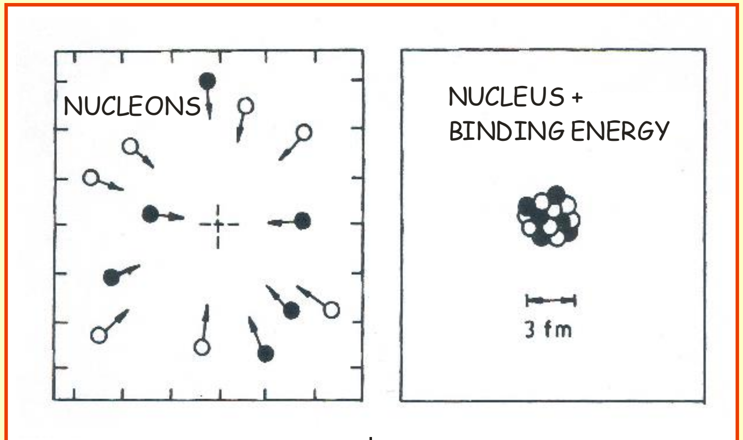
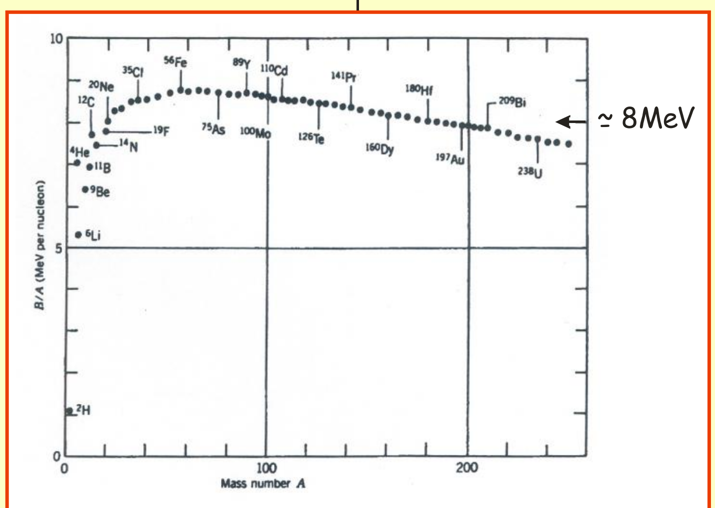
Structure of the atomic nucleus

Some basic facts about the atomic nucleus: a bit of history and unveiling the important degrees of freedom

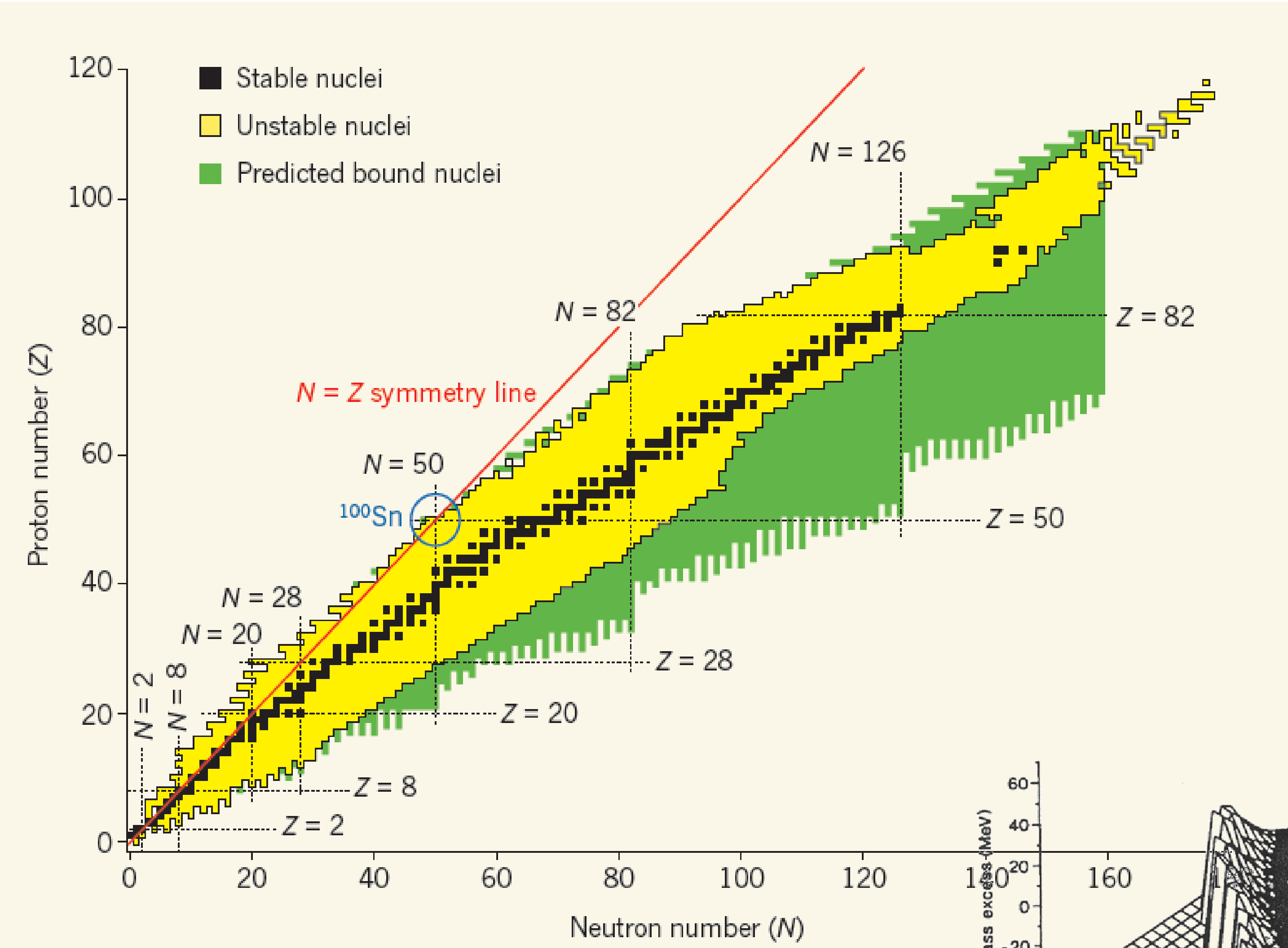
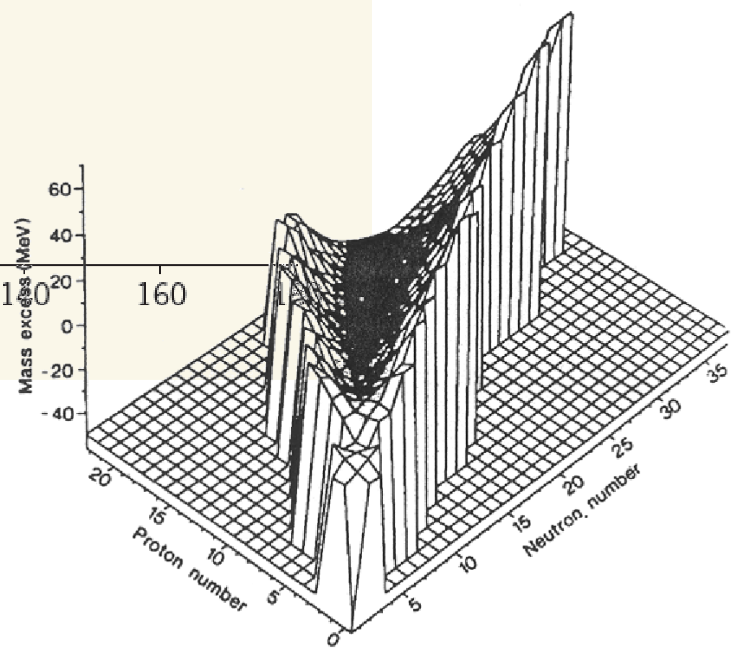
THE ATOMIC NUCLEUS AS A BOUND SYSTEM



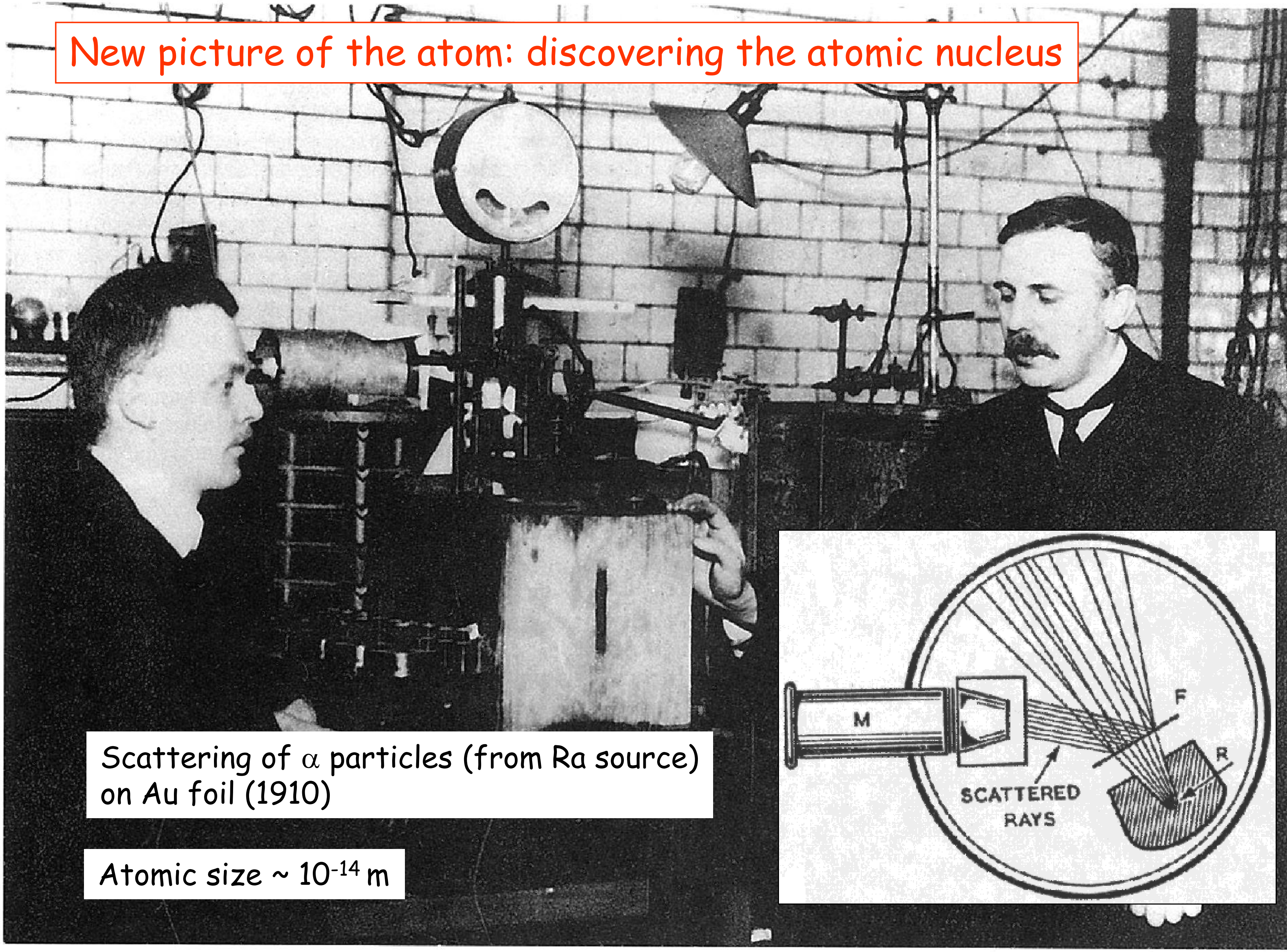
NUCLEAR BINDING ENERGY / NUCLEON



≃ 8MeV


Stable nuclei
Unstable nuclei
Predicted bound nuclei
N = Z symmetry line
N = 2
N = 8
N = 20
N = 28
N = 50
N = 82
N = 126
Z = 2
Z = 8
Z = 20
Z = 28
Z = 50
Z = 82
100Sn
Proton number (Z)
Neutron number (N)
0
20
40
60
80
100
120
140
160

Mass excess (MeV)
60
40
20
0
-20
-40
Proton number
20
15
10
5
0
Neutron number
5
10
15
20
25
30
35

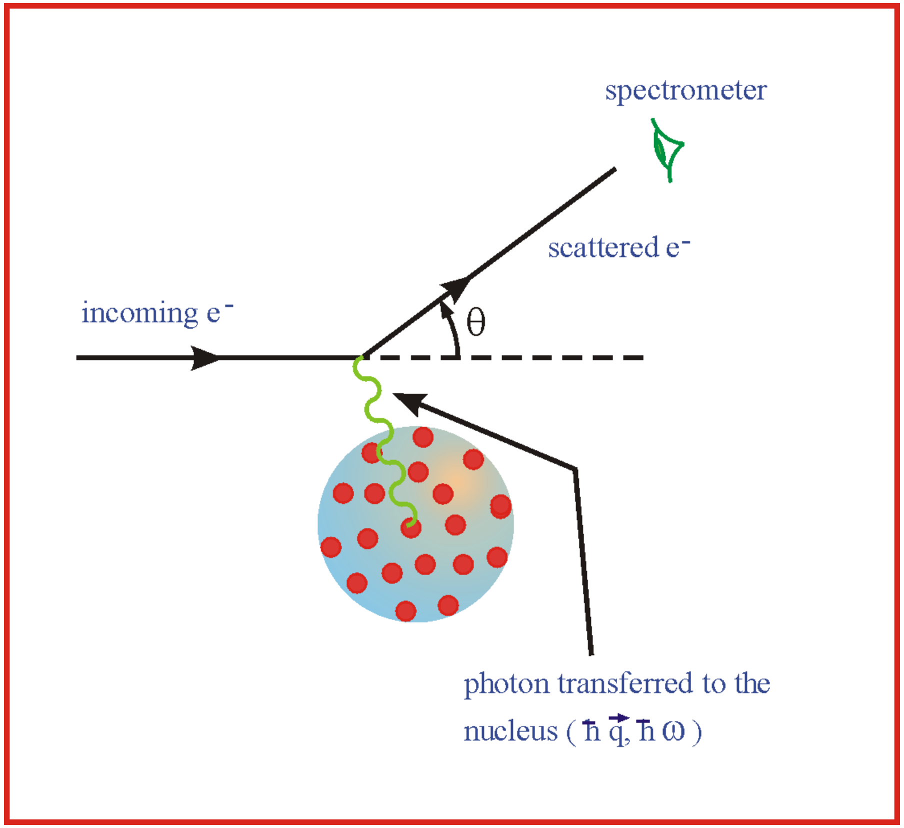
New picture of the atom: discovering the atomic nucleus



Scattering of α particles (from Ra source) on Au foil (1910)

Atomic size ~ 10^{-14} m

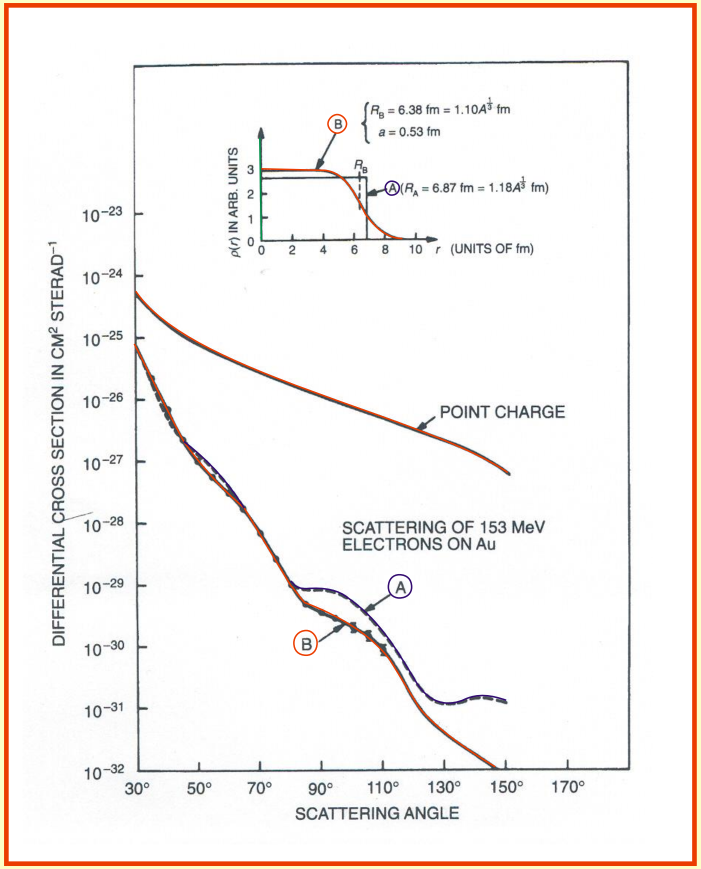
Observing the nucleus with increased resolving power and complementary probes

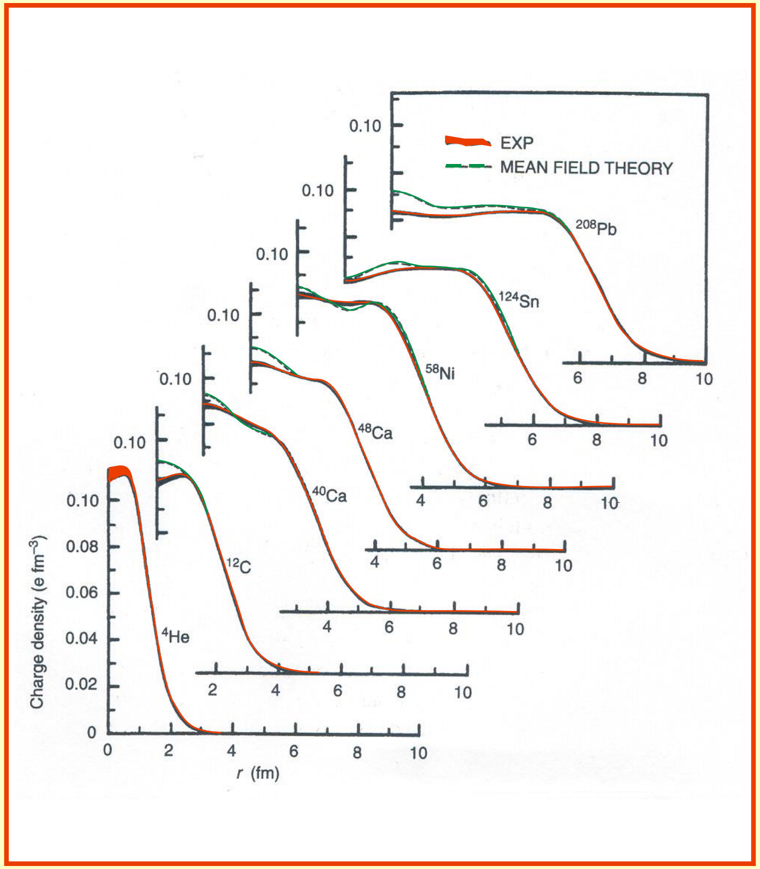


Using electrons, photons, and other strongly interacting particles: α,p,n,…, nuclei.

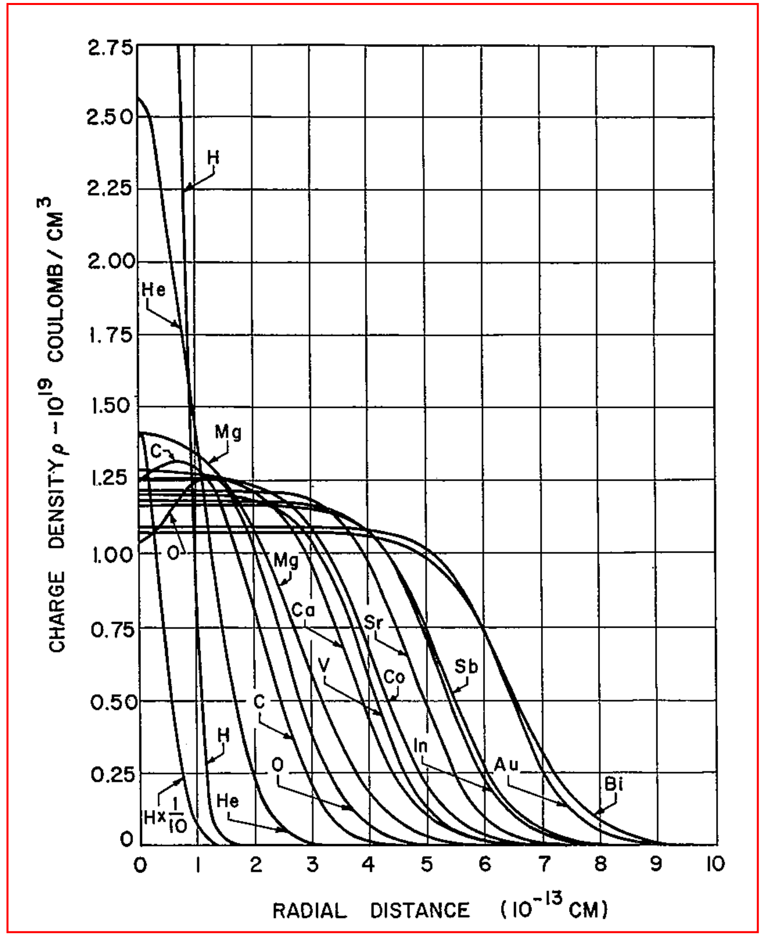
Transfer of energy and momentum: measure the nuclear response to these external probes

NUCLEAR CHARGE DENSITY



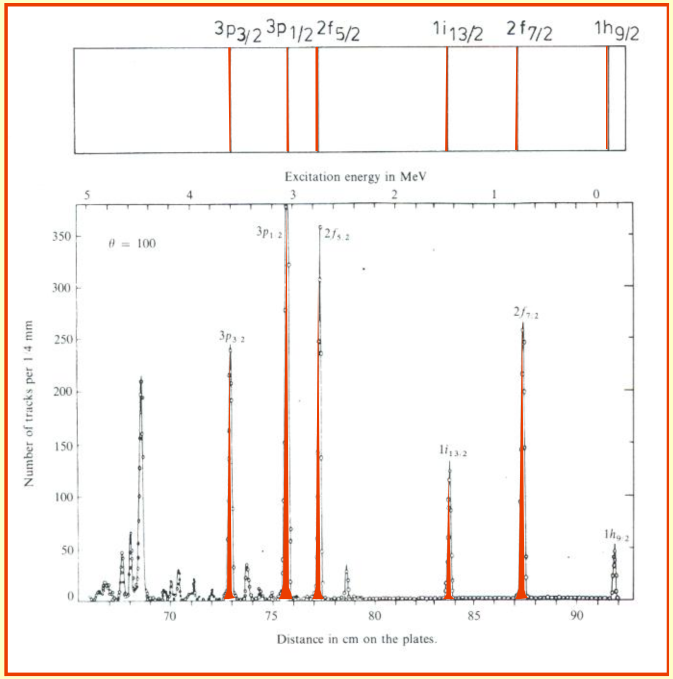


Robert Hofstadter – Nobel prize in physics 1961

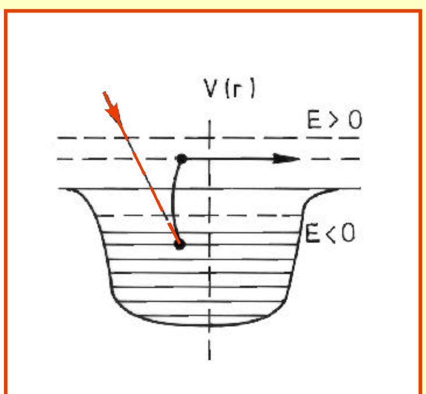


"For his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concering the structure of the nucleons" (work in the period 1953-1956 at Stanford-SLAC).

SINGLE-NUCLEON TRANSFER REACTIONS



$^{208}Pb(^{3}He,d)^{209}Bi$



Single-particle transfer reactions testing the single-particle structure of levels next to closed shell nuclei

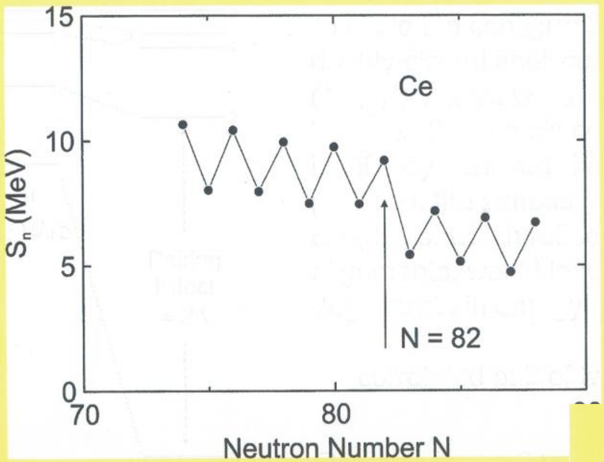
C. Ellegaard and B. Vedelsby, PL26B (1968), 155

Tandem at Niels Bohr Insitute

Deuteron spectrum measured at 85° and 110° in magnetic spectrograph

(i) Odd-even effect: mass of an odd-even nucleus is larger than the mean of adjacent two even-even nuclear masses → shows up in S_n and S_p for all nuclei.

Example: $S_n = BE(A,Z) - BE(A\text{-}1,Z)$ of Ce nuclei



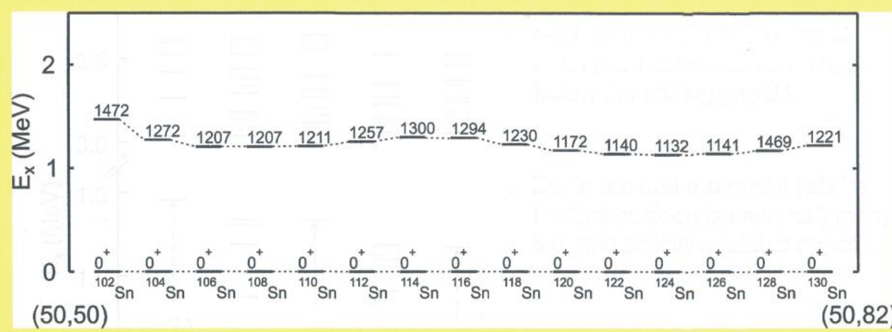
- Behavior points towards pair formation of nucleons.

Pairing of nucleons

Essential to describe odd-mass and even-even nuclei.

(iii) The excitation energy of the first excited 2^+ state in nuclei remains remarkably constant over large intervals of neutron (proton) numbers.

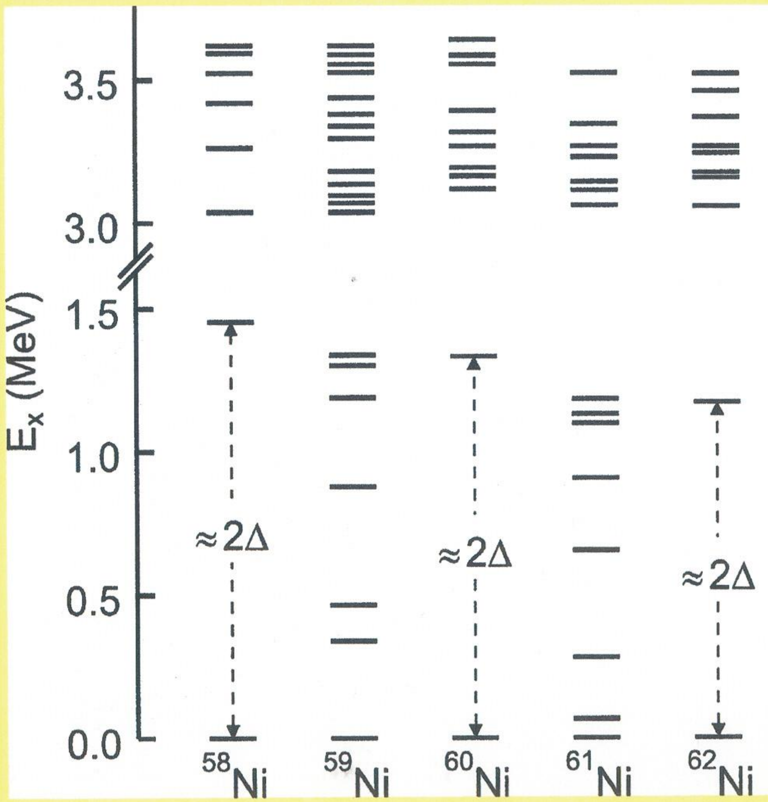
Example: 2^+_1 excitation energy in Sn nuclei



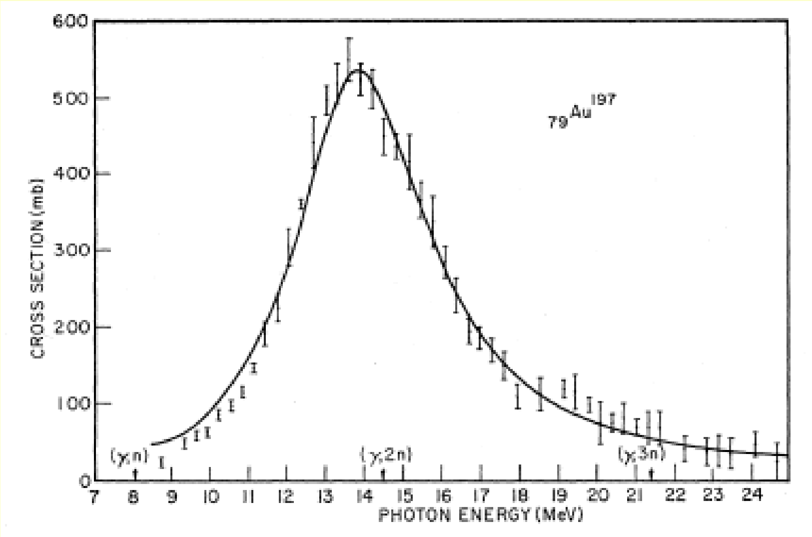
- These 2^+ states are not rotational states but are connected to a coherent pairing condensate.
- Pair breaking energy: $2\Delta \approx 2$ MeV

A.Bohr, B.Mottelson and D.Pines, PR110(1958),936

(iv) Energy gap: odd-even and even-odd nuclei (especially deformed nuclei) have energy spectra different from even-even nuclei.
Example: Ni isotopes



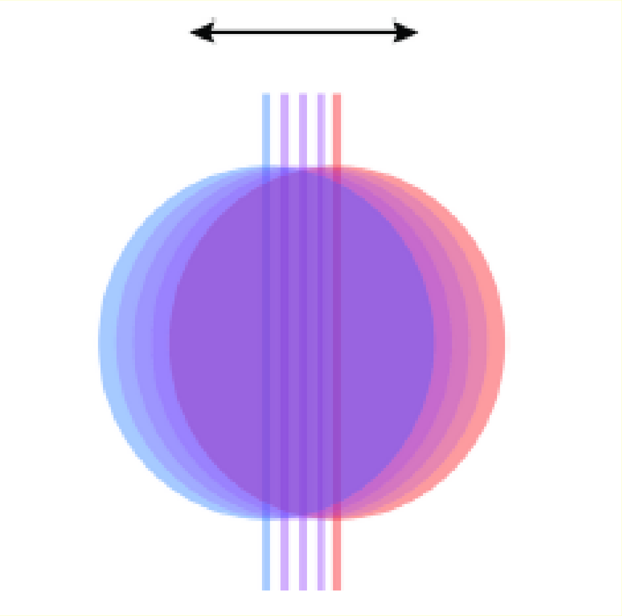
- e-e nuclei: only a few states at most (vibrations, rotations) appear below the pairing gap 2Δ.
- But in o-e and e-o nuclei (where the last nucleon is unpaired) many s.p. and collective states appear.
- Note: above the pair breaking energy 2Δ many excited states are possible → level density $\rho = \rho(\Delta)$



Photoneutron cross-sections on Au using monochromatic photons

Lawrence Radiation Lab. Livermore

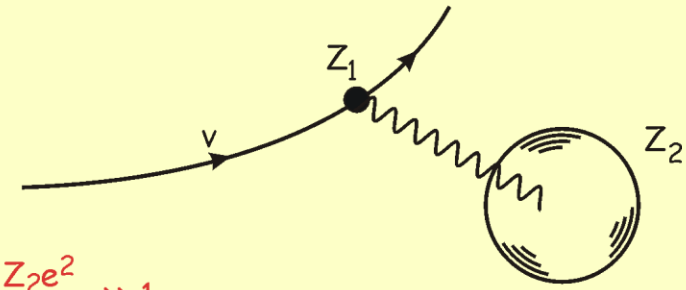
Fultz et al., PRC127 (1962),1273



Nuclear electric dipole vibrational mode

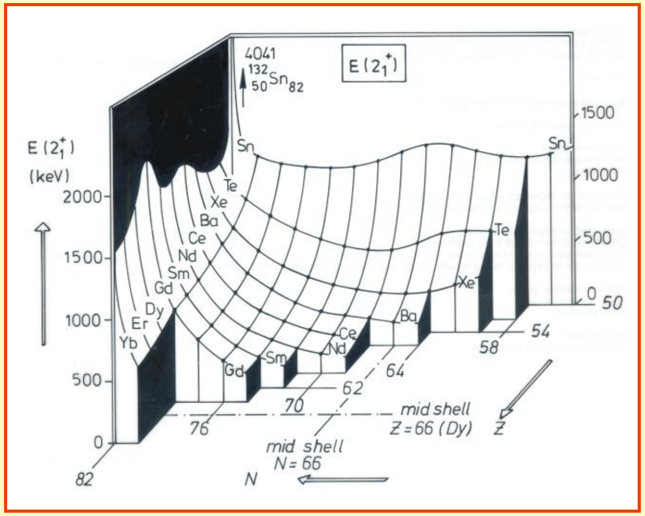
Experiments where target nucleus is 'excited' through the electric field of projectile

$\Rightarrow$ semi-classical calculation

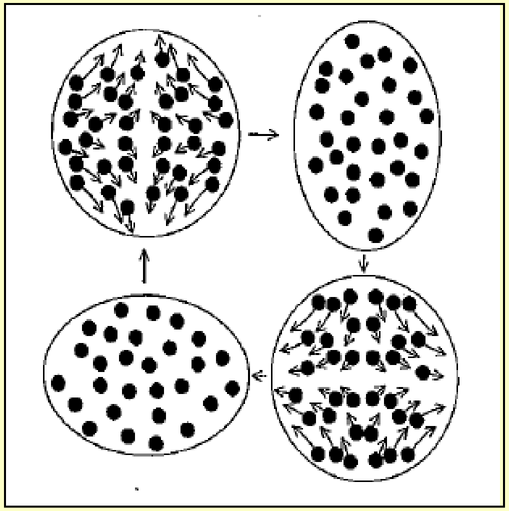


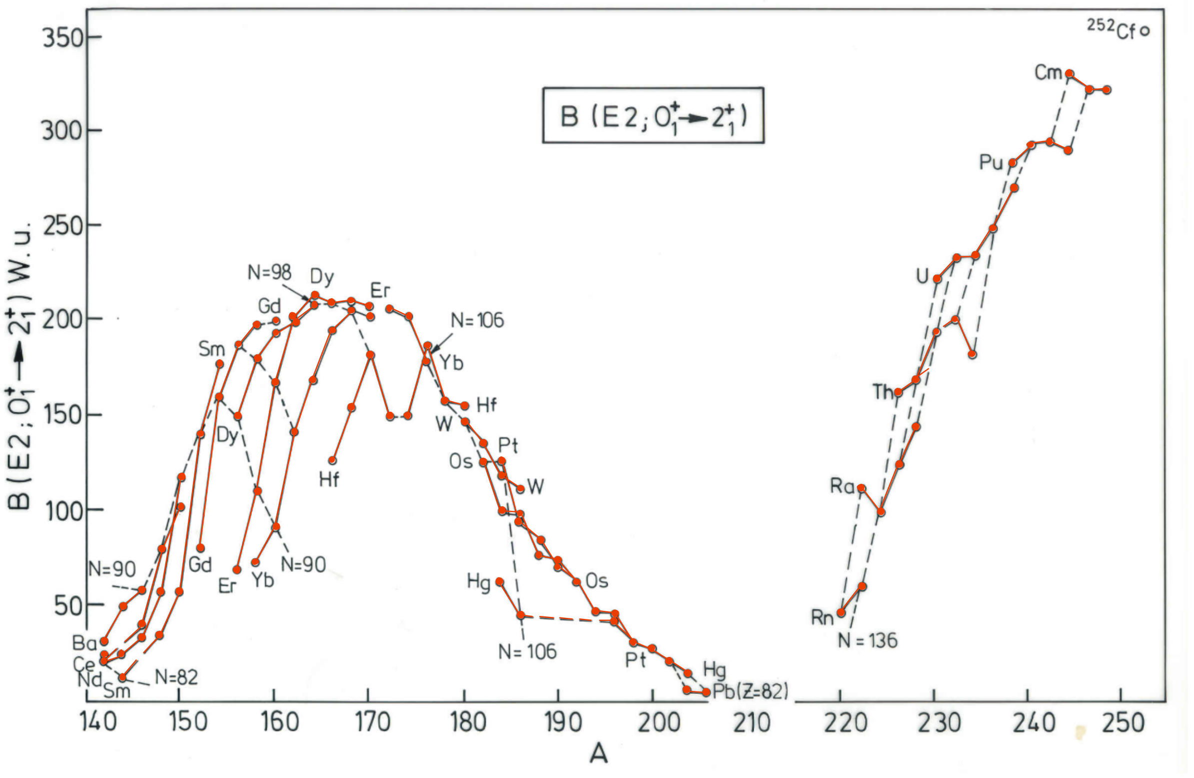
- $\frac{Z_1 Z_2 e^2}{\hbar v} \gg 1$
- $\frac{Z_1 Z_2 e^2}{\hbar v} \cdot \frac{\Delta E}{2E} \ll 1$ ΔE : targ. excit. energy; E : proj. kinetic energy

$\sigma_{EL} \propto B(EL; J_i \rightarrow J_f)$ E. M. transition probabilities

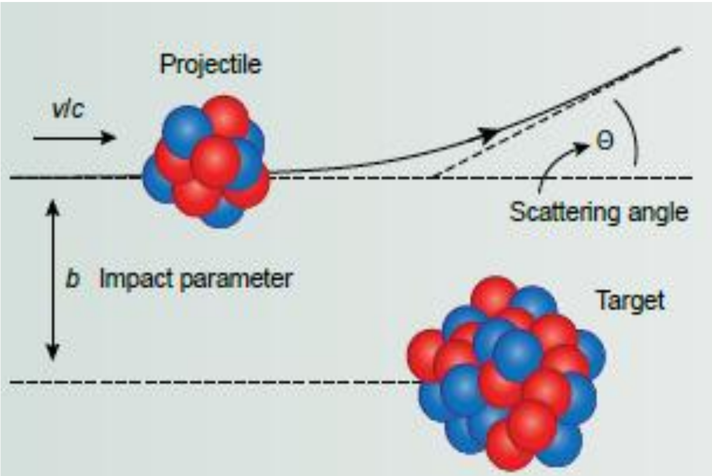


Coulomb excitation, lifetime data, inelastic scattering,..



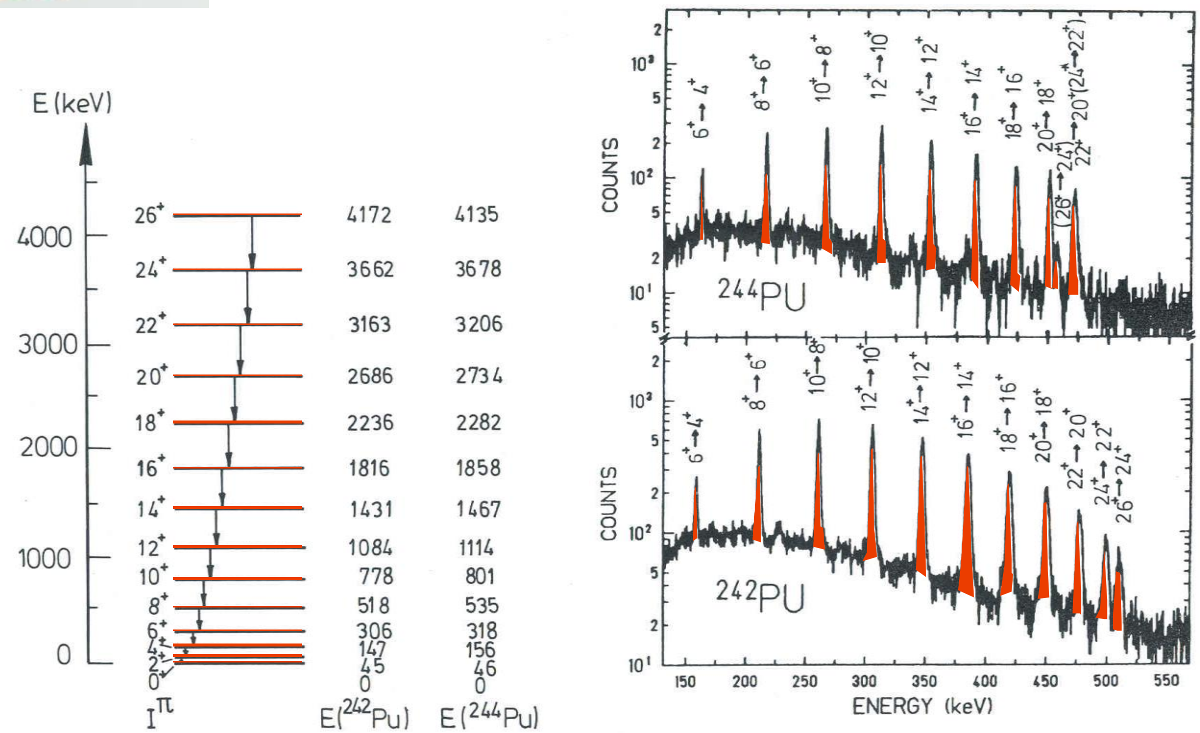


Nuclear collective quadrupole modes

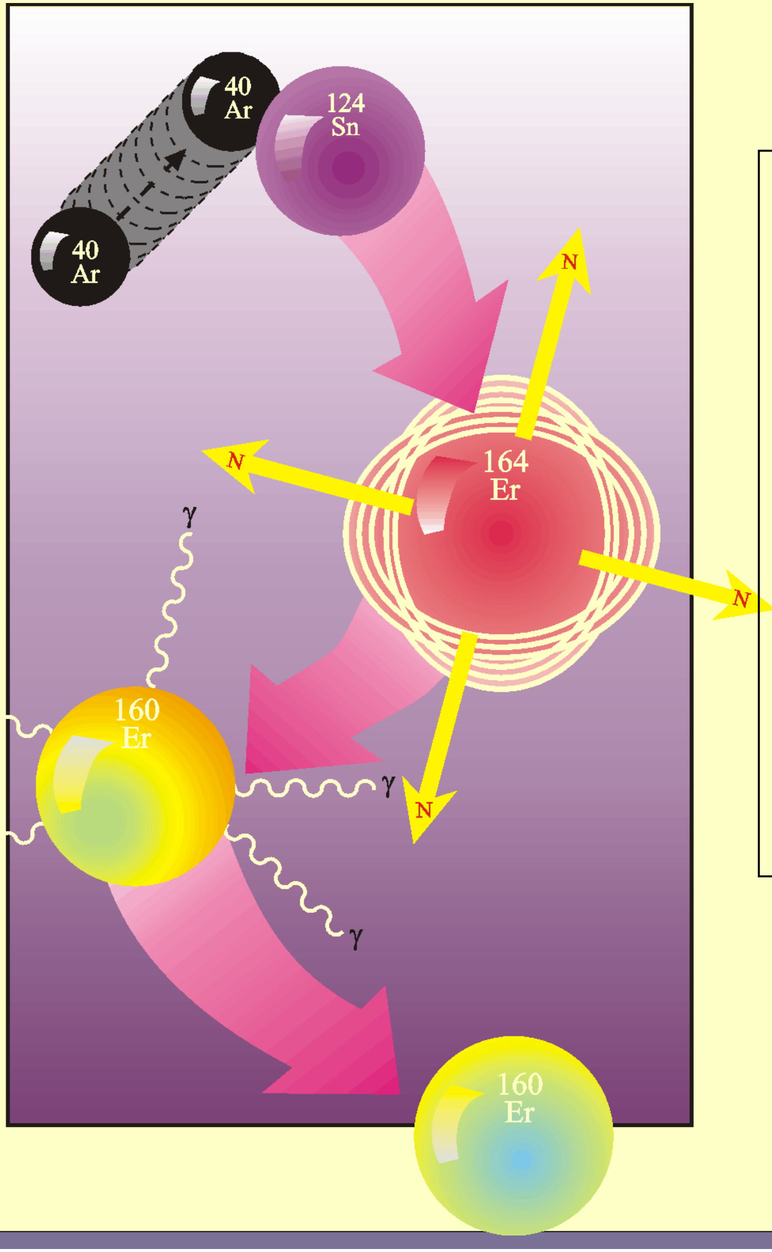


Observation of rotational bands following Coulomb excitation of $^{242,244}Pu$

Projectile: beam of ^{208}Pb



W. Spreng et al.,
PRL 51(1983),1522



Heavy-ion fusion-evaporation Reactions

^{40}Ar on ^{124}Sn forms the compound nucleus ^{164}Er in a state of rapid rotation.

Unbound: 4 neutrons emitted to form ^{160}Er which decays further with emission of γ rays down to ground state

- THERE EXISTS A RATHER CONSTANT NUCLEAR CHARGE AND MATTER DENSITY DISTRIBUTION $\rho_{ch}(r),\rho_m(r)$, WITH A SHARP RADIUS $R \sim r_0 A^{1/3}$
- ONE NUCLEON TRANSFER REACTIONS GIVE EVIDENCE FOR SINGLE-PARTICLE MOTION WITH STRONG SPIN-ORBIT SPLITTING AND LARGE SHELL GAPS

➡ Independent-particle motion near the Fermi level

- ONE NUCLEON VS. TWO NUCLEON SEPARATION; TWO-NUCLEON SPECTRA, SPECTRA IN SERIES OF ISOTOPES (ISOTONES)

➡ Superfluid (pairing) structure at low excitation energy

- COULOMB EXCITATION; SCATTERING OF d,α,p,...; HEAVY-ION FUSION-EVAPORATION REACTIONS.

➡ Presence of multipole (dipole,quadrupole) modes exhibiting vibrational, rotational patterns.

EMERGENCE OF EFFECTIVE DEGREES OF FREEDOM IN THE ATOMIC NUCLEUS

Theoretical concepts ensueing from the data set to describe the essential degrees of freedom

Maria Goeppert Mayer, J.Hans D. Jensen – 1949

"for their discoveries concerning nuclear shell studies" (1963)

Shell closure at Z=2,8,20,28,50,82,..
N=2,8,20,28,50,82,126,..

On Closed Shells in Nuclei. II

MARIA GOEPPERT MAYER
Argonne National Laboratory and Department of Physics, University of Chicago, Chicago, Illinois
February 4, 1949

THE spins and magnetic moments of the even-odd nuclei have been used by Feenberg[1,2] and Nordheim[3] to determine the angular momentum of the eigenfunction of the odd particle. The tabulations given by them indicate that spin orbit coupling favors the state of higher total angular momentum. If strong spin-orbit coupling, increasing with angular momentum, is assumed, a level assignment different from either Feenberg or Nordheim is obtained. This assignment encounters a very few contradictions with experimental facts and requires no major crossing of the levels from those of a square well potential. The magic numbers 50, 82, and 126 occur at the place of the spin-orbit splitting of levels of high angular momentum.

Phys.Rev.75,1969 (1949)

On the "Magic Numbers" in Nuclear Structure

OTTO HAXEL
Max Planck Institut, Göttingen
J. HANS D. JENSEN
Institut f. theor. Physik, Heidelberg
AND
HANS E. SUESS
Inst. f. phys. Chemie, Hamburg
April 18, 1949

A SIMPLE explanation of the "magic numbers" 14, 28, 50, 82, 126 follows at once from the oscillator model of the nucleus,[1] if one assumes that the spin-orbit coupling in the Yukawa field theory of nuclear forces leads to a strong splitting of a term with angular momentum l into two distinct terms $j=l\pm\frac{1}{2}$.

Phys.Rev.75,1766(1949)

Aage Bohr, Ben Mottelson and James Rainwater – 1950-1952

"for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection" (1975)

PHYSICAL REVIEW VOLUME 79, NUMBER 3 AUGUST 1, 1950

Nuclear Energy Level Argument for a Spheroidal Nuclear Model*

JAMES RAINWATER
Columbia University, New York, New York
(Received April 17, 1950)

Det Kongelige Danske Videnskabernes Selskab
Matematisk-fysiske Meddelelser, bind 27, no. 16.
Mat. Fys. Medd. Dan. Vid. Selsk. 27, no. 16 (1953)(ed. 2, 1957)

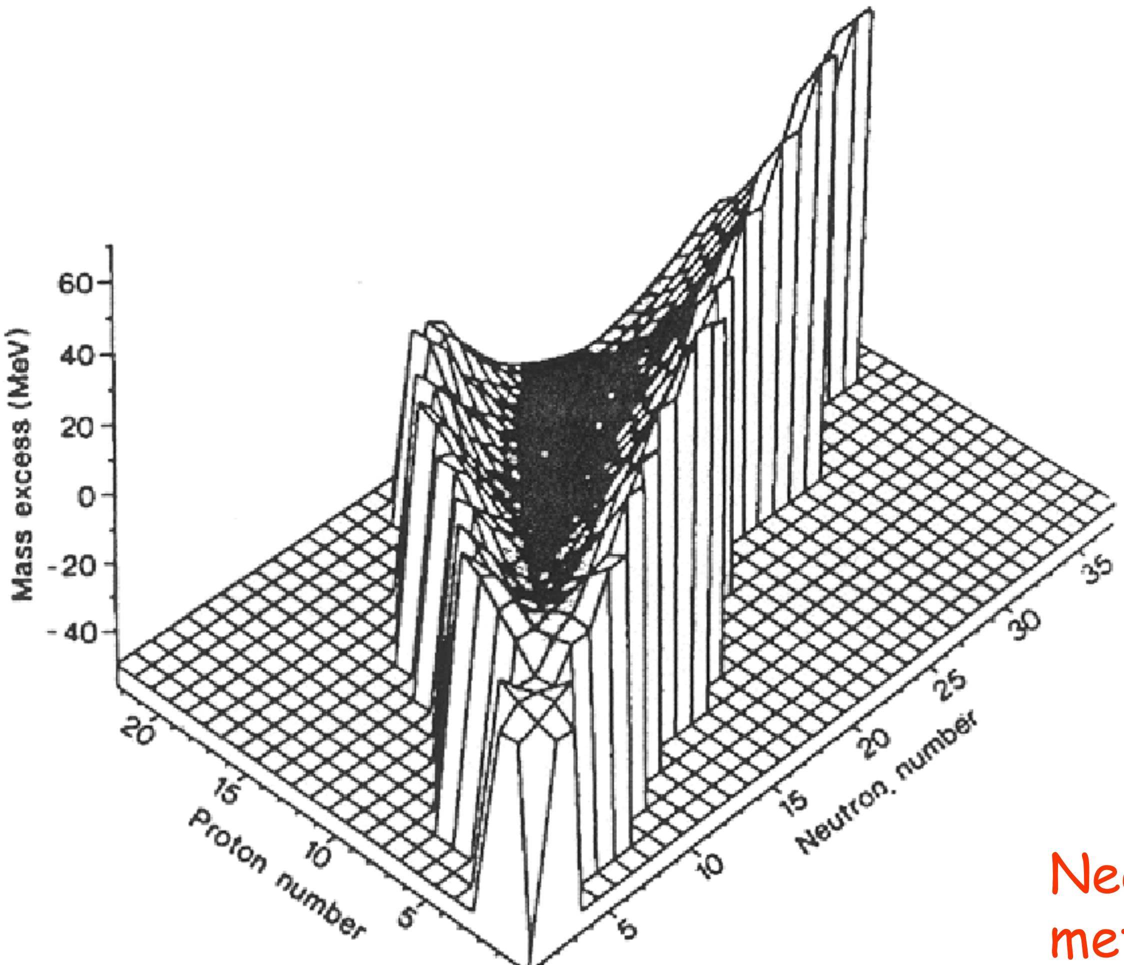
COLLECTIVE AND INDIVIDUAL-PARTICLE ASPECTS OF NUCLEAR STRUCTURE

BY

AAGE BOHR AND BEN R. MOTTELSON

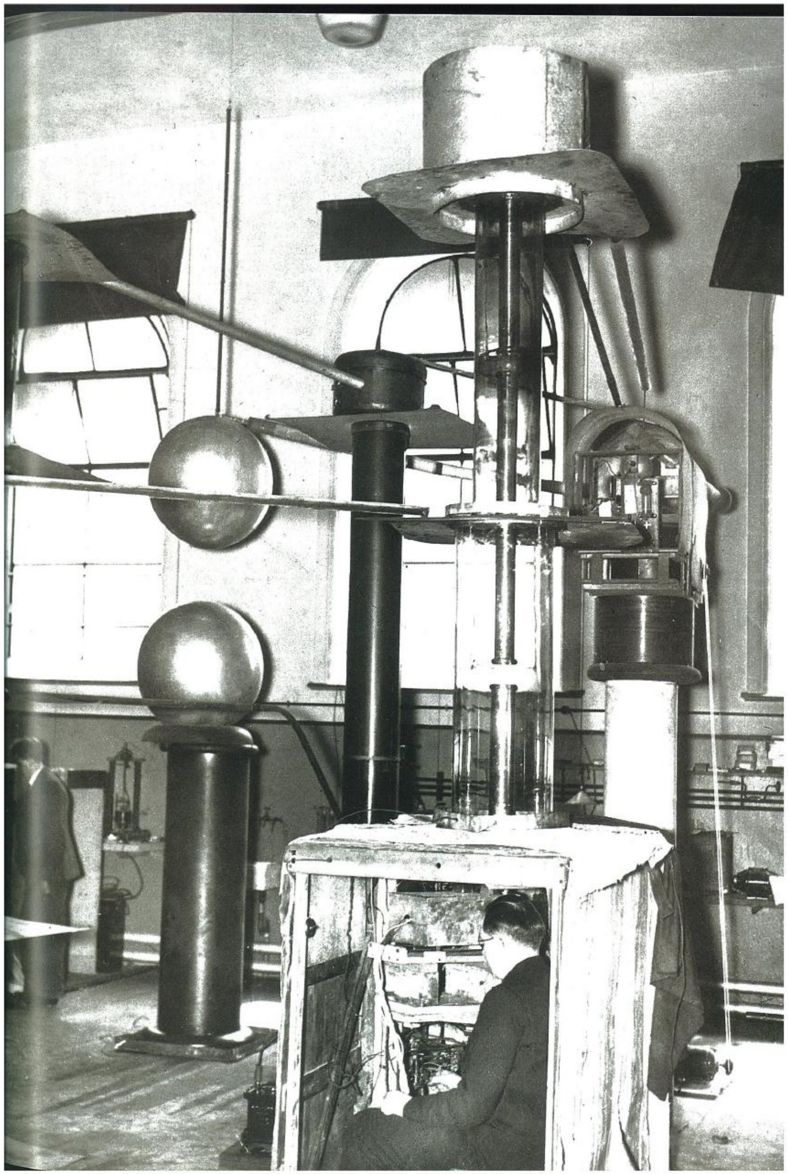
SECOND EDITION

Exploring the mass landscape beyond the region close to stability



Need for new experimental methods: using unstable beams

First accelerator: 800 keV protons at Cavendish (Cambridge)



E. Walton, E. Rutherford and J. Cockcroft (1932)

"Splitting the atom"

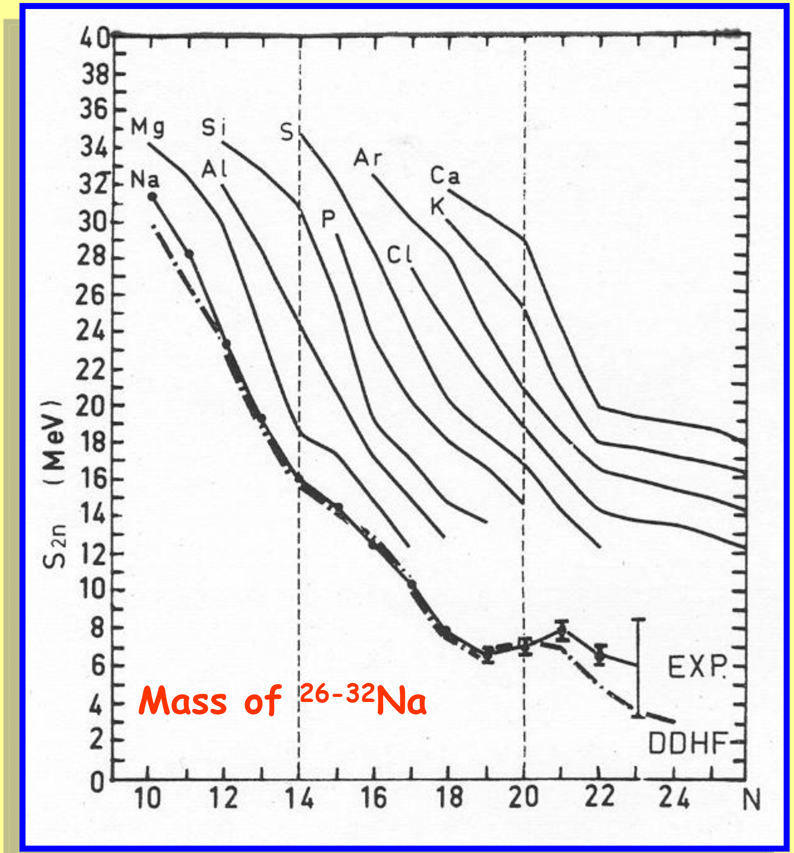
First reaction: $^{7}Li + p \rightarrow {}^{8}Be \rightarrow \alpha + \alpha$

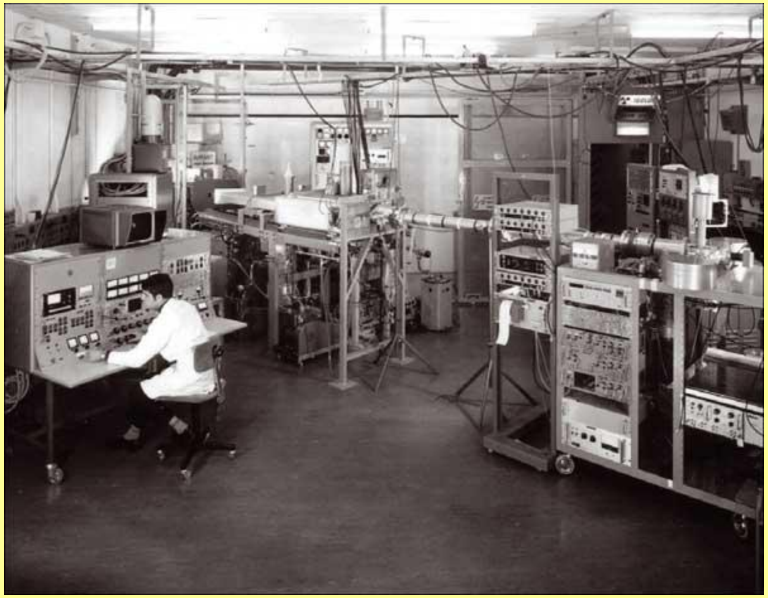
Eventually he came out, sat on a stool and said:
'*Those scintillations look mighty like alpha-particle ones. I should know an alpha-particle when I see one for I was in at the birth of the alpha-particle and I have been observing them ever since*'! (E.Walton)

The early ISOLDE separator beam line in 1967 at the SC at CERN

Na nuclei

Thibault et al., PRC 12 (1975)

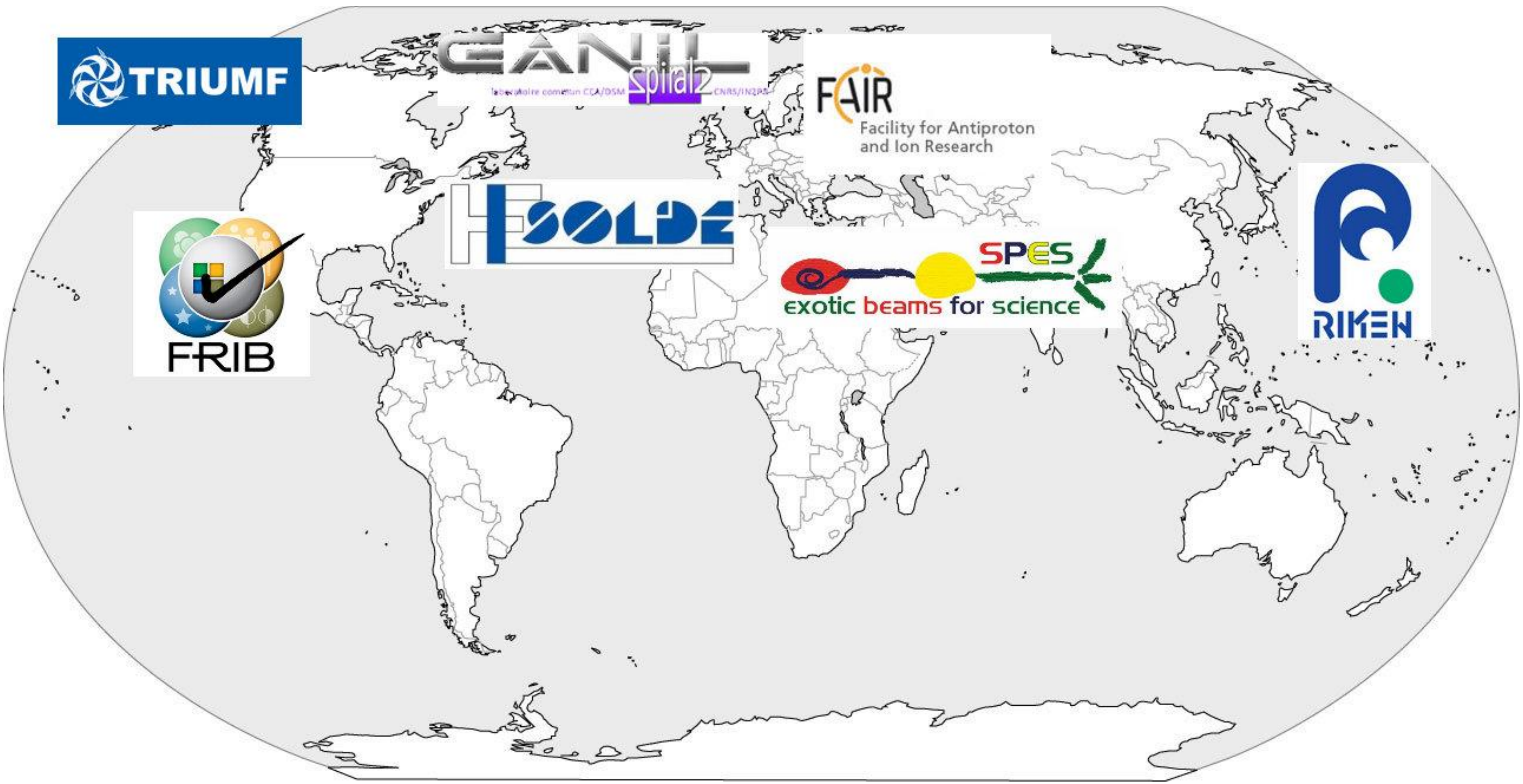




Experiments with unstable beams:

Direct mass measurements

..to the present beam-lines layout and research with postaccelerated beams at Mini-ball @ REX-ISOLDE -2010-2012


TRIUMF
GANIL
spiral2
FAIR
Facility for Antiproton and Ion Research
ISOLDE
SPES
exotic beams for science
FRIB
RIKEN

In order to make steady progress in exploring the atomic nucleus and its structure, starting from the interplay of many nucleons (protons,neutrons) interacting with an « in-medium » effective nucleon-nucleon interaction.

Need for developments on the side of both accelerators, detection systems and analyzing algorithms.

Discoveries will follow as shown many times in the past.

The atomic nucleus: a bound system of interacting nucleons

1. Nuclear forces and very light nuclei

2. The nuclear shell model: from independent particle motion towards modern applications

3. Nuclear deformation and collective motion: phenomenological models and self-consistent mean-field theory