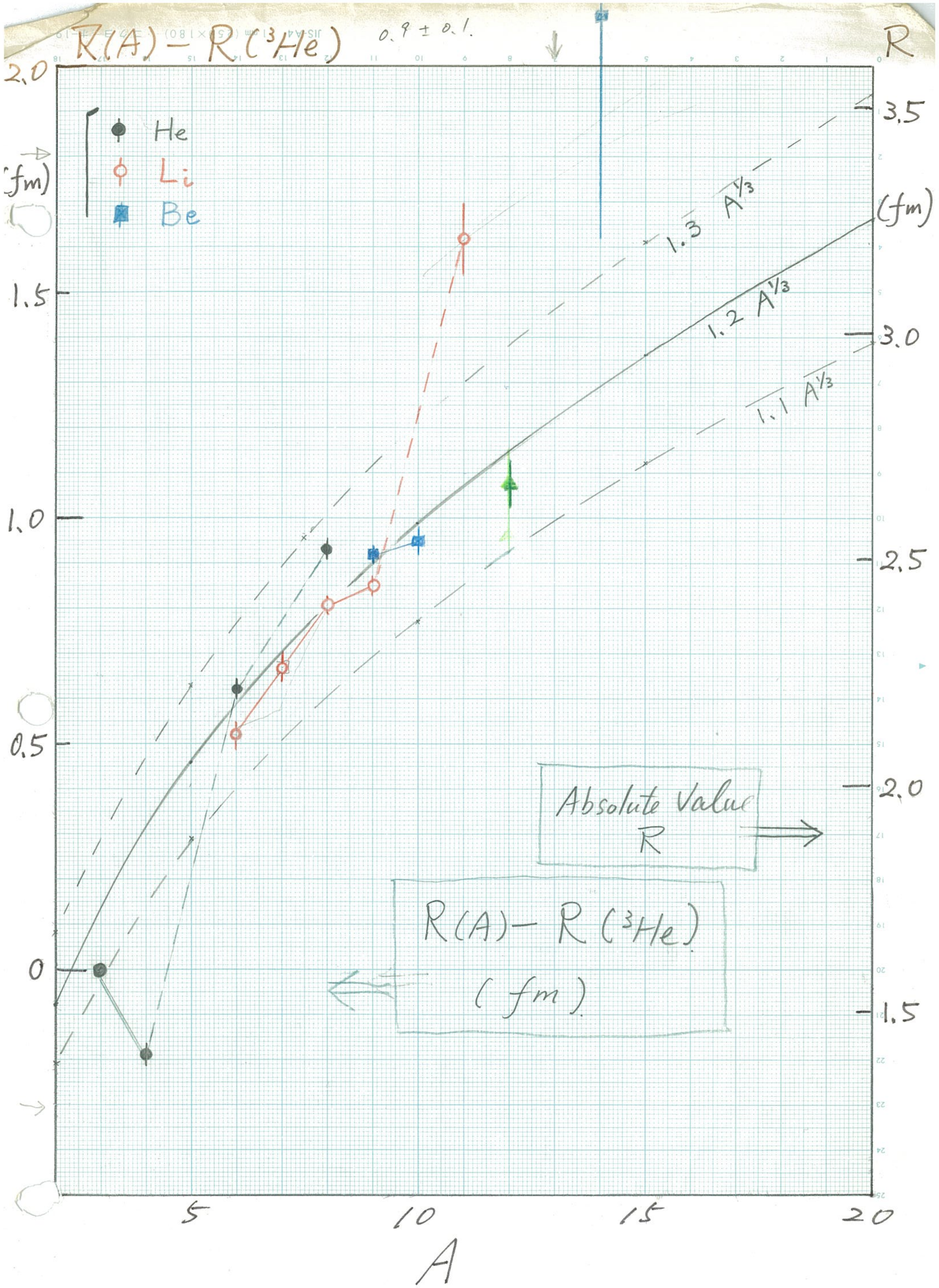
Interaction Cross Section and Radii

- **Can one define "interaction radius of nucleus?"**
  - $\sigma_I(A,B) = \pi\,[R_I(A) + R_I(B)]^2$

- $\sigma_I(A,A) = 4\pi\,[R_I(A)]^2$, $\sigma_I(B,B) = 4\pi\,[R_I(B)]^2$ **or**

- $\sigma_I(A,C) = \pi\,[R_I(A) + R_I(C)]^2$



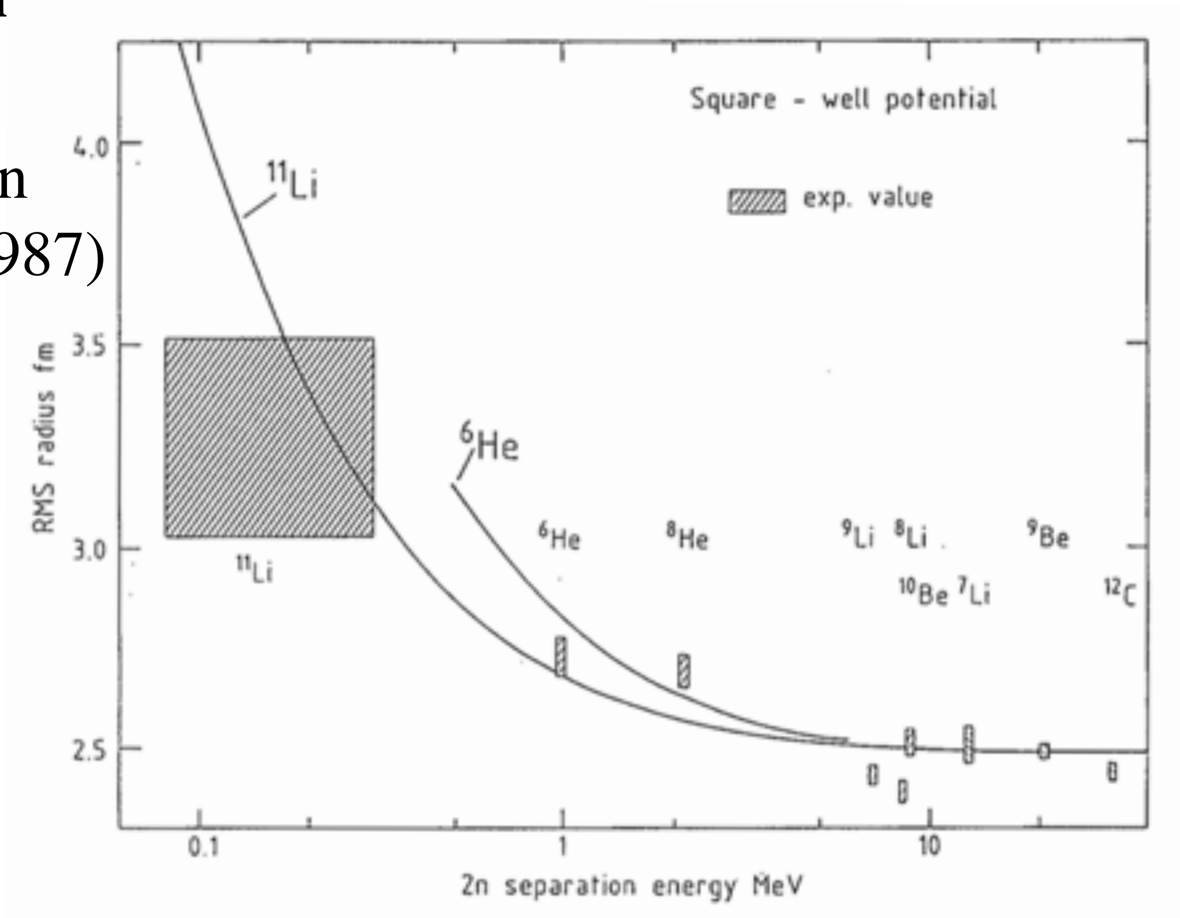


R(A) − R(³He)
0.9 ± 0.1
R
2.0
1.5
1.0
0.5
0
(fm)
3.5
3.0
2.5
2.0
1.5
(fm)
He
Li
Be
1.3 A^1/3
1.2 A^1/3
1.1 A^1/3
Absolute Value R
R(A) − R(³He) (fm)
5
10
15
20
A

Hansen, Jonson

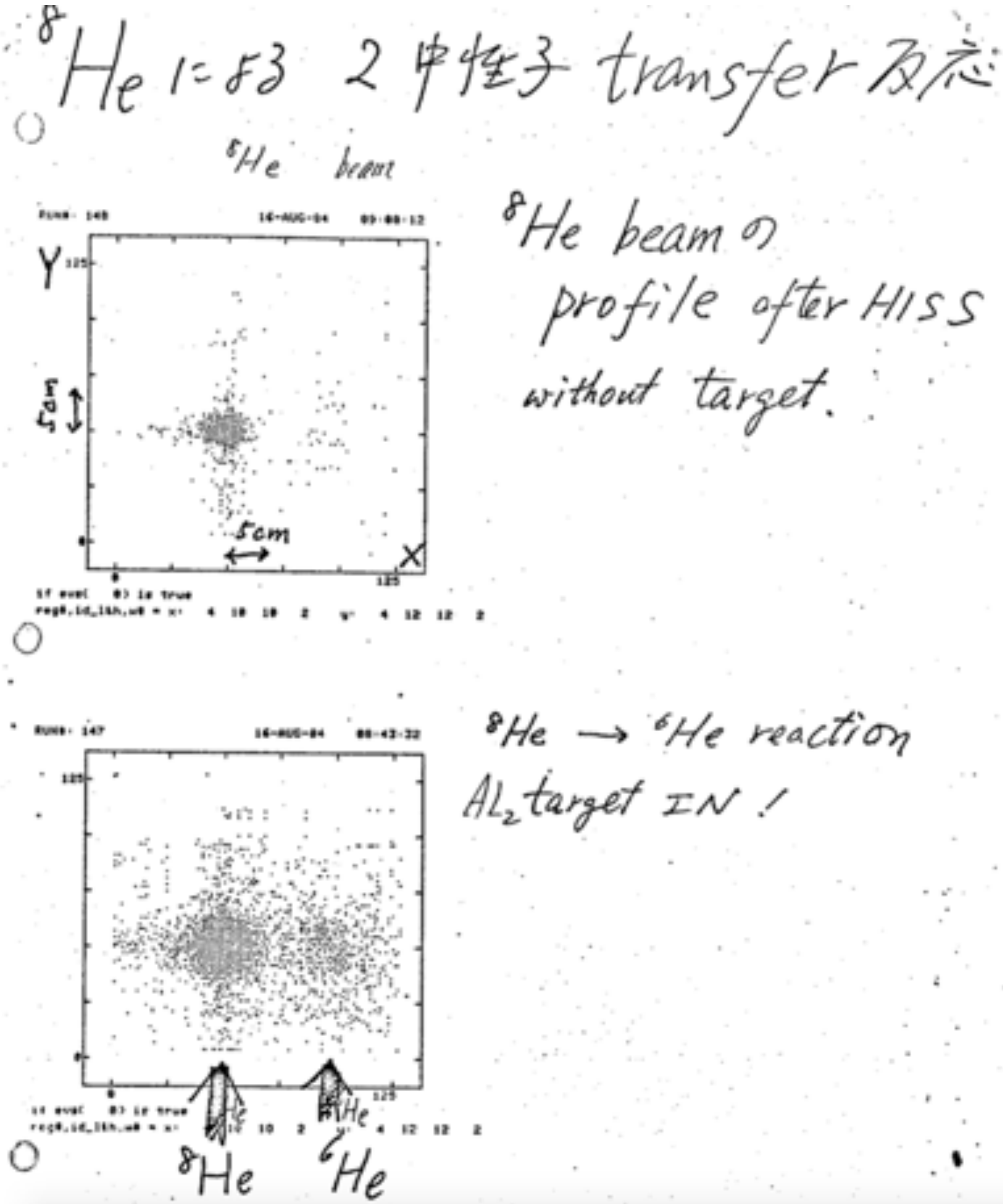
- **Radius relation**

G. Hansen and B. Jonson
Euro. Phys. Letters 4 (1987) 409.

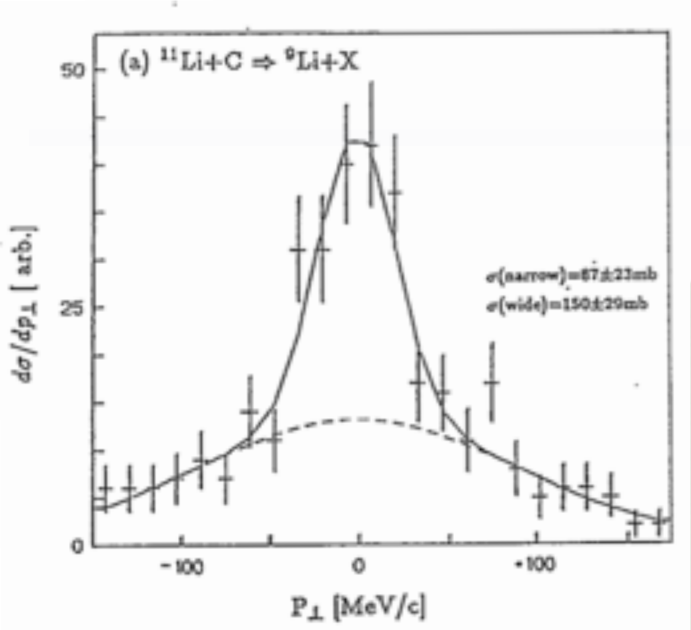


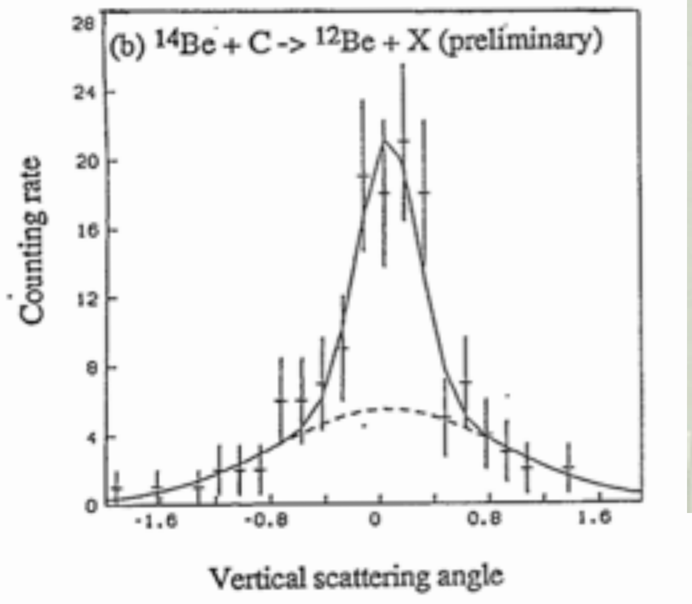
- **Prediction of enhancement of EMD**

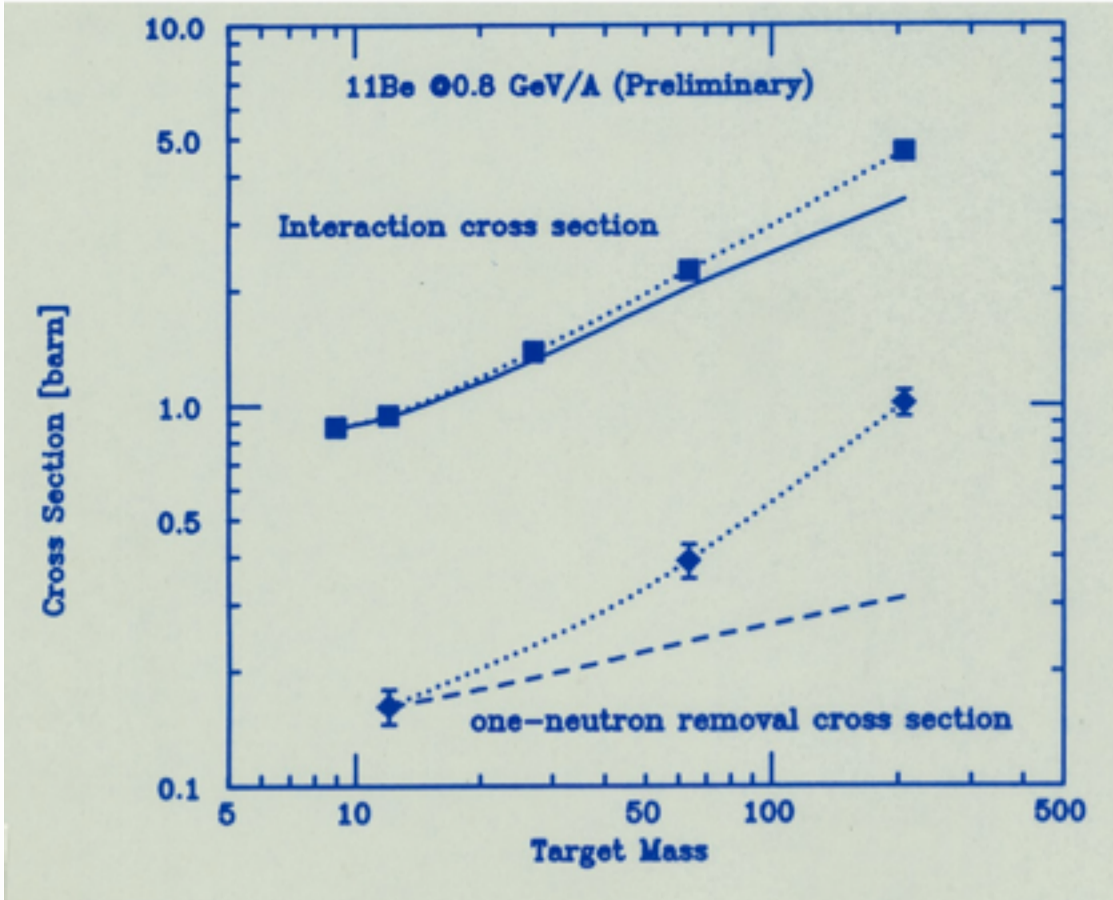
The first observation of fragmentation of RIB

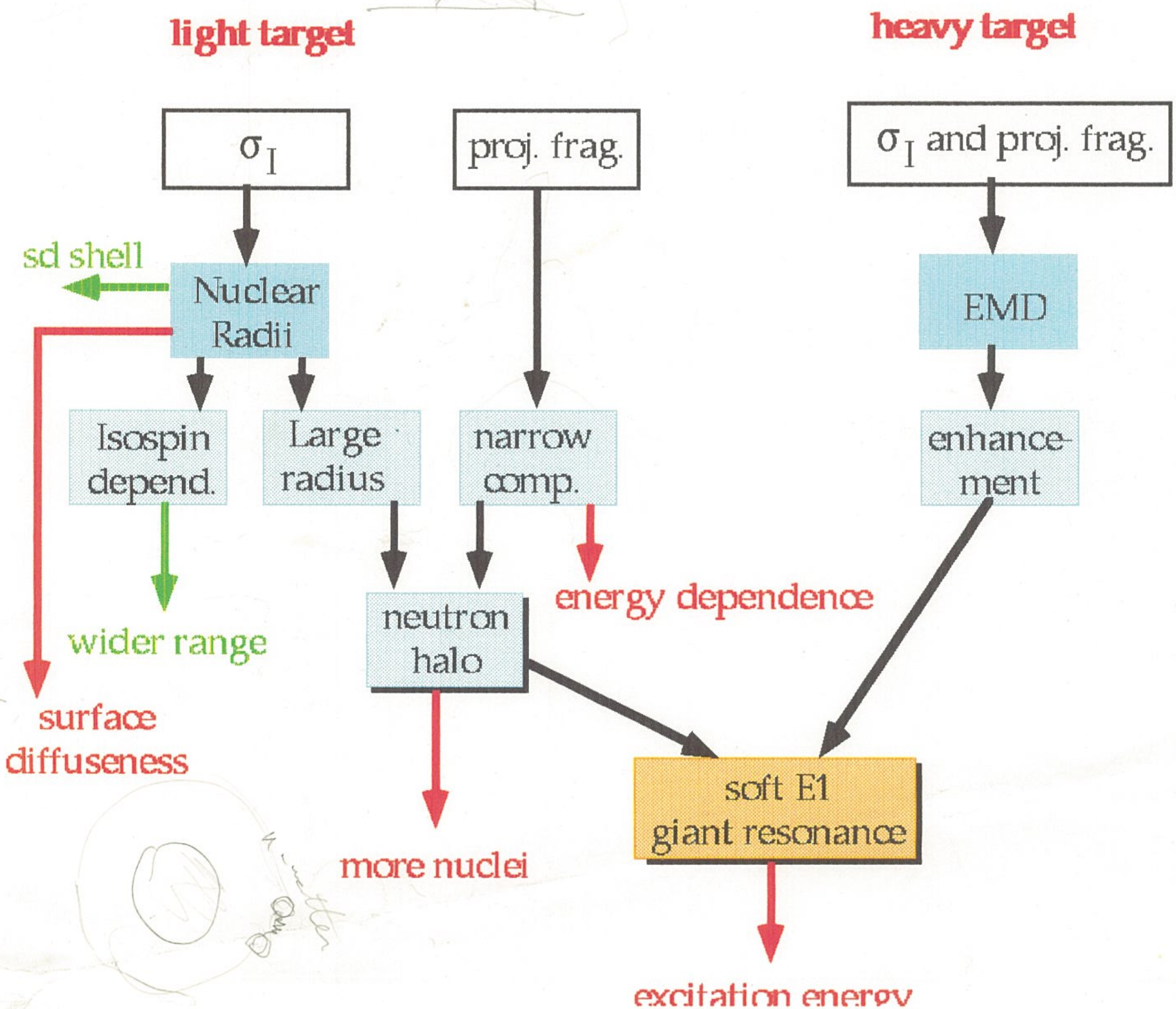


Neutron halo established








light target
heavy target
σ_I
proj. frag.
σ_I and proj. frag.
sd shell
Nuclear Radii
EMD
Isospin depend.
Large radius
narrow comp.
enhance-ment
wider range
surface diffuseness
neutron halo
energy dependence
more nuclei
soft E1 giant resonance
excitation energy

What we have learned (Experimental)

What we have learned (Experimental)

point nucleon radii (σ_I)

What we have learned (Experimental)

point nucleon radii (σ_I)

neutron halo

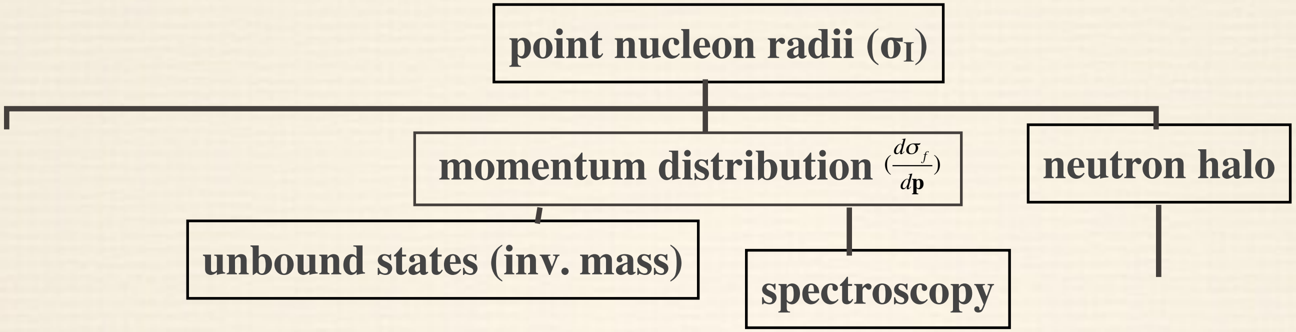
What we have learned (Experimental)

point nucleon radii (σ_I)

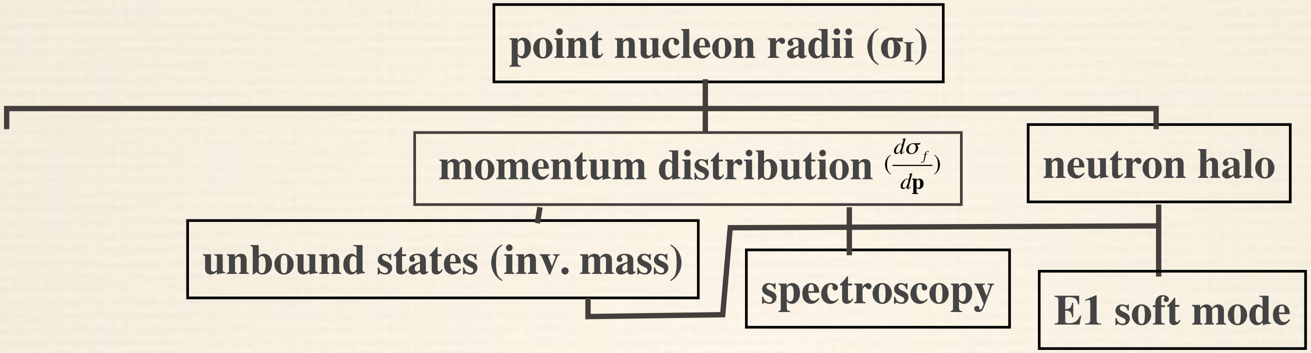
momentum distribution $(\frac{d\sigma_f}{d\mathbf{p}})$

neutron halo

What we have learned (Experimental)



What we have learned (Experimental)



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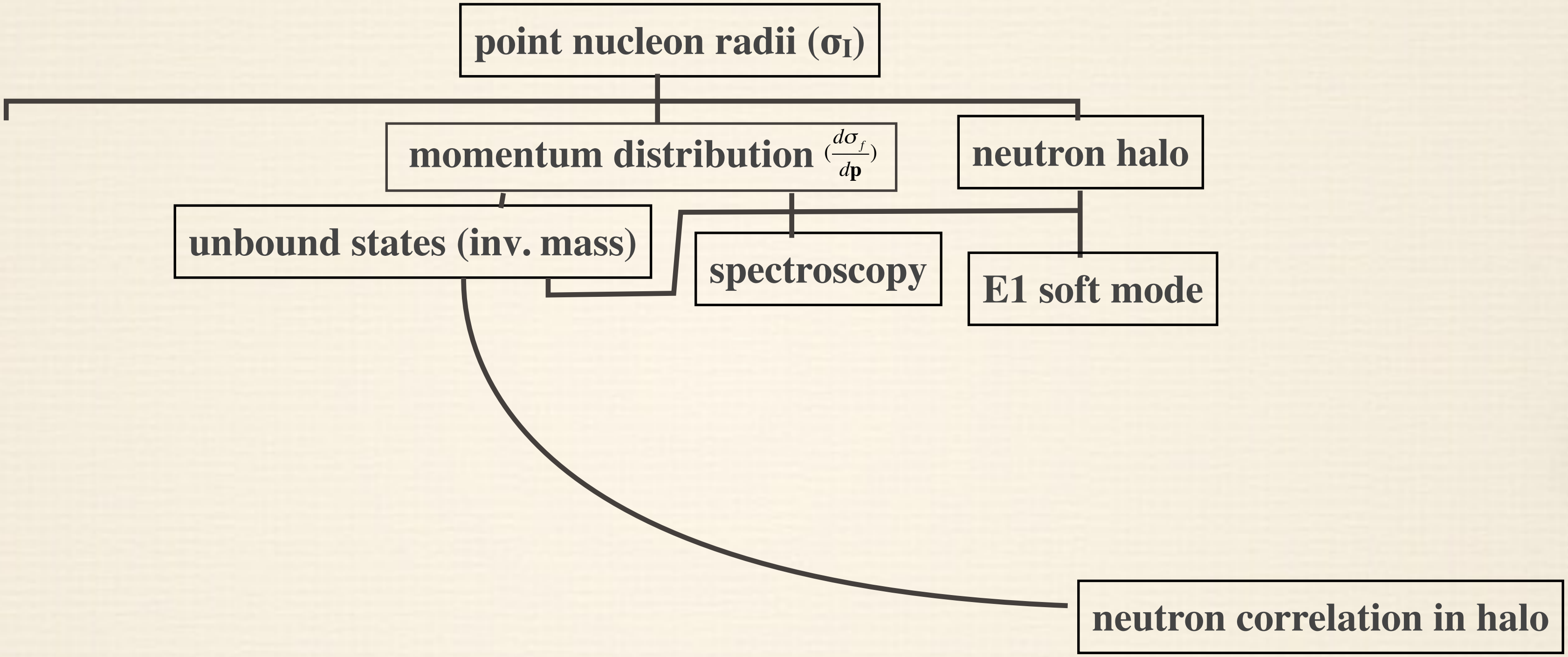

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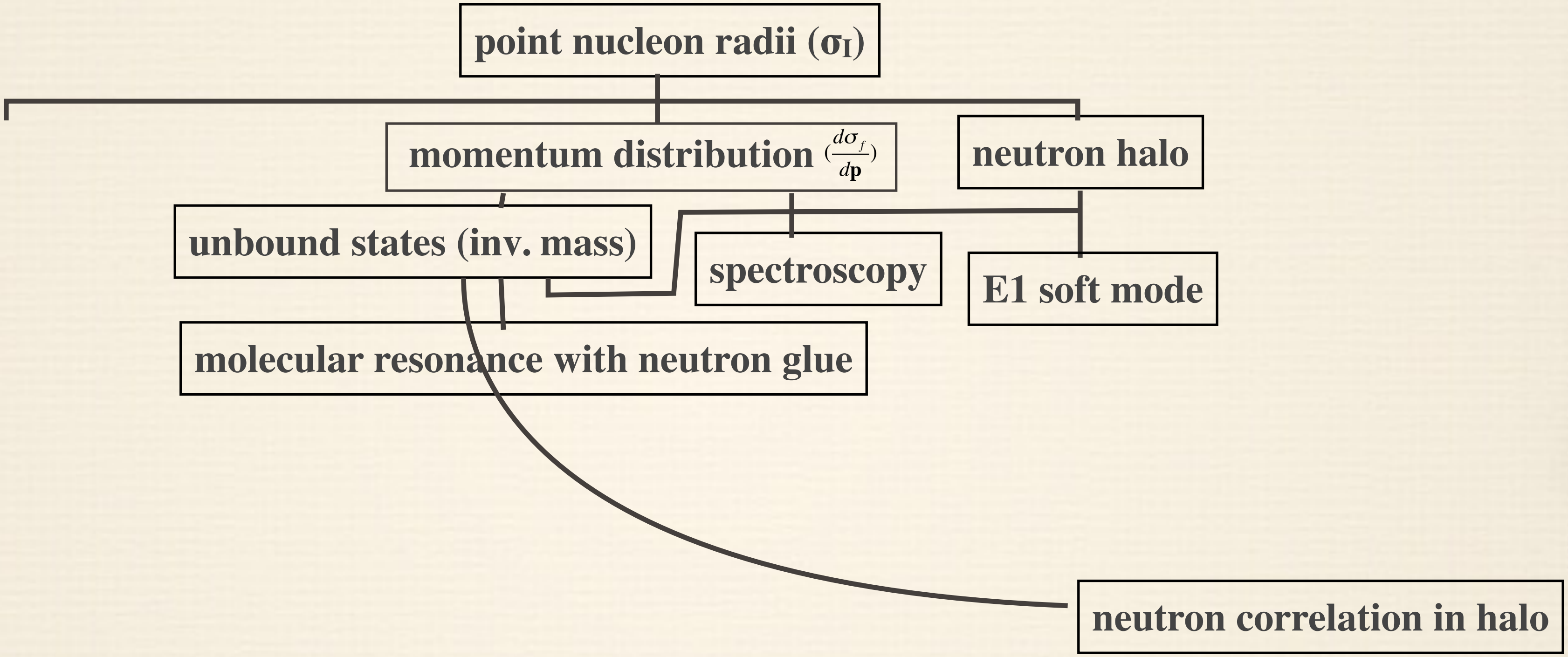

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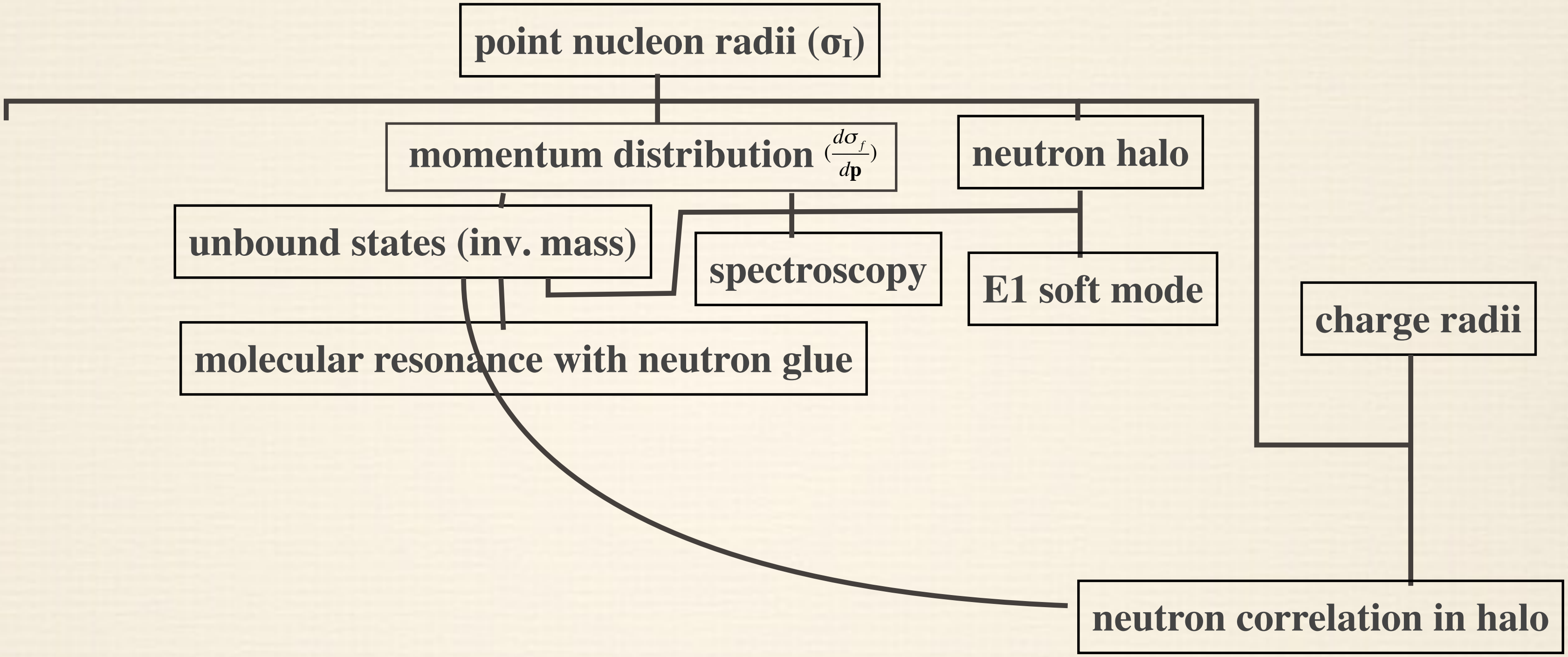

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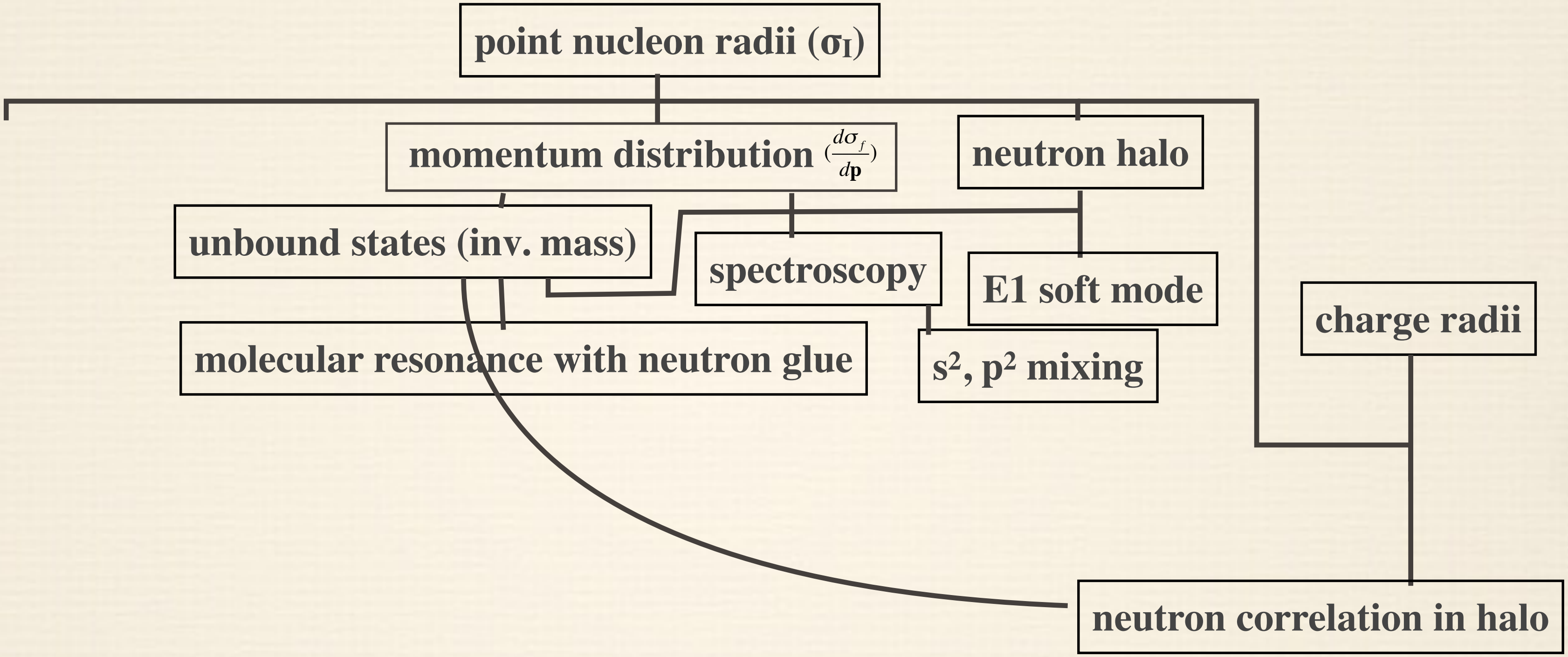

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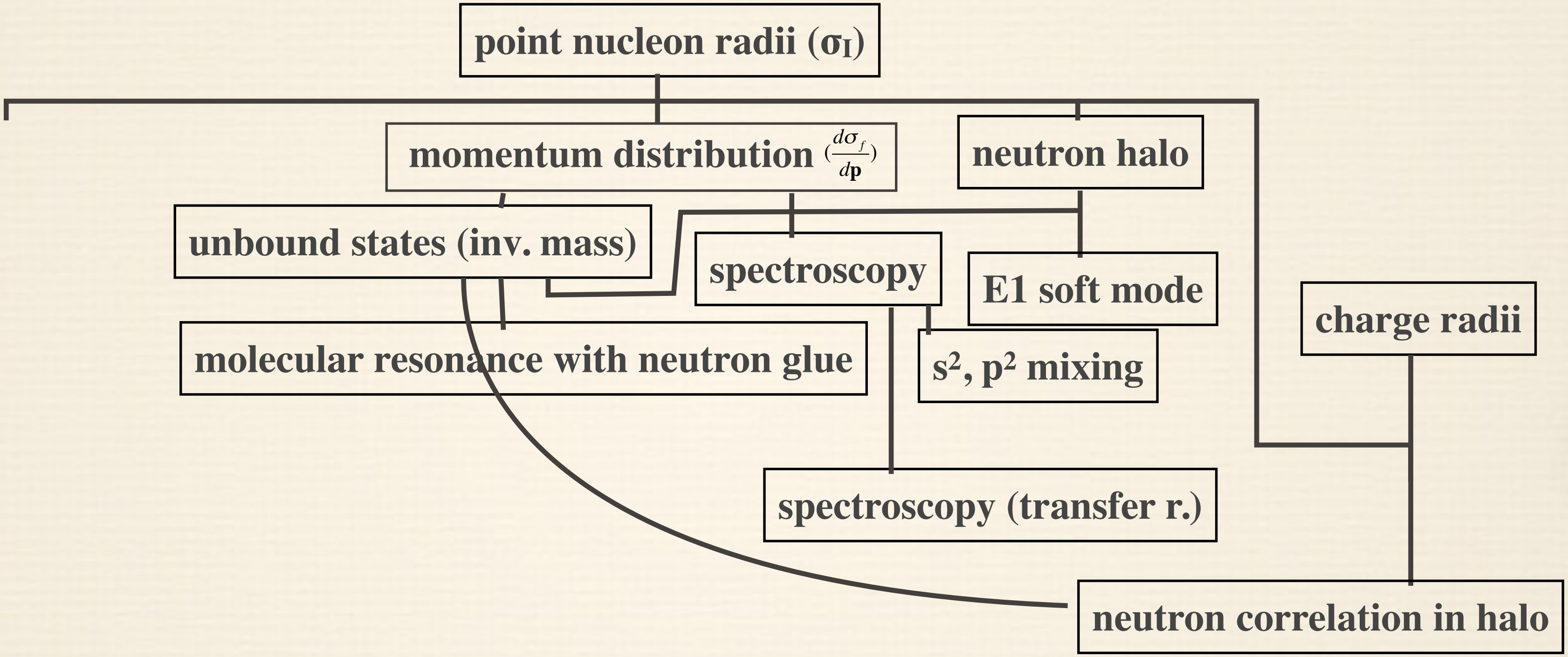

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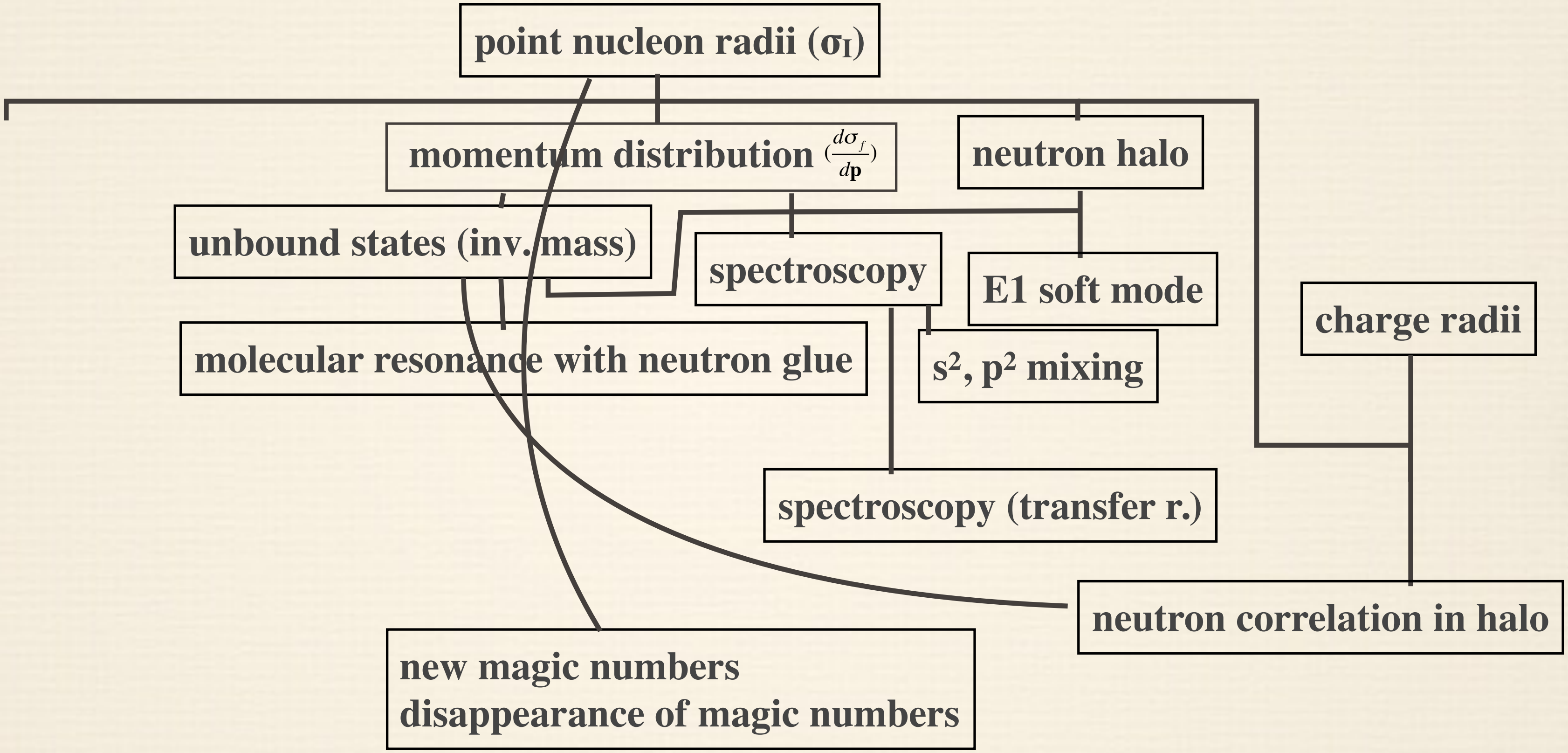

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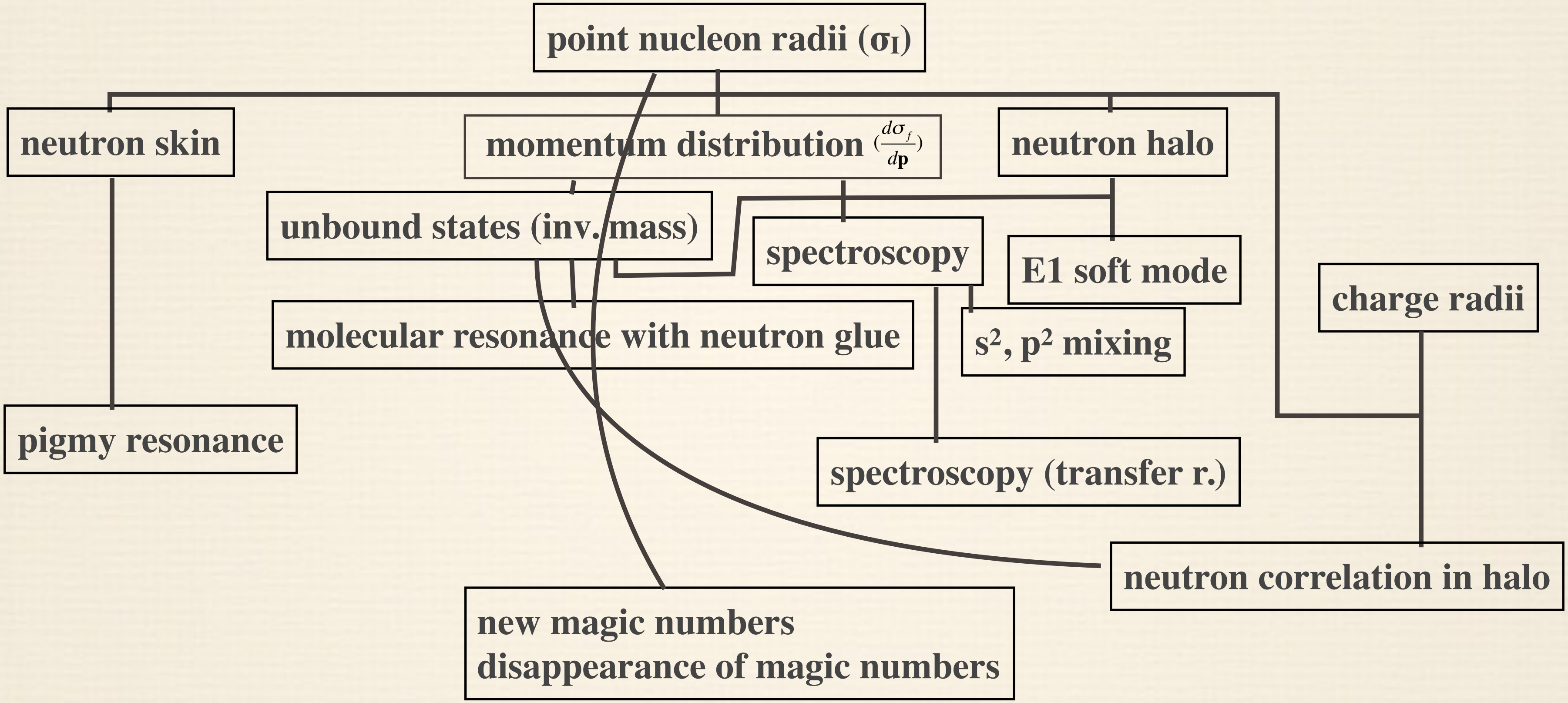
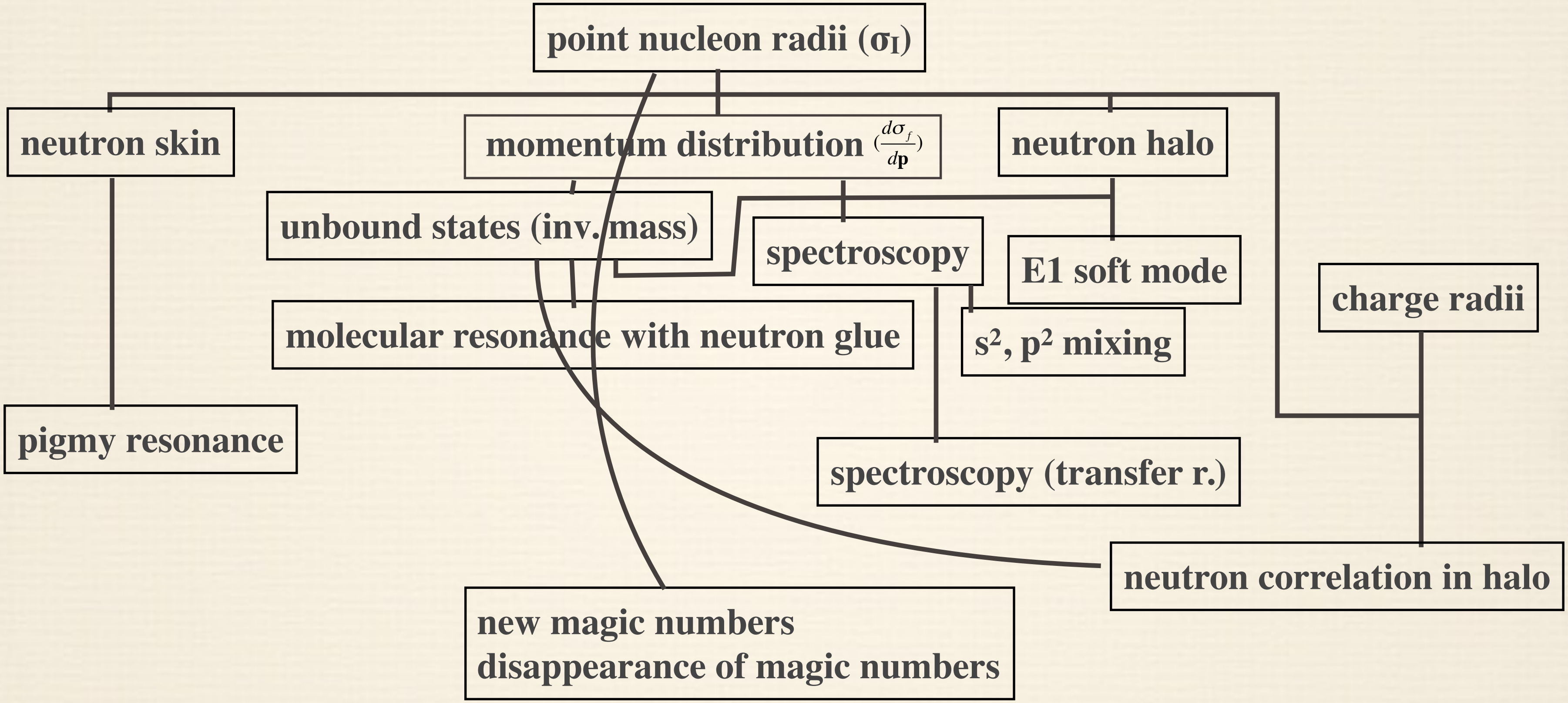


What we have learned
(Experimental) (Theory)



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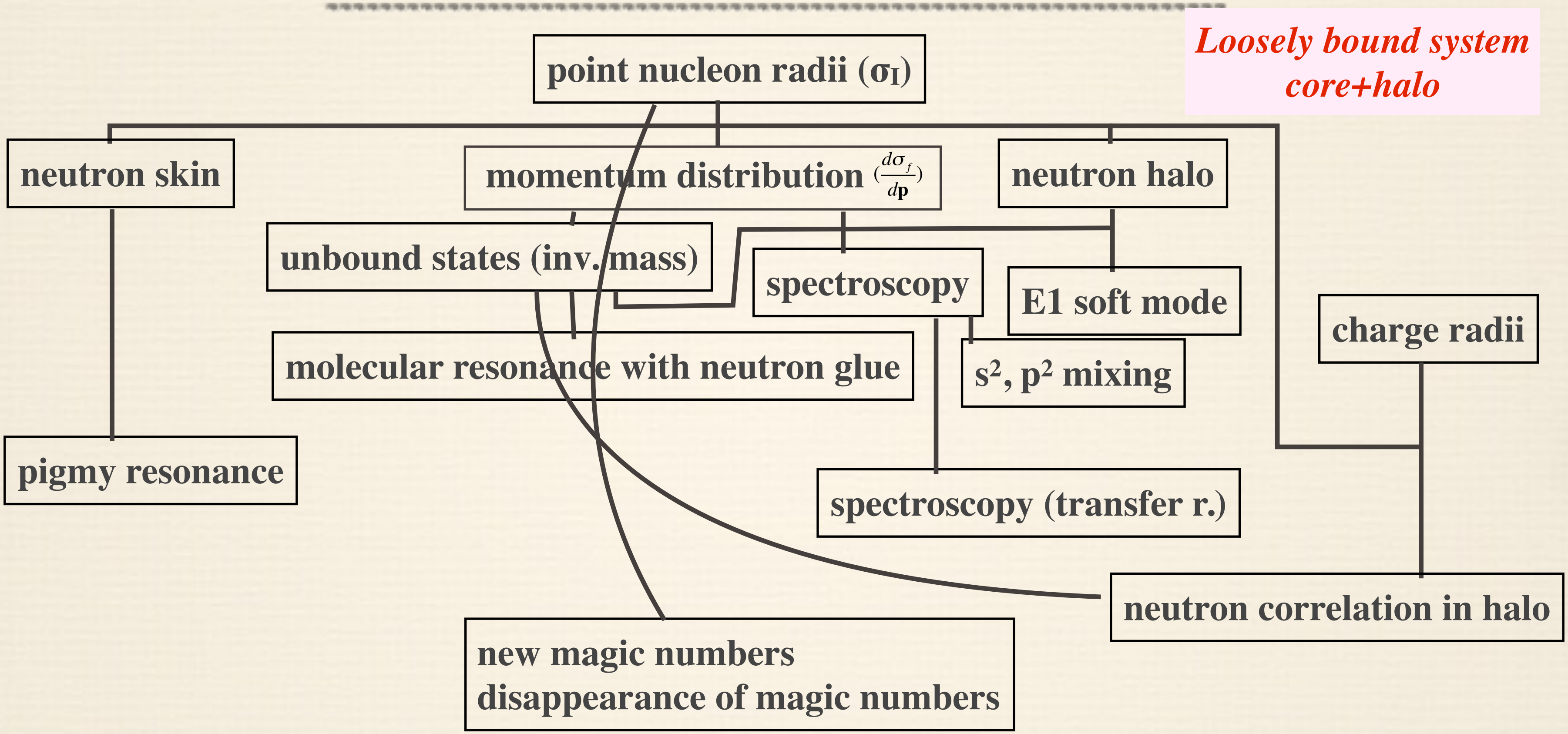

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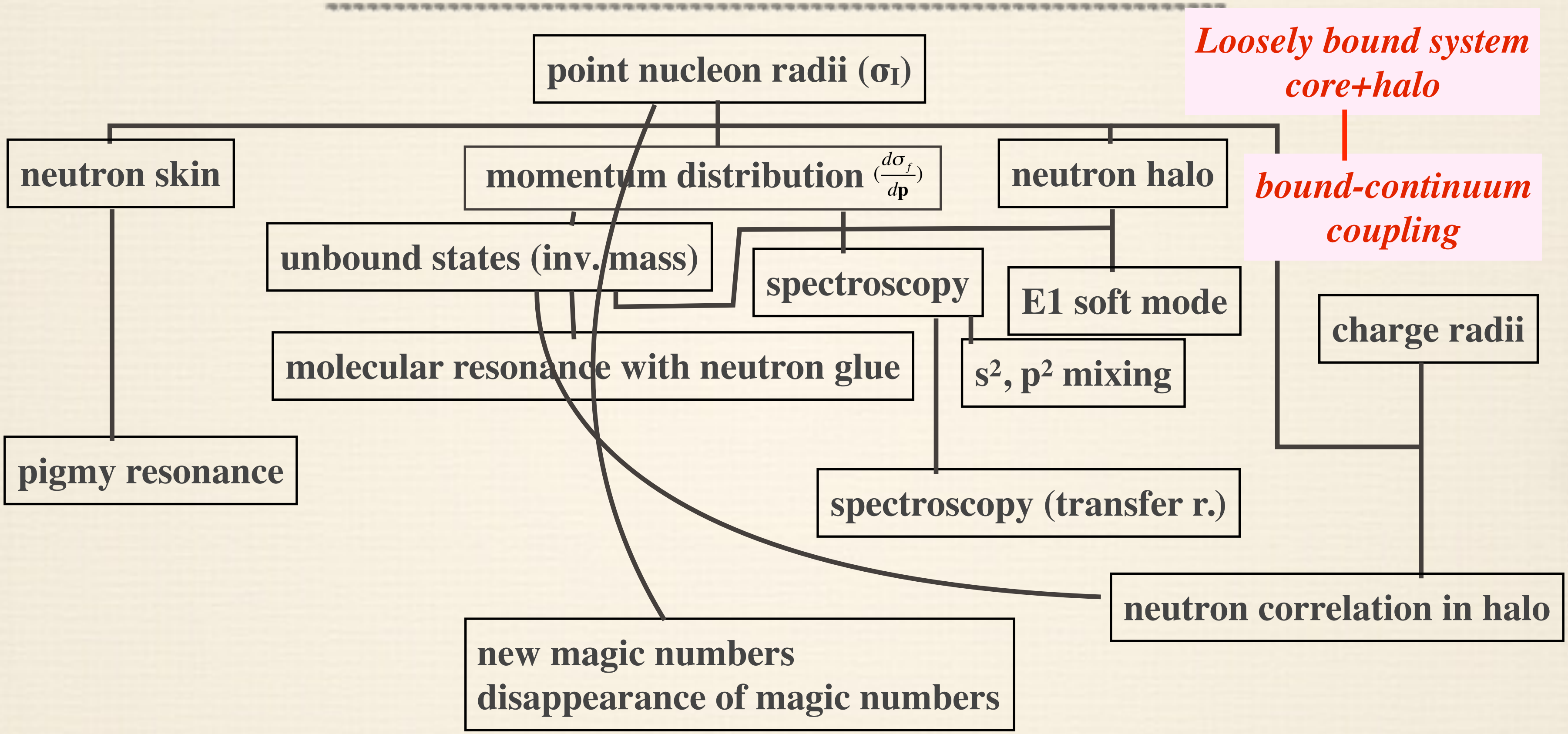

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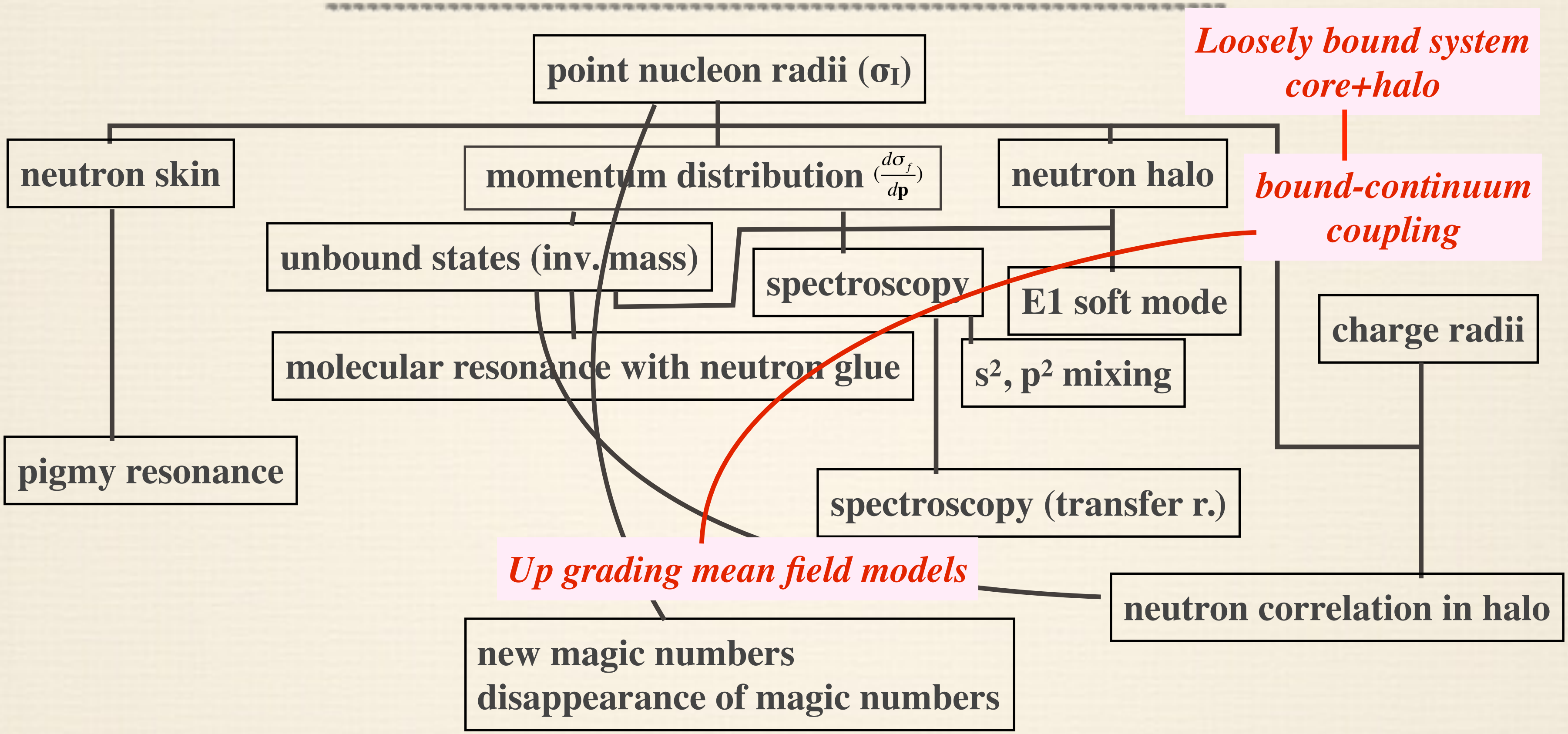

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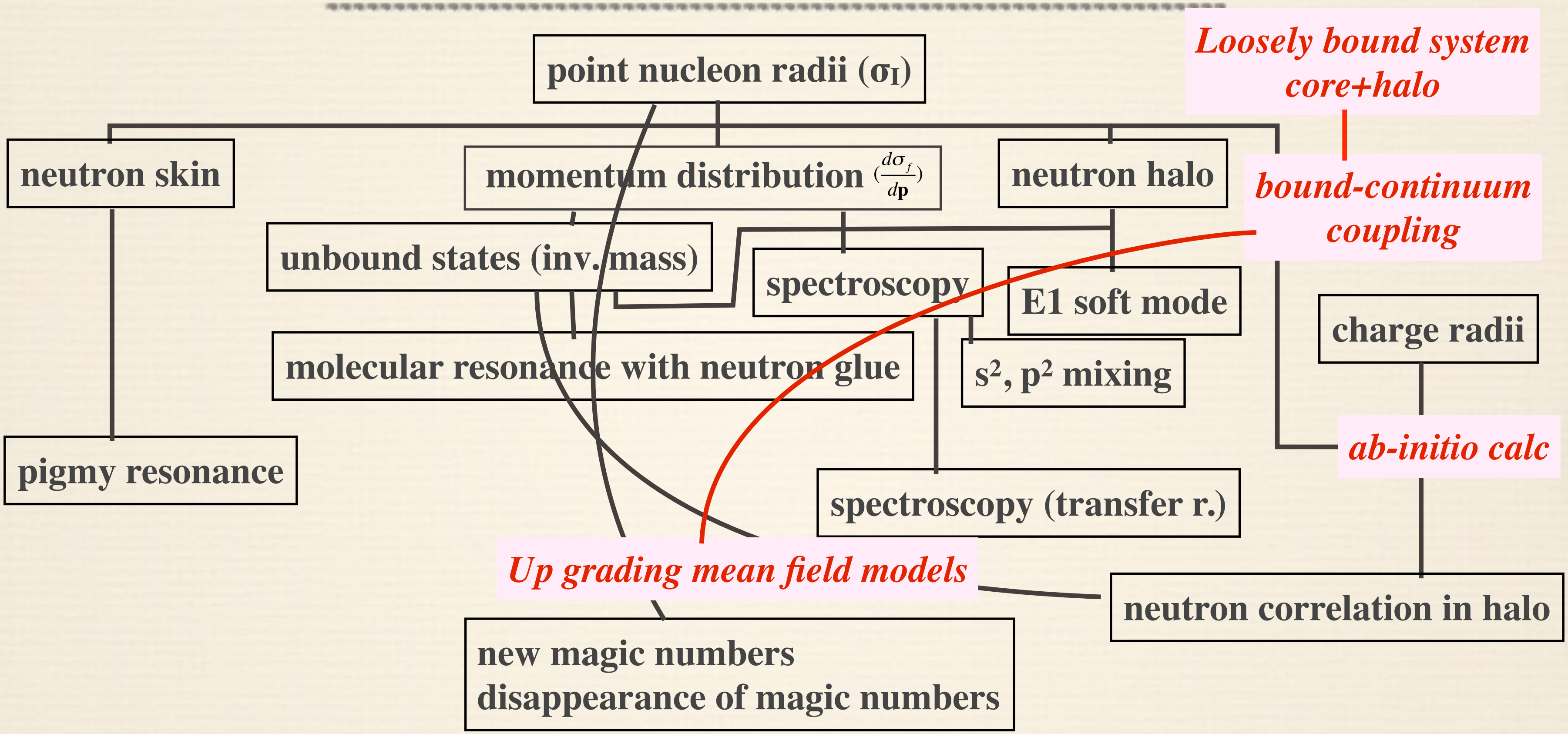

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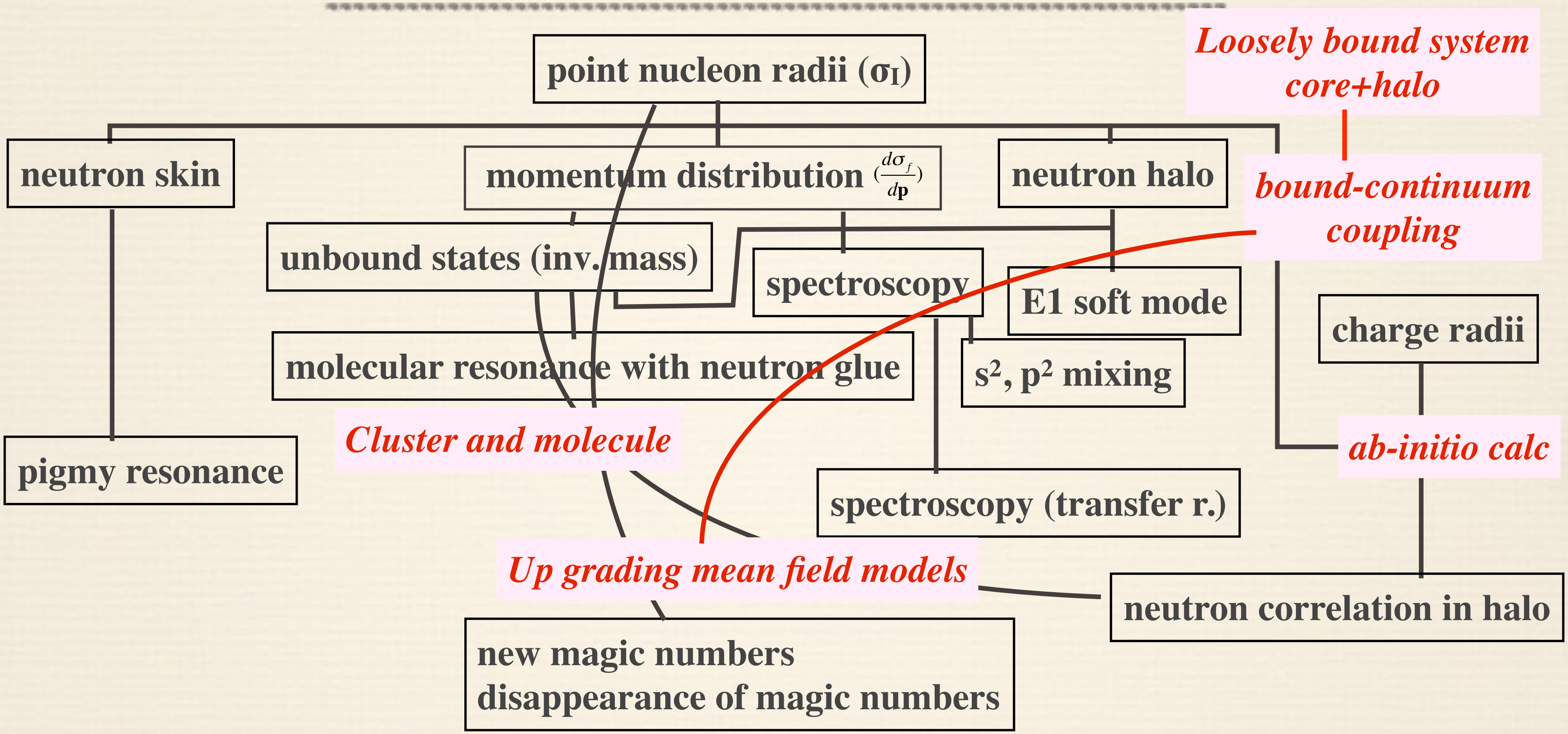

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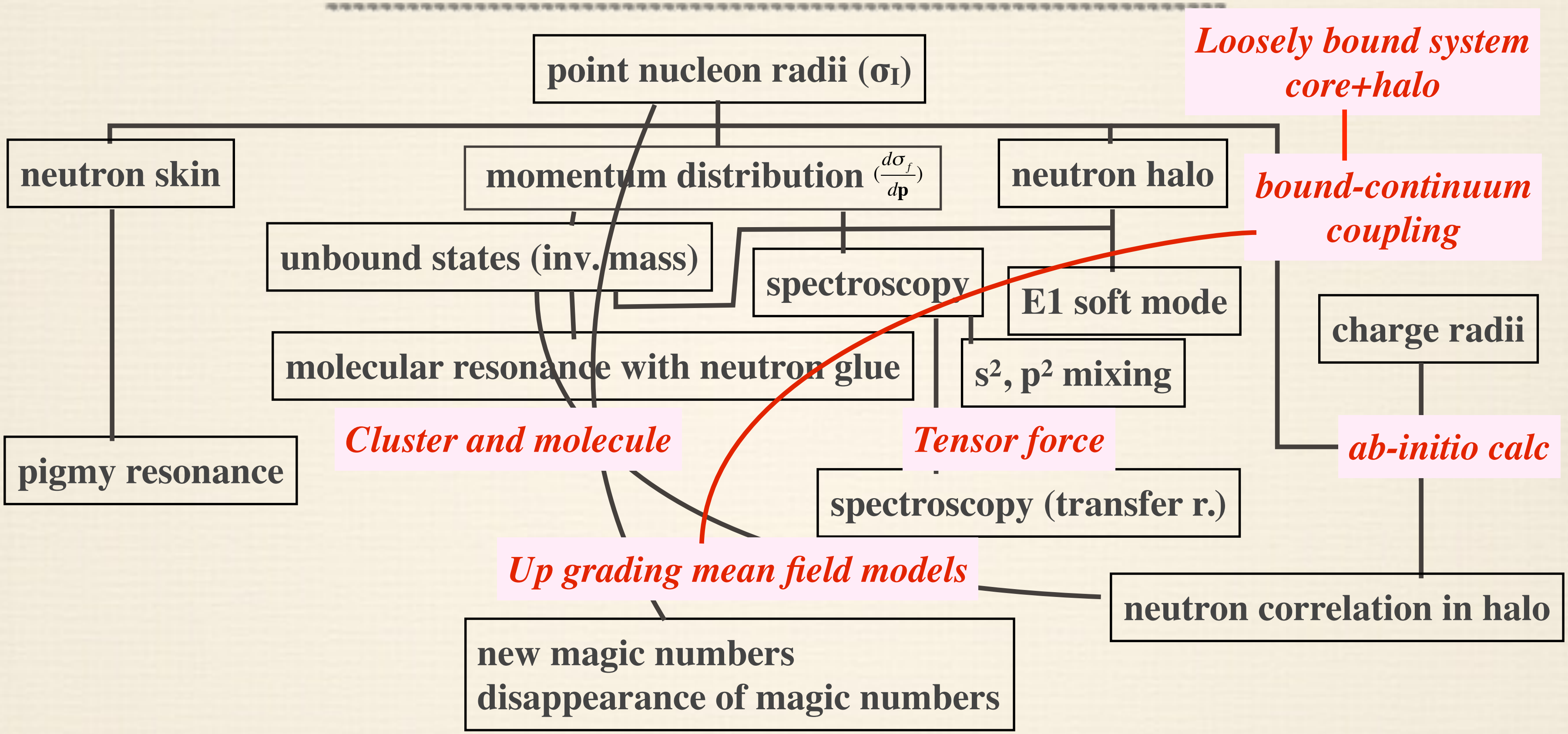
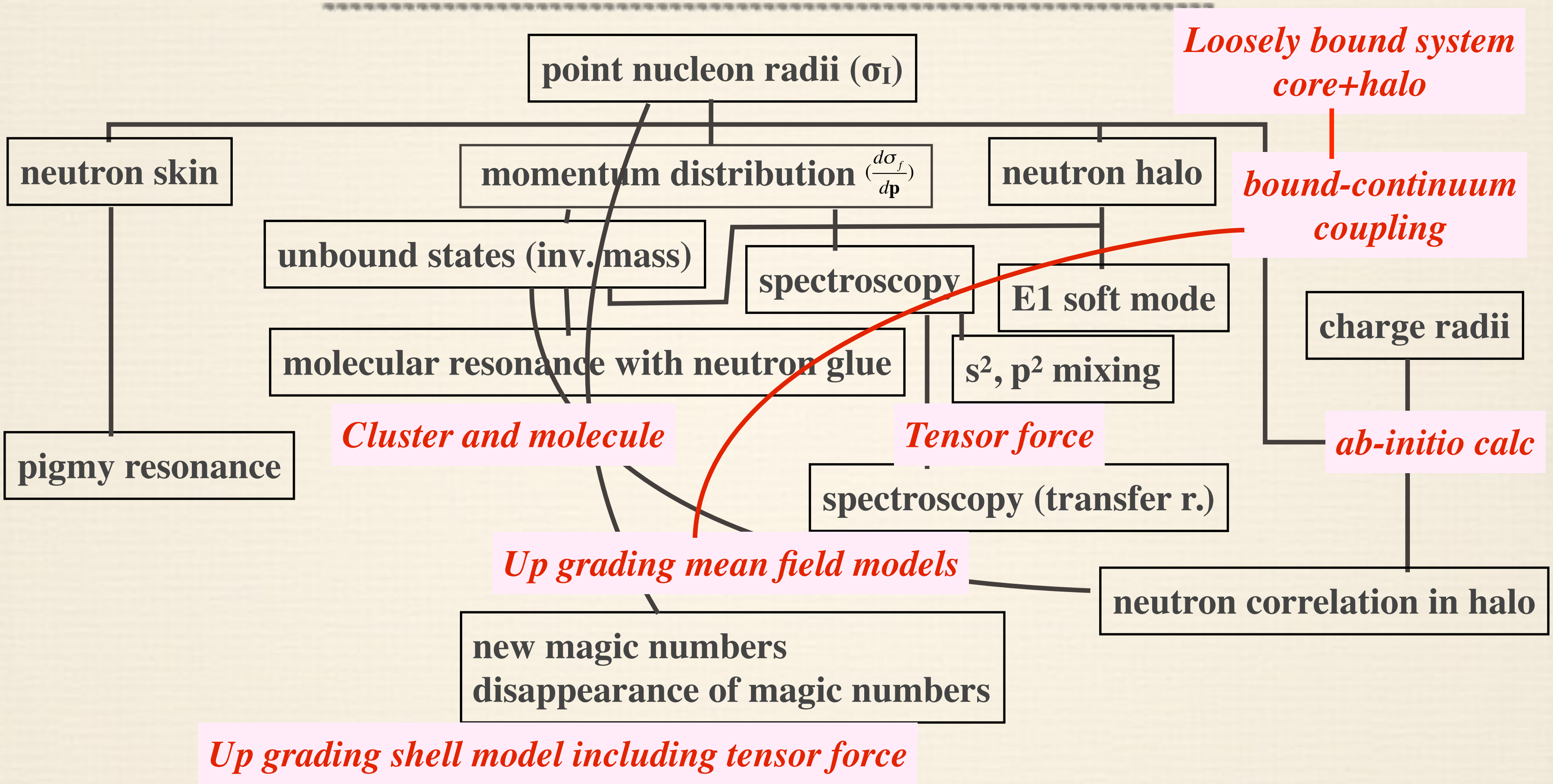
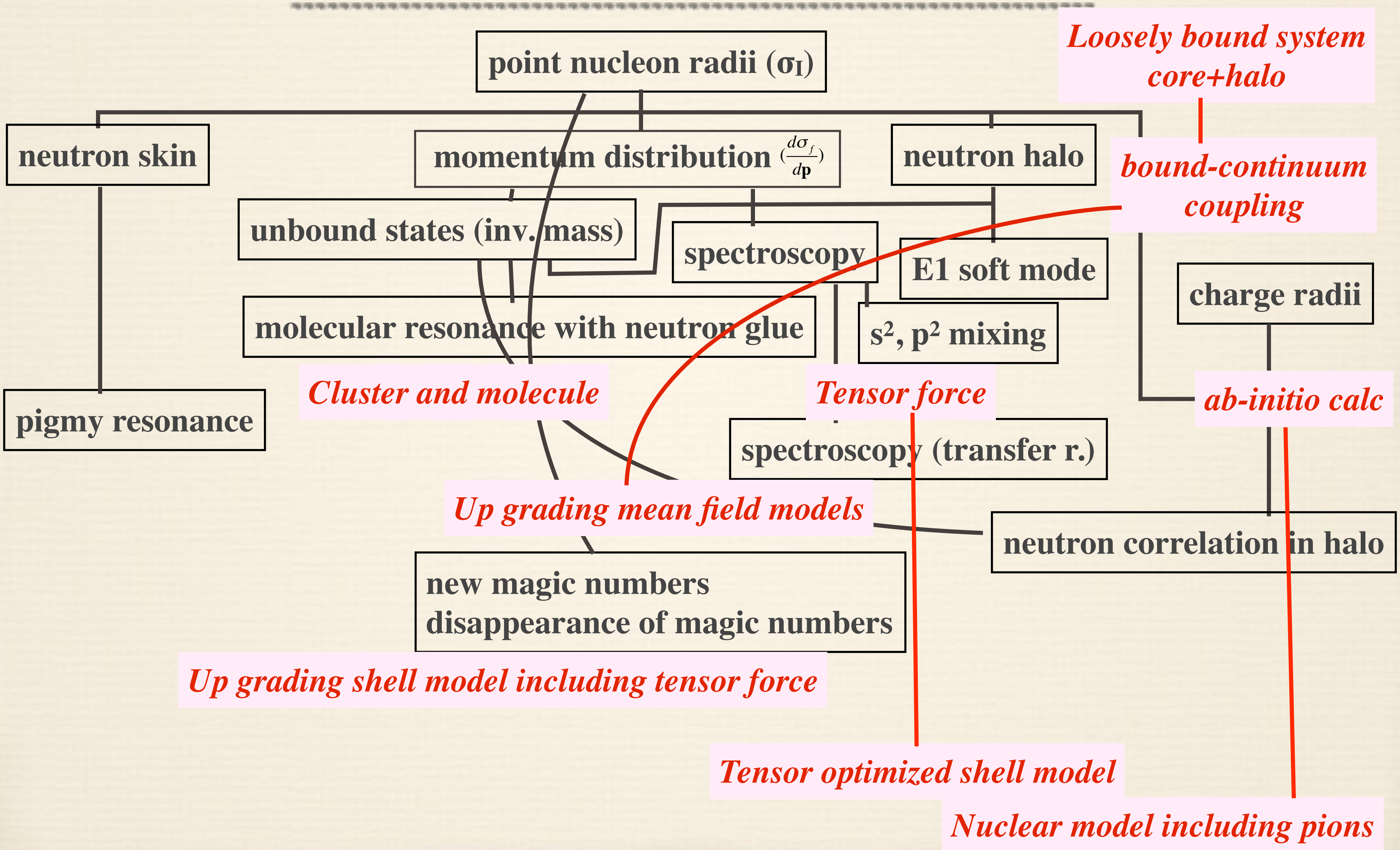


What we have learned (Experimental) (Theory)



What we have learned
(Experimental) (Theory)



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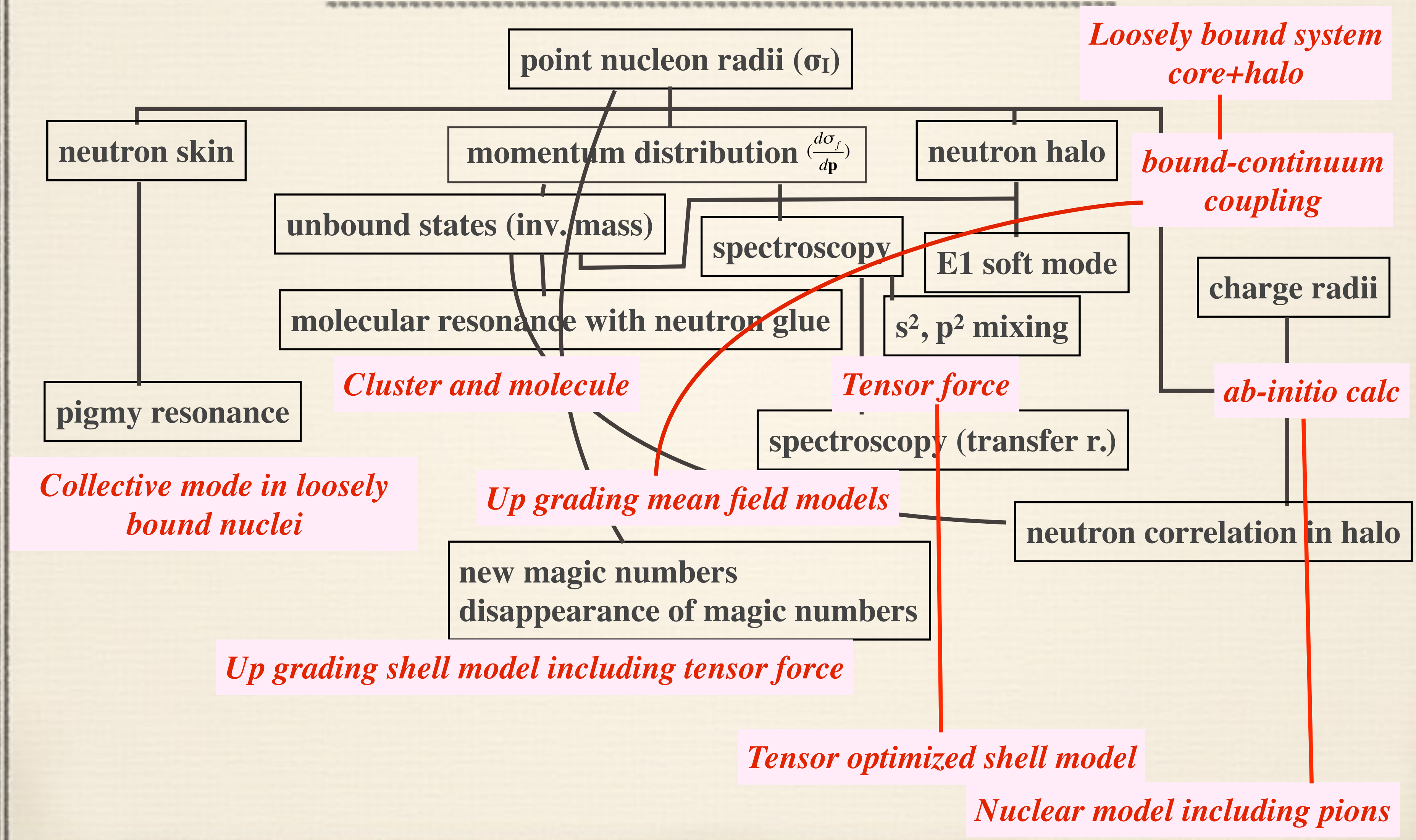
(Experimental) (Theory)



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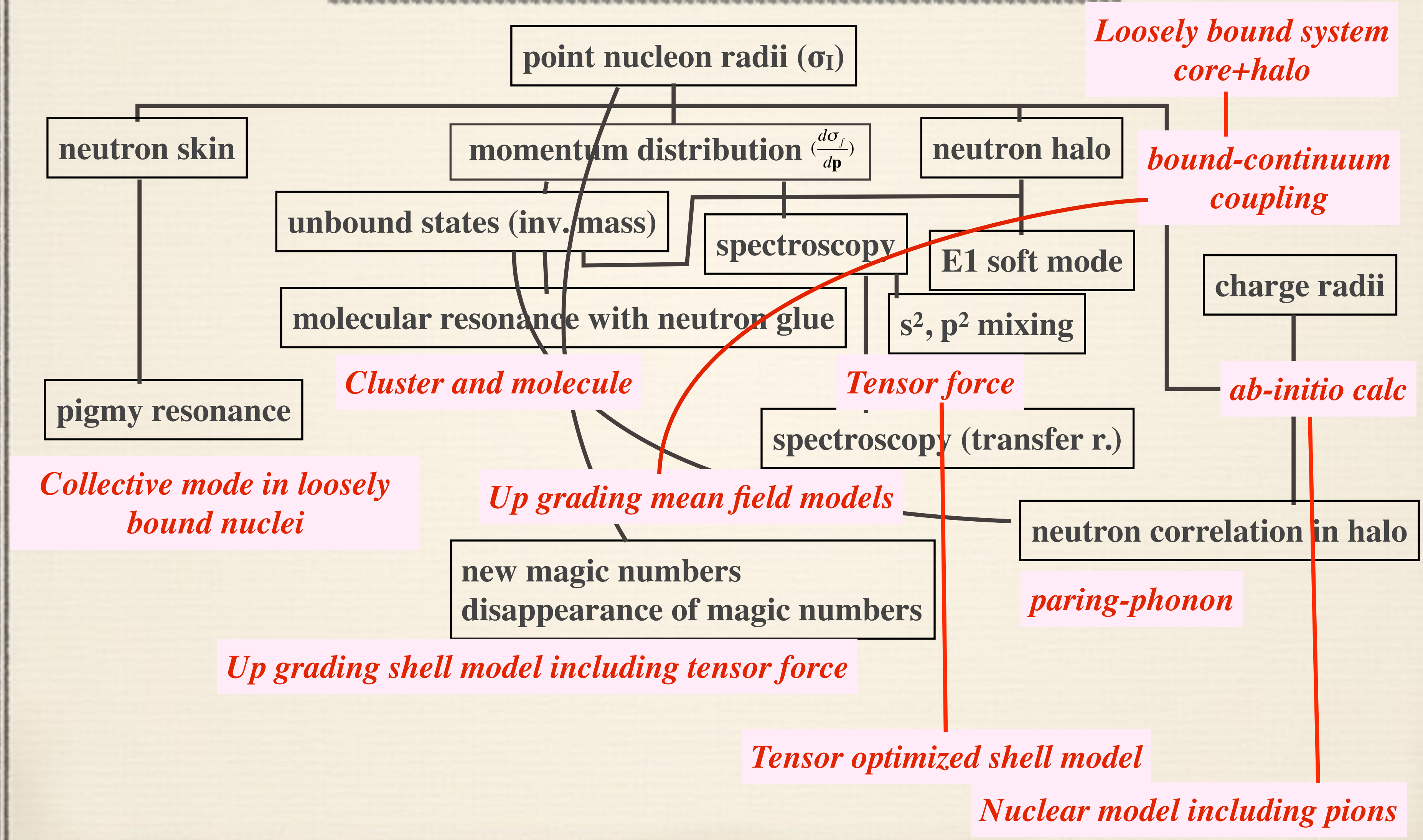

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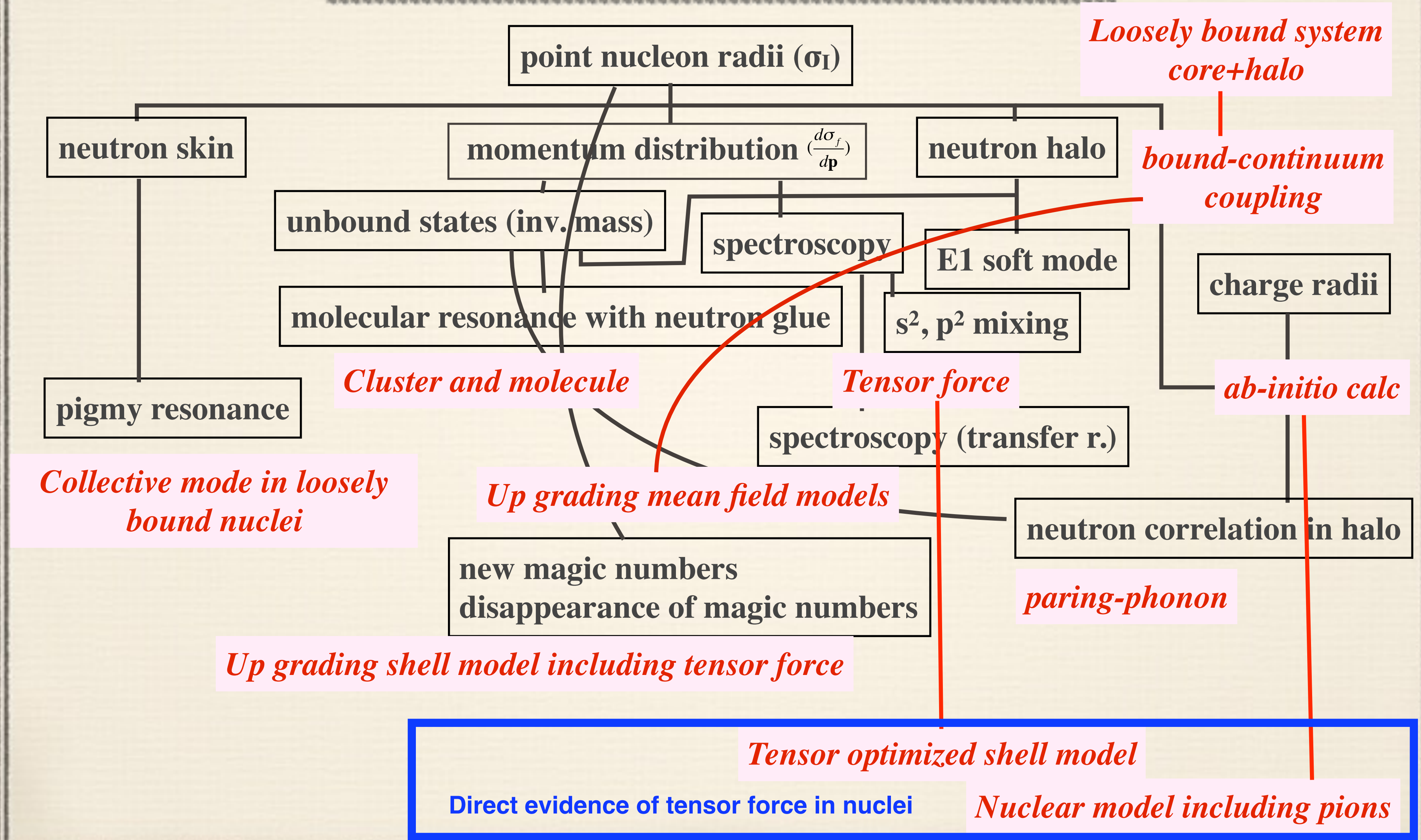

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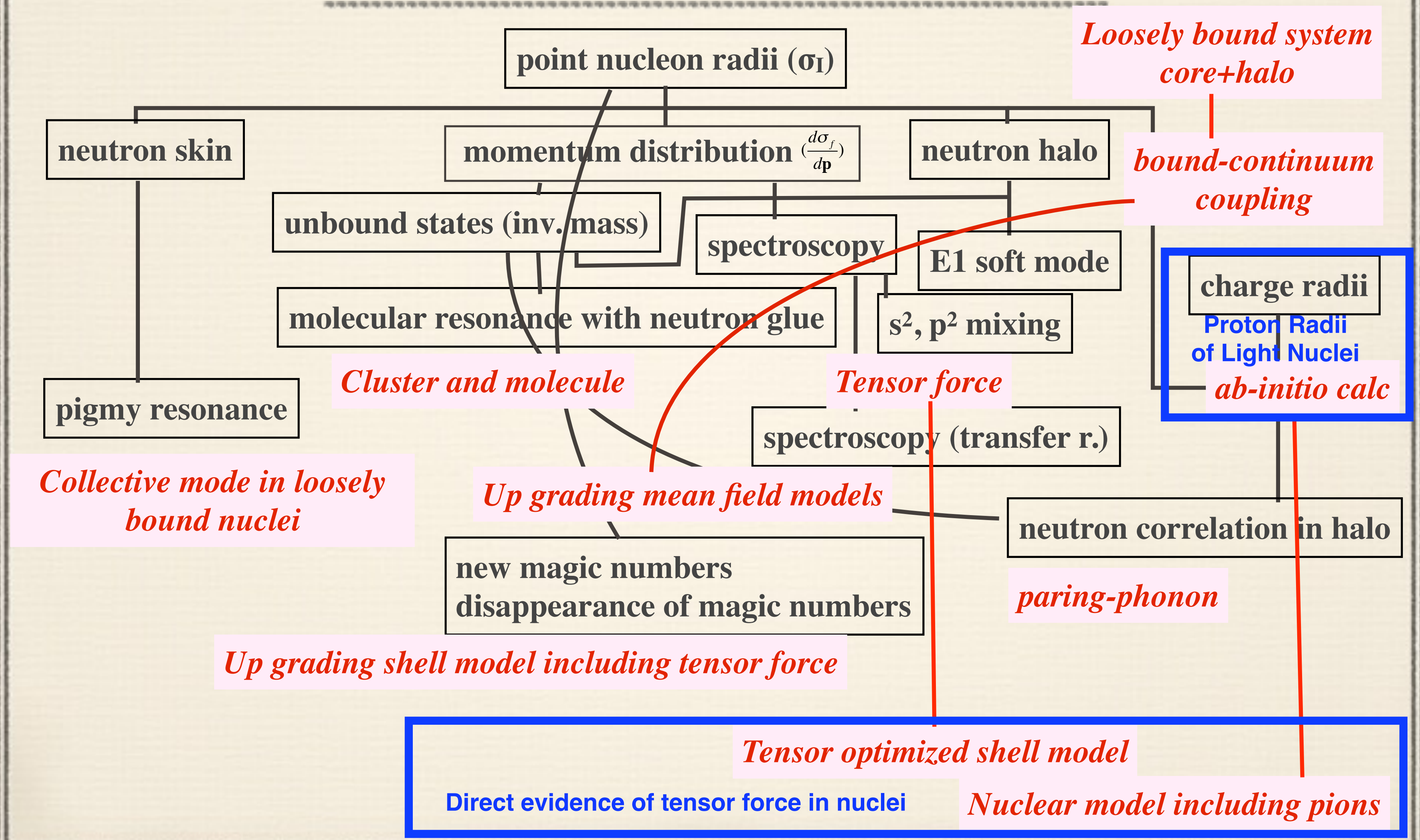
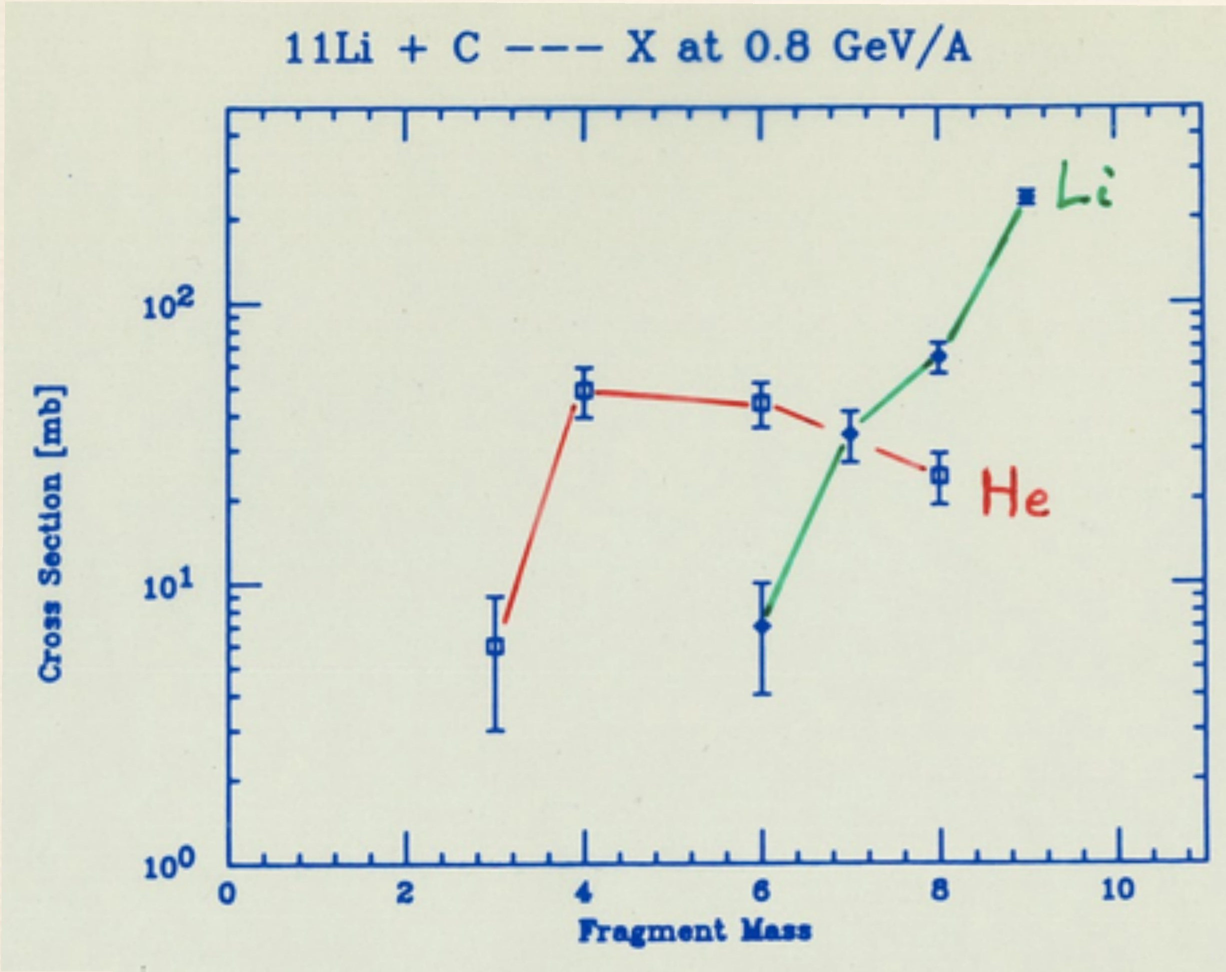
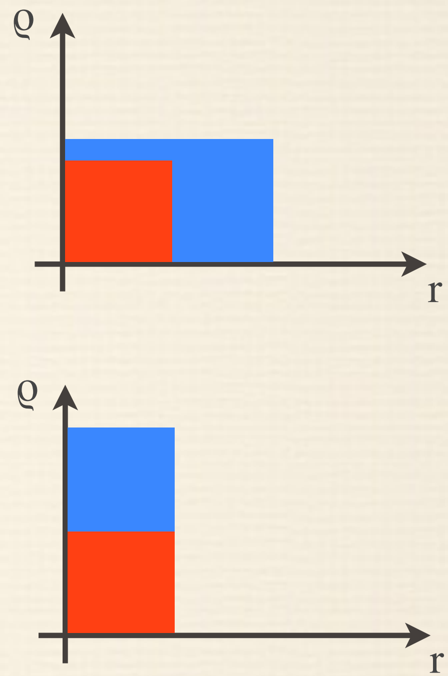


Neutron excess on the surface?

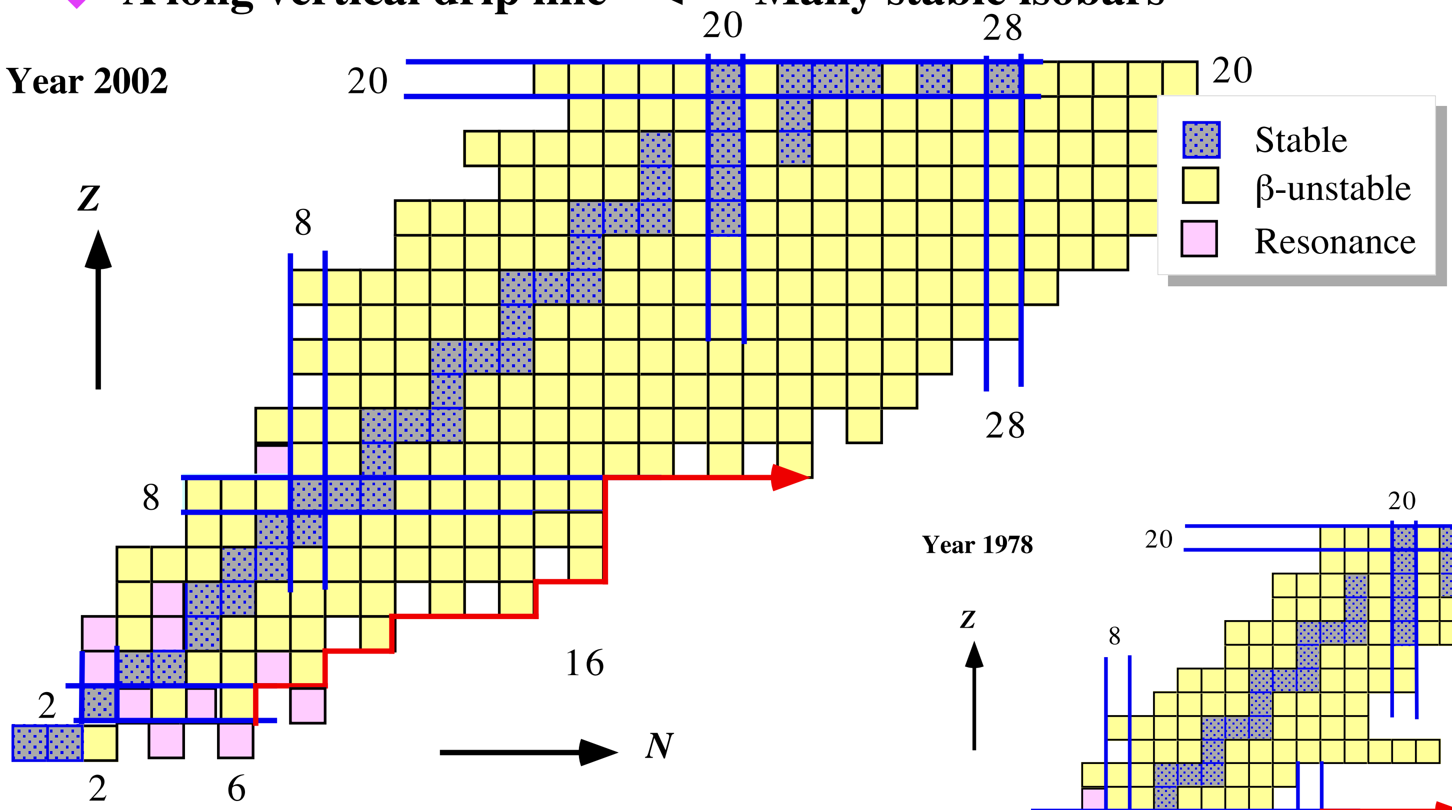


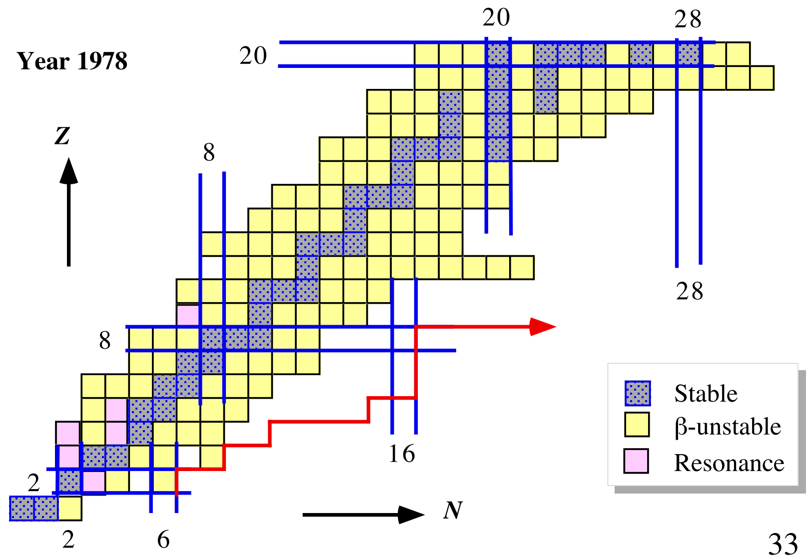


15年7月21日火曜日

A New Magic Number *N*=16

- **A long vertical drip line <--- Many stable isobars**





New Magic Number, $N = 16$, near the Neutron Drip Line

PRL 84 (2000) 5493.

A. Ozawa,[1] T. Kobayashi,[2] T. Suzuki,[3] K. Yoshida,[1] and I. Tanihata[1]
[1]The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan
[2]Department of Physics, Tohoku University, Miyagi 980-8578, Japan
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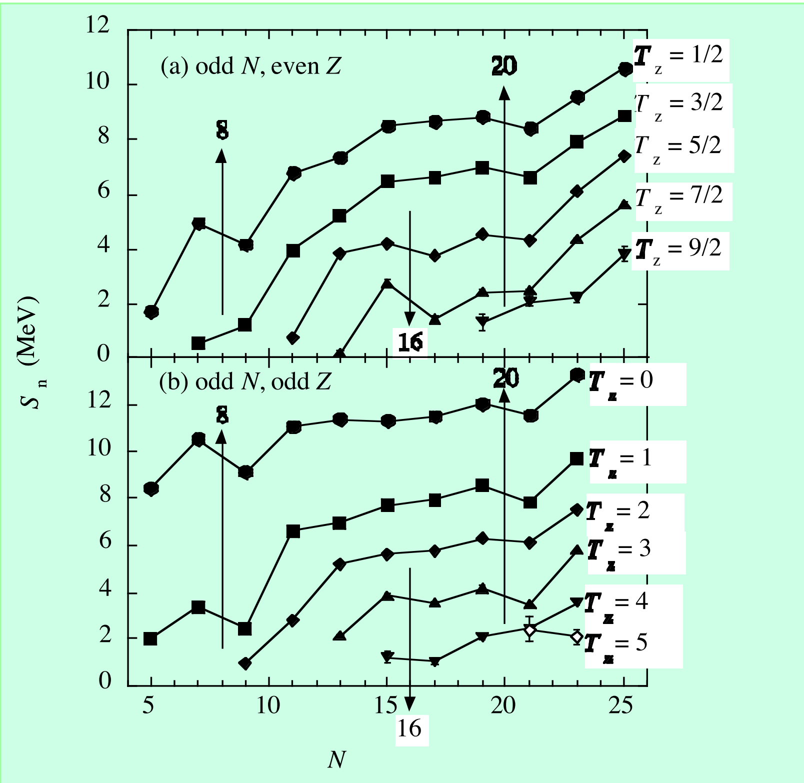
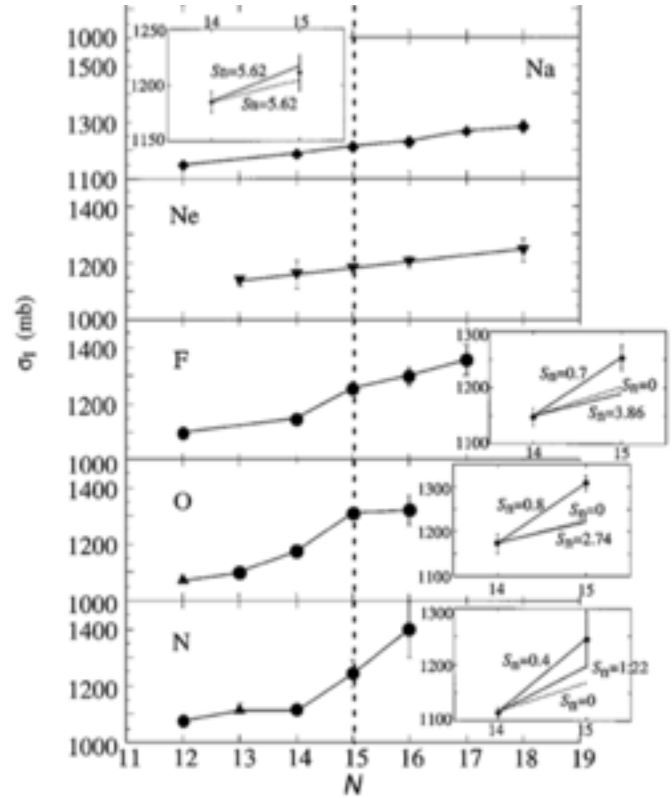
We have surveyed the neutron separation energies (S_n) and the interaction cross sections (σ_I) for the neutron-rich p-sd and the sd shell region. Very recently, both measurements reached up to the neutron drip line, or close to the drip line, for nuclei of $Z \leq 8$. A neutron-number dependence of S_n shows clear breaks at $N = 16$ near the neutron drip line ($T_Z \geq 3$), which shows the creation of a new magic number. A neutron-number dependence of σ_I shows a large increase of σ_I for $N = 15$, which supports the new magic number. The origin of the new magic number is also discussed.





Many dicoveries were by accident

- **Enjoy troubles in research.**
- **To find troubles you have to know what is expected.**
- **Good luck for your future.**