

*Viaggio al  
centro del  
nucleo*

Irene Zanon

13/02/2023

Giornata internazionale  
delle donne nella scienza



# L'inizio del viaggio



Alcune dovute  
premesse...

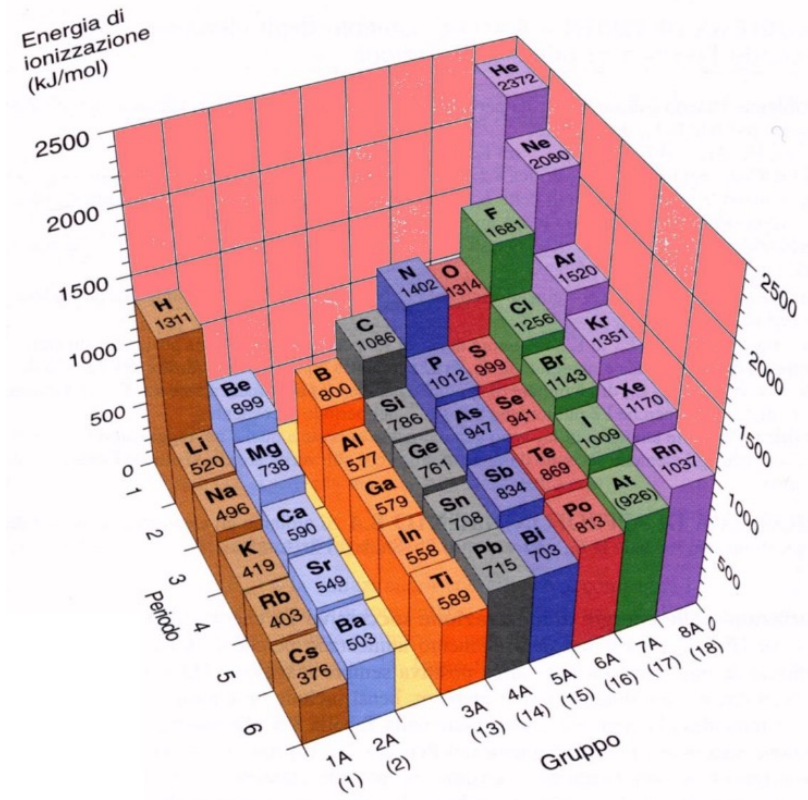
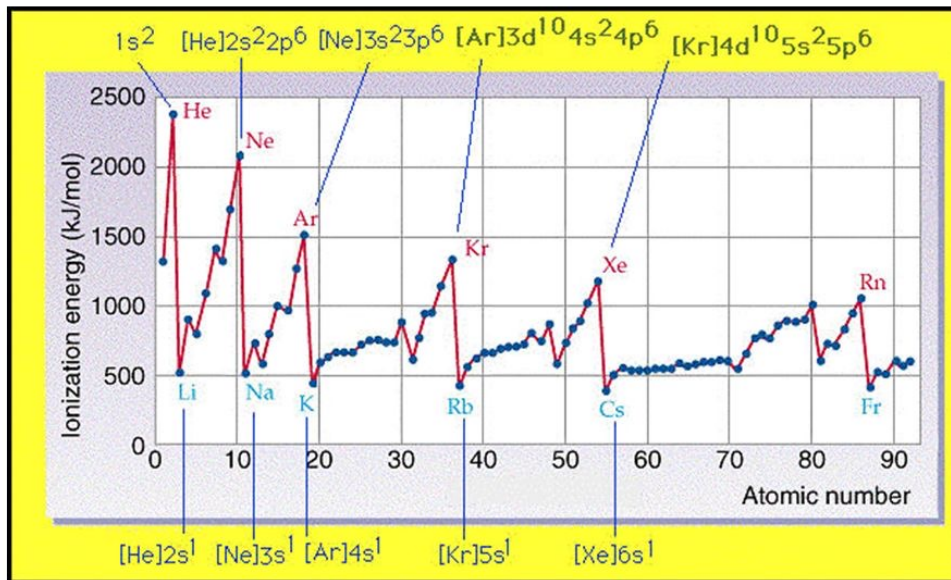
# Periodic Table of the Elements

| 1<br>IA<br>1A               |                            | 2<br>IIA<br>2A              |                               |                           |                            |                              |                            |                              |                            |                              |                                 |                                |                               | 13<br>IIIA<br>3A                | 14<br>IVA<br>4A             | 15<br>VA<br>5A                 | 16<br>VIA<br>6A             | 17<br>VIIA<br>7A               | VIIIA<br>8A<br>8A             |                                |                               |                               |                                |                                 |                            |                              |                              |                              |                           |                               |                                |                               |                                |                               |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
|-----------------------------|----------------------------|-----------------------------|-------------------------------|---------------------------|----------------------------|------------------------------|----------------------------|------------------------------|----------------------------|------------------------------|---------------------------------|--------------------------------|-------------------------------|---------------------------------|-----------------------------|--------------------------------|-----------------------------|--------------------------------|-------------------------------|--------------------------------|-------------------------------|-------------------------------|--------------------------------|---------------------------------|----------------------------|------------------------------|------------------------------|------------------------------|---------------------------|-------------------------------|--------------------------------|-------------------------------|--------------------------------|-------------------------------|------------------------------|--------------------------------|--------------------------------|------------------------------|---------------------------------|-------------------------------|---------------------------------|----------------------------------|---------------------------------|--------------------------------|---------------------------------|-------------------------------|--------------------------------|-------------------------------|---------------------------|---------------------------------|--------------------------------|------------------------------|-----------------------------|-------------------------------|-------------------------------|----------------------------|-------------------------------|---------------------------------|-------------------------------|--------------------------------|------------------------------|-------------------------------|--------------------------------|-----------------------------|-------------------------------|---------------------------------|---------------------------|--------------------------------|-----------------------------------|---------------------------------|------------------------------|---------------------------------|-------------------------------|---------------------------|-------------------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|----------------------------------|------------------------------------|-----------------------------------|-----------------------------------|------------------------------------|---------------------------------|--------------------------------------|-----------------------------------|--------------------------------------|-------------------------------------|
| 3                           |                            | 4                           |                               | 3<br>IIIB<br>3B           |                            |                              | 4<br>IVB<br>4B             |                              | 5<br>VB<br>5B              |                              | 6<br>VIB<br>6B                  |                                | 7<br>VIIB<br>7B               |                                 | 8<br>VIII<br>8              |                                | 9<br>VIII<br>8              |                                | 10<br>VIII<br>8               |                                | 11<br>IB<br>1B                |                               | 12<br>IIB<br>2B                |                                 | 5                          |                              | 6                            |                              | 7                         |                               | 8                              |                               | 9                              |                               | 10                           |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 11                          |                            | 12                          |                               |                           |                            |                              |                            |                              |                            |                              |                                 |                                |                               |                                 |                             |                                |                             |                                |                               |                                |                               |                               |                                |                                 | 13                         |                              | 14                           |                              | 15                        |                               | 16                             |                               | 17                             |                               | 18                           |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 19                          |                            | 20                          |                               | 21                        |                            | 22                           |                            | 23                           |                            | 24                           |                                 | 25                             |                               | 26                              |                             | 27                             |                             | 28                             |                               | 29                             |                               | 30                            |                                | 31                              |                            | 32                           |                              | 33                           |                           | 34                            |                                | 35                            |                                | 36                            |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 37                          |                            | 38                          |                               | 39                        |                            | 40                           |                            | 41                           |                            | 42                           |                                 | 43                             |                               | 44                              |                             | 45                             |                             | 46                             |                               | 47                             |                               | 48                            |                                | 49                              |                            | 50                           |                              | 51                           |                           | 52                            |                                | 53                            |                                | 54                            |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 55                          |                            | 56                          |                               | 57-71                     |                            | 72                           |                            | 73                           |                            | 74                           |                                 | 75                             |                               | 76                              |                             | 77                             |                             | 78                             |                               | 79                             |                               | 80                            |                                | 81                              |                            | 82                           |                              | 83                           |                           | 84                            |                                | 85                            |                                | 86                            |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 87                          |                            | 88                          |                               | 89-103                    |                            | 104                          |                            | 105                          |                            | 106                          |                                 | 107                            |                               | 108                             |                             | 109                            |                             | 110                            |                               | 111                            |                               | 112                           |                                | 113                             |                            | 114                          |                              | 115                          |                           | 116                           |                                | 117                           |                                | 118                           |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| Lanthanide Series           |                            | 57                          |                               | 58                        |                            | 59                           |                            | 60                           |                            | 61                           |                                 | 62                             |                               | 63                              |                             | 64                             |                             | 65                             |                               | 66                             |                               | 67                            |                                | 68                              |                            | 69                           |                              | 70                           |                           | 71                            |                                |                               |                                |                               |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| Actinide Series             |                            | 89                          |                               | 90                        |                            | 91                           |                            | 92                           |                            | 93                           |                                 | 94                             |                               | 95                              |                             | 96                             |                             | 97                             |                               | 98                             |                               | 99                            |                                | 100                             |                            | 101                          |                              | 102                          |                           | 103                           |                                |                               |                                |                               |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| Alkali Metal                |                            | Alkaline Earth              |                               | Transition Metal          |                            | Basic Metal                  |                            | Semimetal                    |                            | Nonmetal                     |                                 | Halogen                        |                               | Noble Gas                       |                             | Lanthanide                     |                             | Actinide                       |                               |                                |                               |                               |                                |                                 |                            |                              |                              |                              |                           |                               |                                |                               |                                |                               |                              |                                |                                |                              |                                 |                               |                                 |                                  |                                 |                                |                                 |                               |                                |                               |                           |                                 |                                |                              |                             |                               |                               |                            |                               |                                 |                               |                                |                              |                               |                                |                             |                               |                                 |                           |                                |                                   |                                 |                              |                                 |                               |                           |                                     |                               |                                  |                               |                               |                                  |                                    |                                   |                                   |                                    |                                 |                                      |                                   |                                      |                                     |
| 1<br>H<br>Hydrogen<br>1.008 | 2<br>He<br>Helium<br>4.003 | 3<br>Li<br>Lithium<br>6.941 | 4<br>Be<br>Beryllium<br>9.012 | 5<br>B<br>Boron<br>10.811 | 6<br>C<br>Carbon<br>12.011 | 7<br>N<br>Nitrogen<br>14.007 | 8<br>O<br>Oxygen<br>15.999 | 9<br>F<br>Fluorine<br>18.998 | 10<br>Ne<br>Neon<br>20.180 | 11<br>Na<br>Sodium<br>22.990 | 12<br>Mg<br>Magnesium<br>24.305 | 13<br>Al<br>Aluminum<br>26.982 | 14<br>Si<br>Silicon<br>28.086 | 15<br>P<br>Phosphorus<br>30.974 | 16<br>S<br>Sulfur<br>32.066 | 17<br>Cl<br>Chlorine<br>35.453 | 18<br>Ar<br>Argon<br>39.948 | 19<br>K<br>Potassium<br>39.098 | 20<br>Ca<br>Calcium<br>40.078 | 21<br>Sc<br>Scandium<br>44.956 | 22<br>Ti<br>Titanium<br>47.88 | 23<br>V<br>Vanadium<br>50.942 | 24<br>Cr<br>Chromium<br>51.996 | 25<br>Mn<br>Manganese<br>54.938 | 26<br>Fe<br>Iron<br>55.845 | 27<br>Co<br>Cobalt<br>58.933 | 28<br>Ni<br>Nickel<br>58.693 | 29<br>Cu<br>Copper<br>63.546 | 30<br>Zn<br>Zinc<br>65.39 | 31<br>Ga<br>Gallium<br>69.723 | 32<br>Ge<br>Germanium<br>72.61 | 33<br>As<br>Arsenic<br>74.922 | 34<br>Se<br>Selenium<br>78.972 | 35<br>Br<br>Bromine<br>79.904 | 36<br>Kr<br>Krypton<br>83.80 | 37<br>Rb<br>Rubidium<br>84.468 | 38<br>Sr<br>Strontium<br>87.62 | 39<br>Y<br>Yttrium<br>88.906 | 40<br>Zr<br>Zirconium<br>91.224 | 41<br>Nb<br>Niobium<br>92.906 | 42<br>Mo<br>Molybdenum<br>95.95 | 43<br>Tc<br>Technetium<br>98.907 | 44<br>Ru<br>Ruthenium<br>101.07 | 45<br>Rh<br>Rhodium<br>102.906 | 46<br>Pd<br>Palladium<br>106.42 | 47<br>Ag<br>Silver<br>107.868 | 48<br>Cd<br>Cadmium<br>112.411 | 49<br>In<br>Indium<br>114.818 | 50<br>Sn<br>Tin<br>118.71 | 51<br>Sb<br>Antimony<br>121.760 | 52<br>Te<br>Tellurium<br>127.6 | 53<br>I<br>Iodine<br>126.904 | 54<br>Xe<br>Xenon<br>131.29 | 55<br>Cs<br>Cesium<br>132.905 | 56<br>Ba<br>Barium<br>137.327 | 57-71<br>Lanthanide Series | 72<br>Hf<br>Hafnium<br>178.49 | 73<br>Ta<br>Tantalum<br>180.948 | 74<br>W<br>Tungsten<br>183.85 | 75<br>Re<br>Rhenium<br>186.207 | 76<br>Os<br>Osmium<br>190.23 | 77<br>Ir<br>Iridium<br>192.22 | 78<br>Pt<br>Platinum<br>195.08 | 79<br>Au<br>Gold<br>196.967 | 80<br>Hg<br>Mercury<br>200.59 | 81<br>Tl<br>Thallium<br>204.383 | 82<br>Pb<br>Lead<br>207.2 | 83<br>Bi<br>Bismuth<br>208.980 | 84<br>Po<br>Polonium<br>[208.982] | 85<br>At<br>Astatine<br>209.987 | 86<br>Rn<br>Radon<br>222.018 | 87<br>Fr<br>Francium<br>223.020 | 88<br>Ra<br>Radium<br>226.025 | 89-103<br>Actinide Series | 104<br>Rf<br>Rutherfordium<br>[261] | 105<br>Db<br>Dubnium<br>[262] | 106<br>Sg<br>Seaborgium<br>[266] | 107<br>Bh<br>Bohrium<br>[264] | 108<br>Hs<br>Hassium<br>[269] | 109<br>Mt<br>Meitnerium<br>[268] | 110<br>Ds<br>Darmstadtium<br>[269] | 111<br>Rg<br>Roentgenium<br>[272] | 112<br>Cn<br>Copernicium<br>[277] | 113<br>Uut<br>Ununtrium<br>unknown | 114<br>Fl<br>Flerovium<br>[289] | 115<br>Uup<br>Ununpentium<br>unknown | 116<br>Lv<br>Livermorium<br>[298] | 117<br>Uus<br>Ununseptium<br>unknown | 118<br>Uuo<br>Ununoctium<br>unknown |



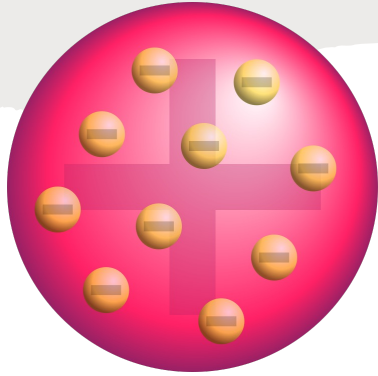
# La struttura dell'atomo

La periodicità è data da alcune proprietà dell'atomo che si ripresentano in modo simile per alcune classi di elementi.



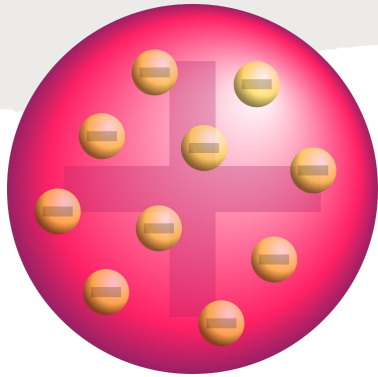
Energia di prima ionizzazione

# I modelli atomici



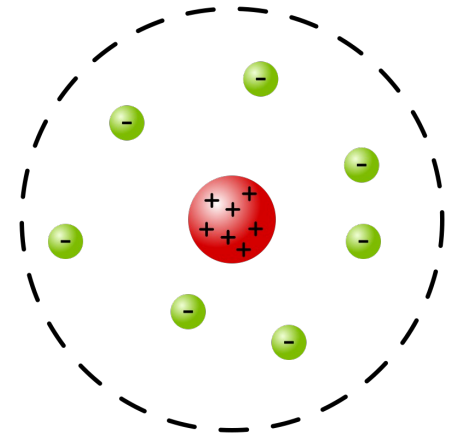
Modello di Thomson  
(1904)

# I modelli atomici

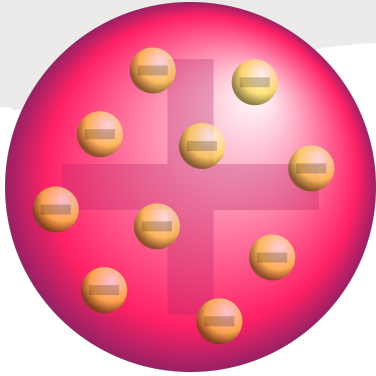


Modello di Thomson  
(1904)

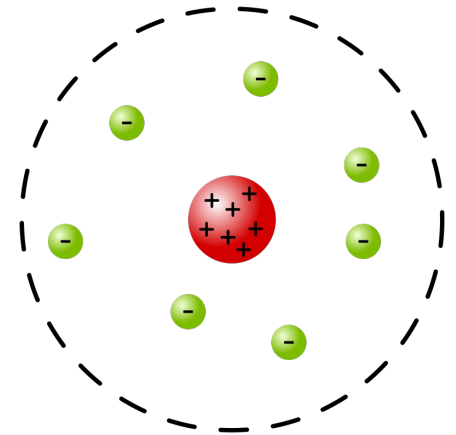
Modello di Rutherford  
(1911)



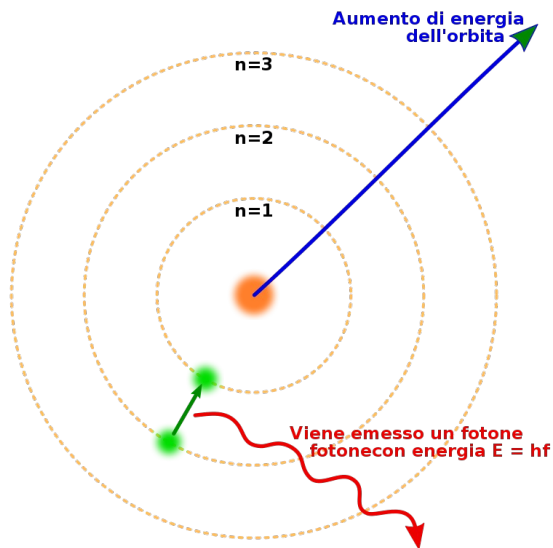
# I modelli atomici



Modello di Thomson  
(1904)



Modello di Rutherford  
(1911)

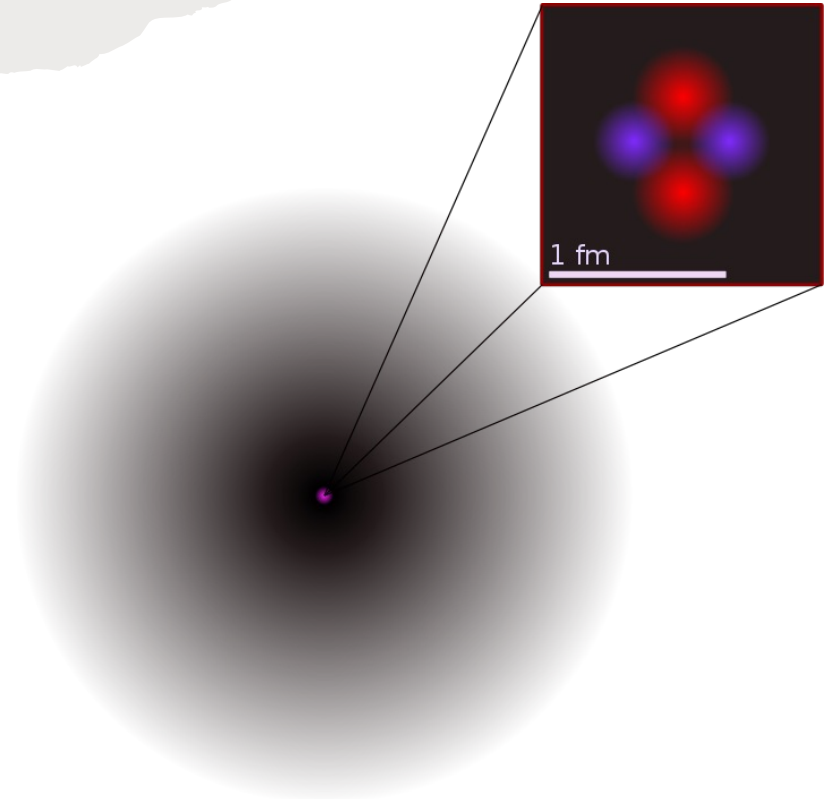


Modello di Bohr-Sommerfeld  
(1913-1916)

# Da orbita ad orbitale

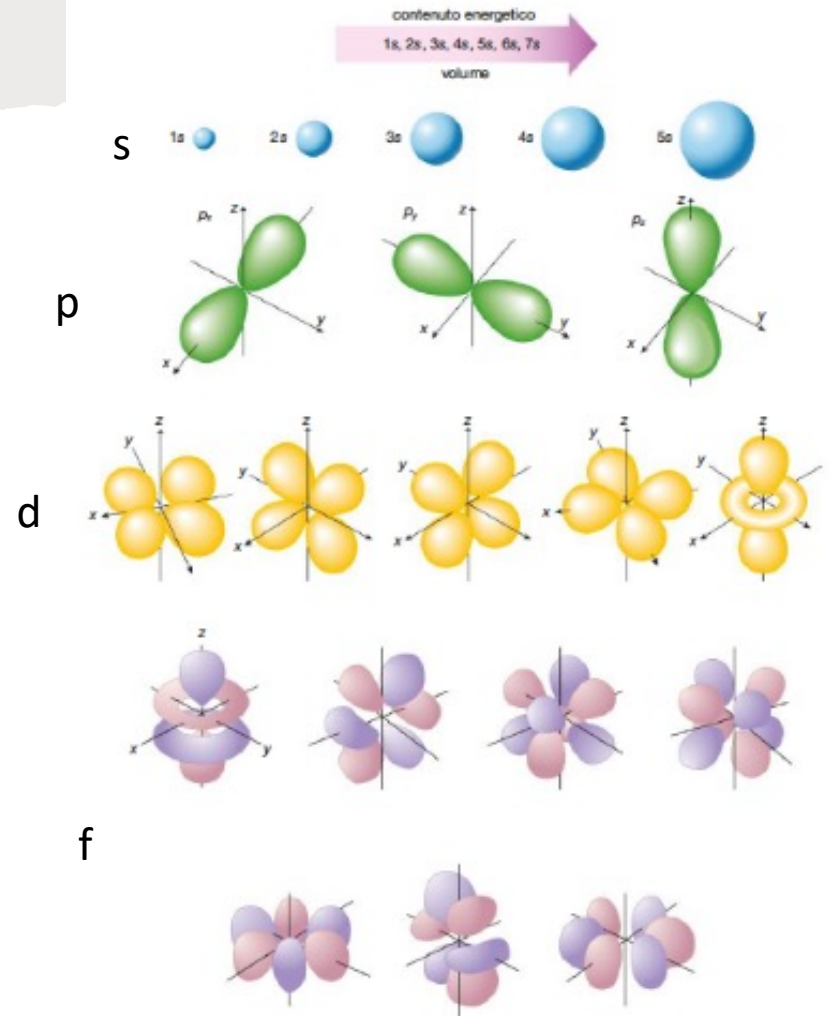
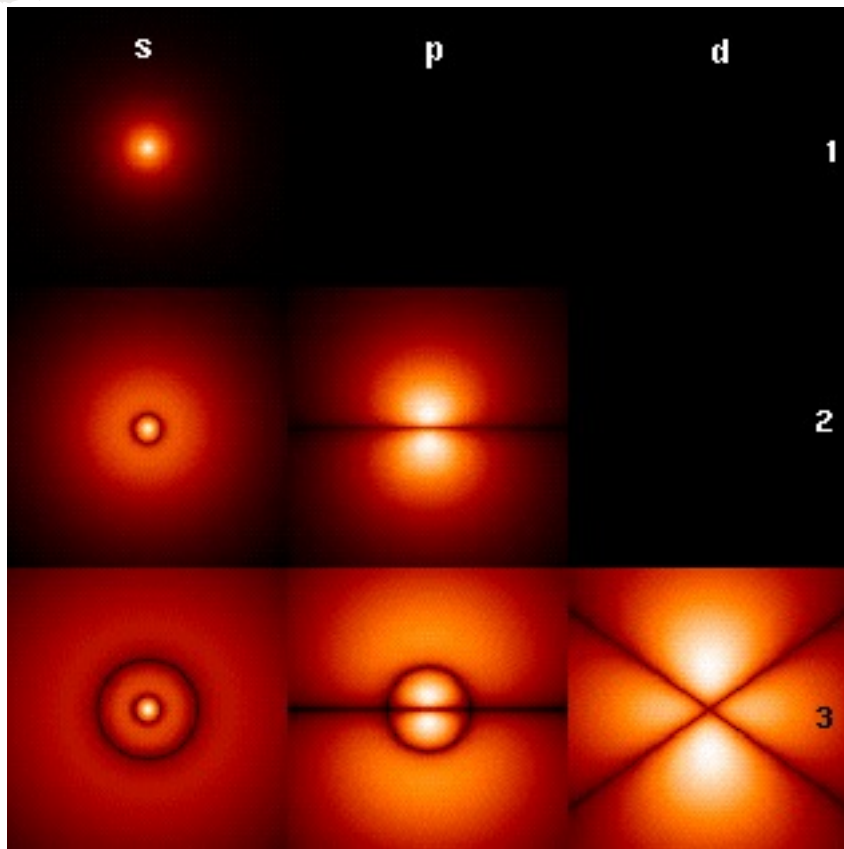
- La descrizione di Bohr-Sommerfeld funziona bene solo per l'atomo di H ma non per elementi più complessi.
- Il modello si basa su assunti deterministici: si passa ad un modello probabilistico;
- Si abbandona il concetto di orbita a favore dell'orbitale;
- L'orbitale è determinato da tre numeri quantici:  $n$ ,  $\ell$  e  $m$  (energia, forma e orientamento)
- Numero di spin ( $+\frac{1}{2}$  o  $-\frac{1}{2}$ )

1 Å = 100 pm



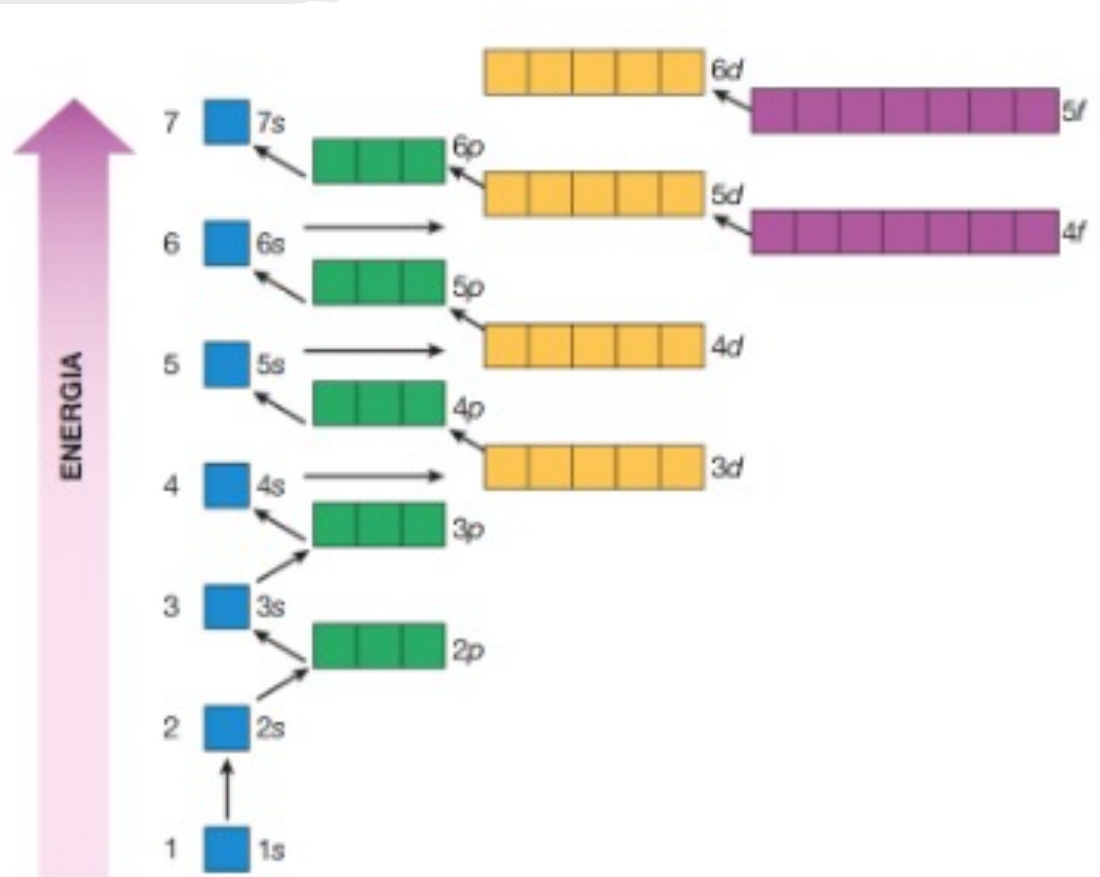


# Gli orbitali atomici



# Gli orbitali atomici

- $n = 1, 2, 3\dots$
- $\ell \geq n-1 = 0, 1, 2\dots$ 
  - $s = 0$
  - $p = 1$
  - $d = 2$
  - $f = 3\dots$
- $-\ell \leq m \leq +\ell$
- $s = \pm \frac{1}{2}$

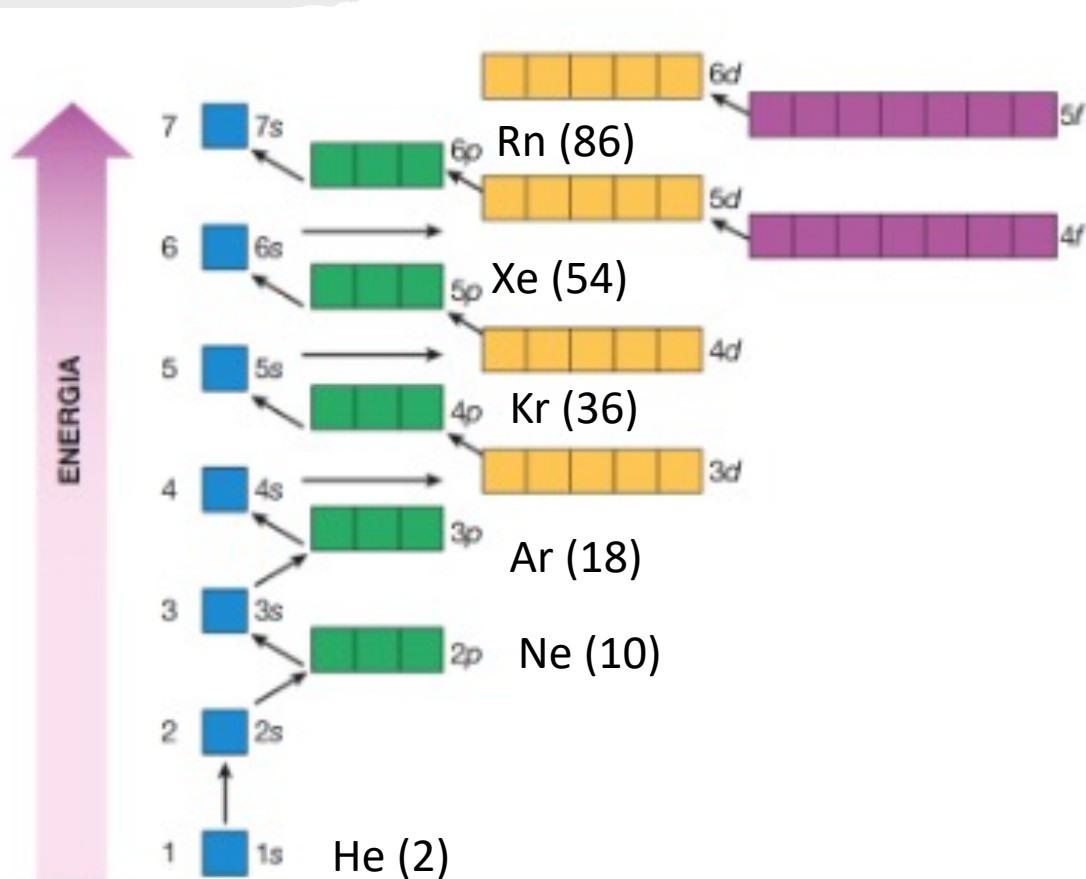


Degenerazione =  $2(2\ell + 1)$

# Gli orbitali atomici

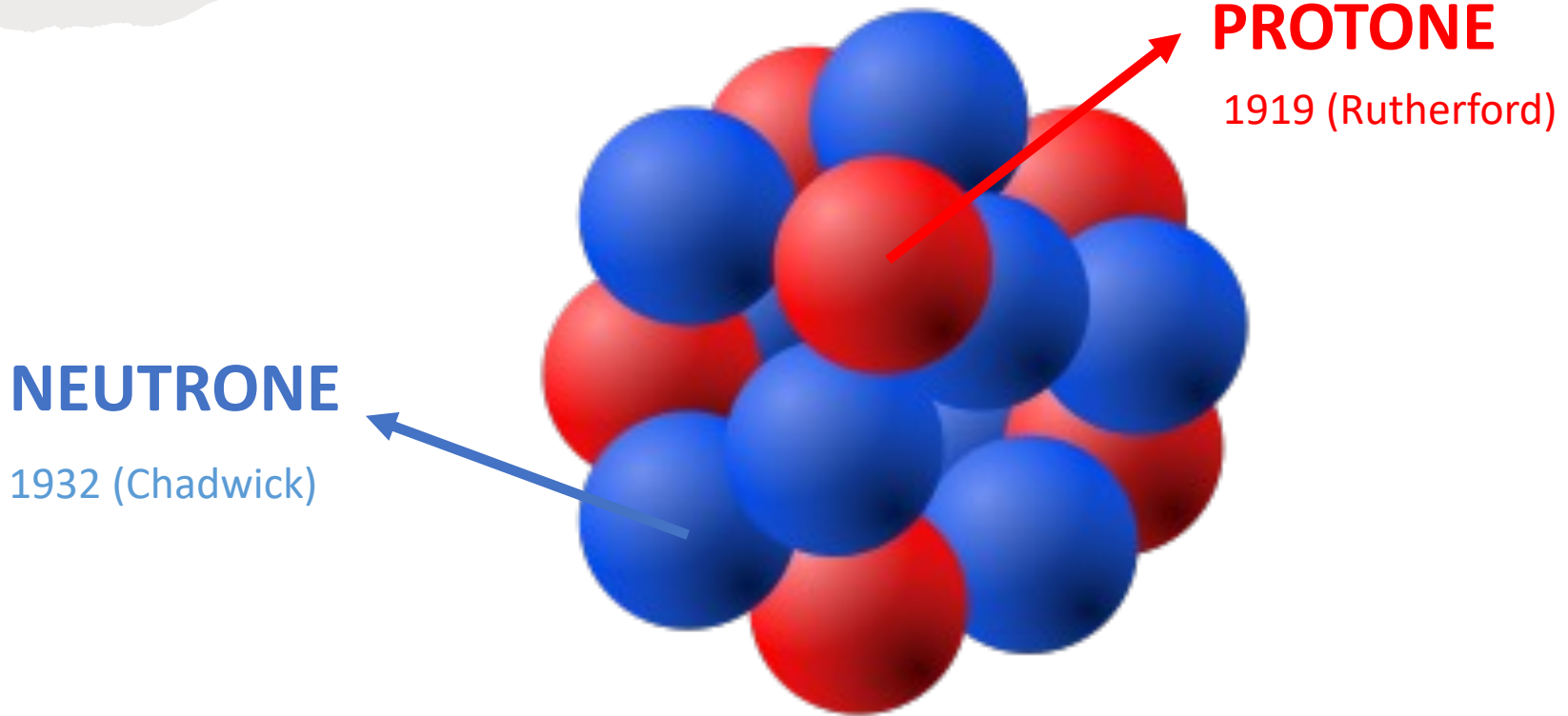
- $n = 1, 2, 3\dots$
- $\ell \geq n-1 = 0, 1, 2\dots$ 
  - $s = 0$
  - $p = 1$
  - $d = 2$
  - $f = 3\dots$
- $-\ell \leq m \leq +\ell$
- $s = \pm \frac{1}{2}$

Oganesson (118)

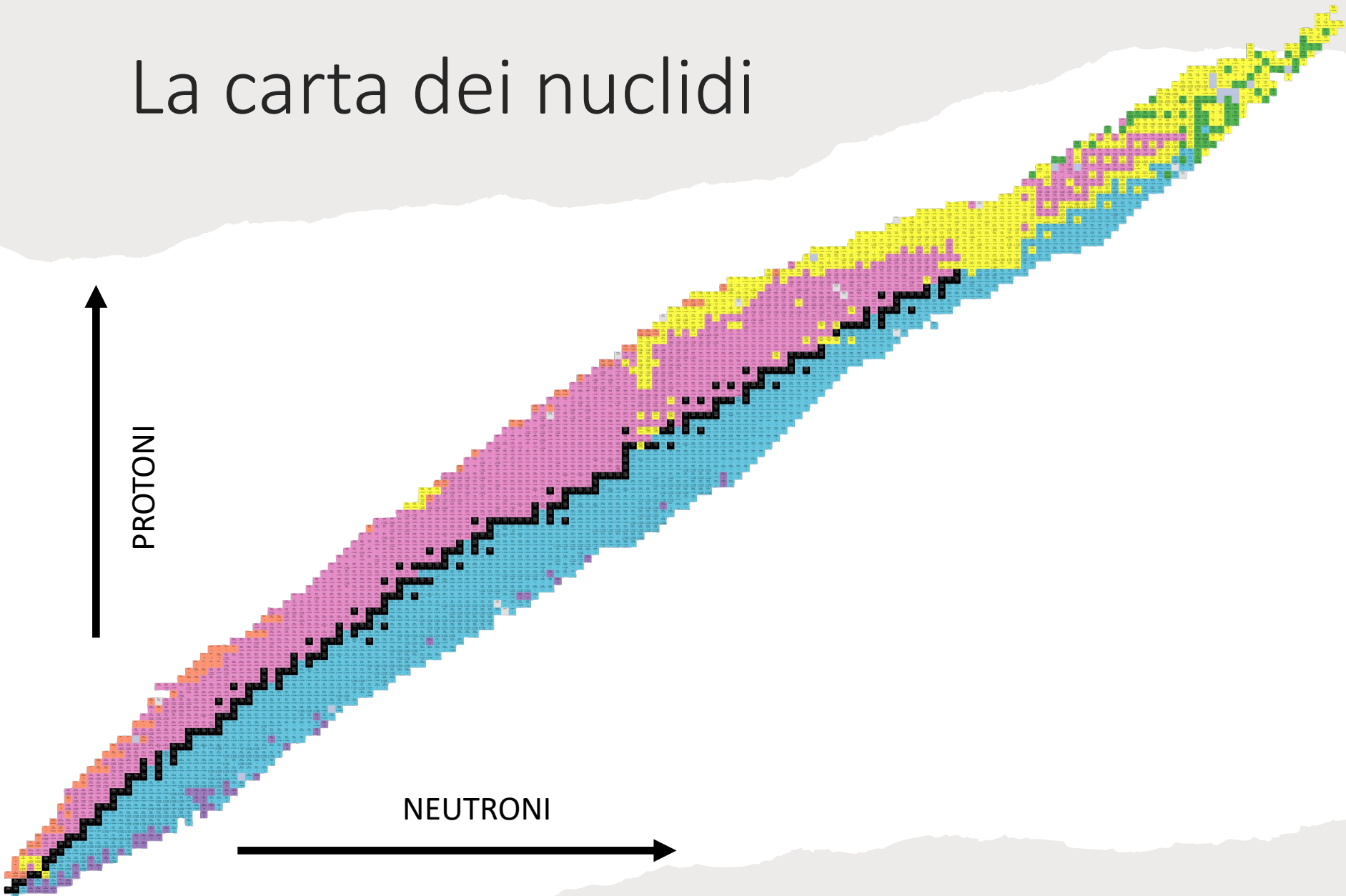


Degenerazione =  $2(2\ell + 1)$

# La struttura del nucleo



# La carta dei nuclidi



PROTONI

NEUTRONI



# Atomo VS Nucleo

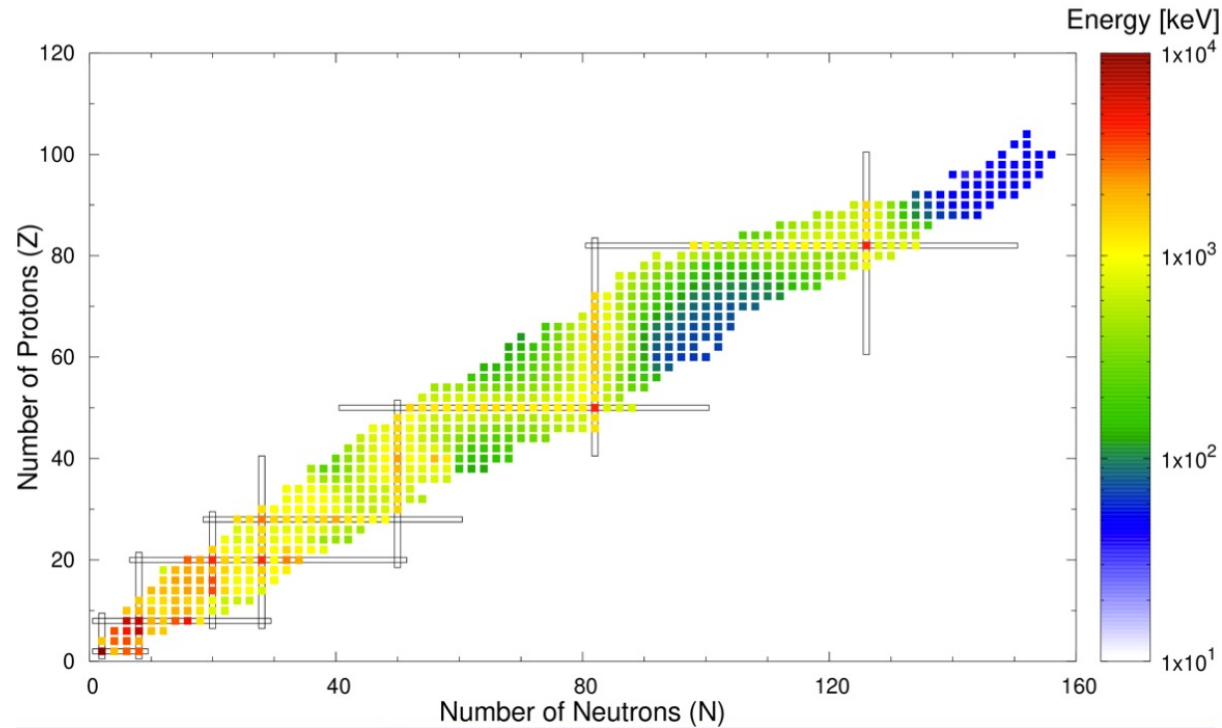
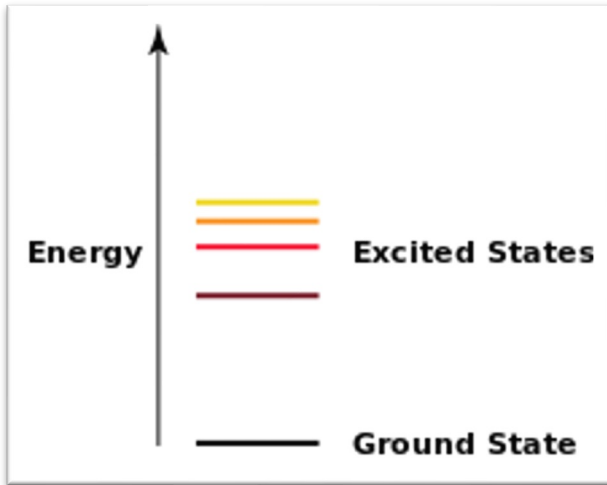
## Atomo

- Sistema di fermioni
- Interazione elettromagnetica
- Particelle elementari
- Struttura a shell

## Nucleo

- Sistema di fermioni
- Interazione elettromagnetica + Interazione nucleare
- Particelle complesse
- Struttura a shell???

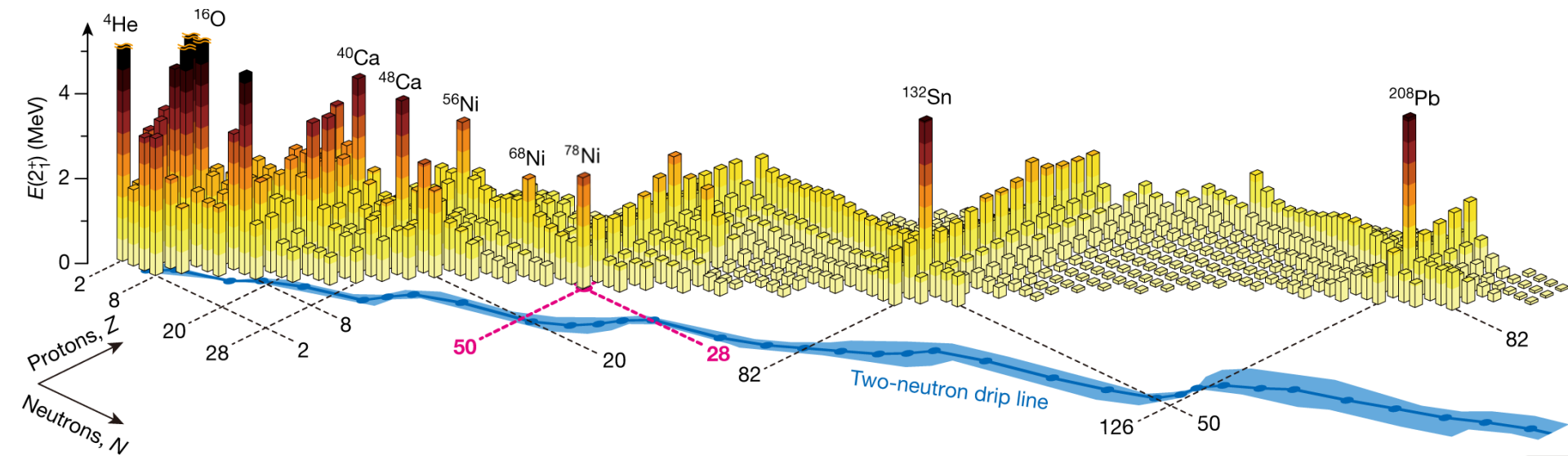
# Evidenze sperimentali



# I numeri magici

$N$  o  $Z = 2, 8, 20, 28, 50, 82, 126$

He, O, Ca, Ni, Sn, Pb, ???



# Atomo VS Nucleo

## Atomo

- Sistema di fermioni
- Interazione elettromagnetica
- Particelle elementari
- Struttura a shell
- 2, 10, 18, 36, 54, 86, 118

## Nucleo

- Sistema di fermioni
- Interazione elettromagnetica +  
Interazione nucleare
- Particelle complesse
- Struttura a shell
- 2, 8, 20, 28, 50, 82, 126

# Il potenziale nucleare

Il potenziale nucleare è più complesso di quello atomico!

- Potenziale a buca infinita;
- Potenziale a oscillatore armonico;
- Potenziale di Wood-Saxon...

---

---

|              |      |          |          |              |              |                  |
|--------------|------|----------|----------|--------------|--------------|------------------|
| $n = 0$      | $1$  | $2$      | $3$      | $4$          | $5$          | $6$              |
| $1s$         | $1p$ | $1d\ 2s$ | $1f\ 2p$ | $1g\ 2d\ 3s$ | $1h\ 2f\ 3p$ | $1i\ 2g\ 3d\ 4s$ |
| $N$ or $Z =$ | $2$  | $8$      | $20$     | $40$         | $70$         | $112$            |

---

---

... Funzionano solo fino a  $Z=20$





## Nuclear Configurations in the Spin-Orbit Coupling Model. I. Empirical Evidence

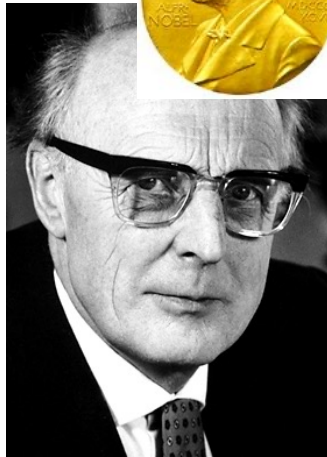
MARIA GOEPPERT MAYER  
*Argonne National Laboratory, Chicago, Illinois*  
 (Received December 7, 1949)

An extreme one particle model of the nucleus is proposed. The model is based on the succession of energy levels of a single particle in a potential between that of a three-dimensional harmonic oscillator and a square well. (1) Strong spin orbit coupling leading to inverted doublets is assumed. (2) An even number of identical nucleons are assumed to couple to zero angular momentum, and, (3) an odd number to the angular momentum of the single odd particle. (4) A (negative) pairing energy, increasing with the  $j$  value of the orbit is assumed. With these four assumptions all but 2 of the 64 known spins of odd nuclei are satisfactorily explained, and all but 1 of the 46 known magnetic moments. The two spin discrepancies are probably due to failure of rule (3). The magnetic moments of the five known odd-odd nuclei are also in agreement with the model. The existence, and region in the periodic table, of nuclear isomerism is correctly predicted.

## Nuclear Configurations in the Spin-Orbit Coupling Model. II. Theoretical Considerations

MARIA GOEPPERT MAYER  
*Argonne National Laboratory, Chicago, Illinois*  
 (Received December 7, 1949)

The assumption of short-range attractive forces between identical nucleons in the  $jj$  coupling model of nuclear structure is in agreement with the empirically observed spins.



## 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



1963

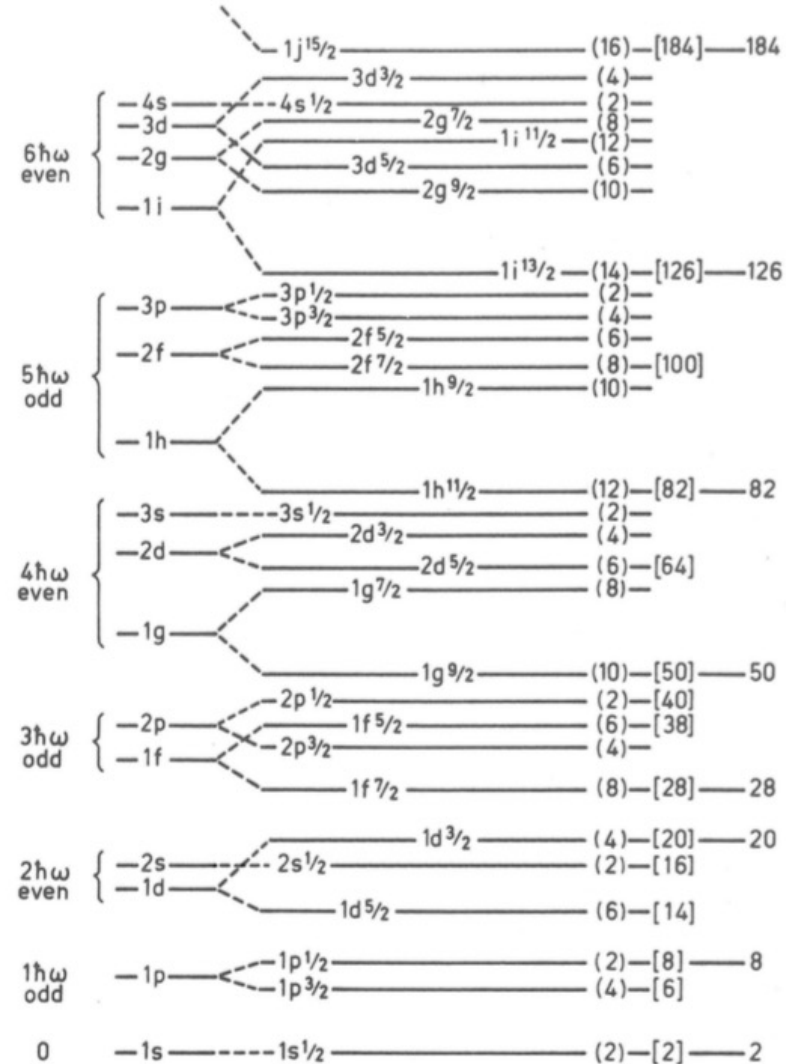
# Il contributo spin-orbita

Ancora una volta la somiglianza deriva dal modello atomico!

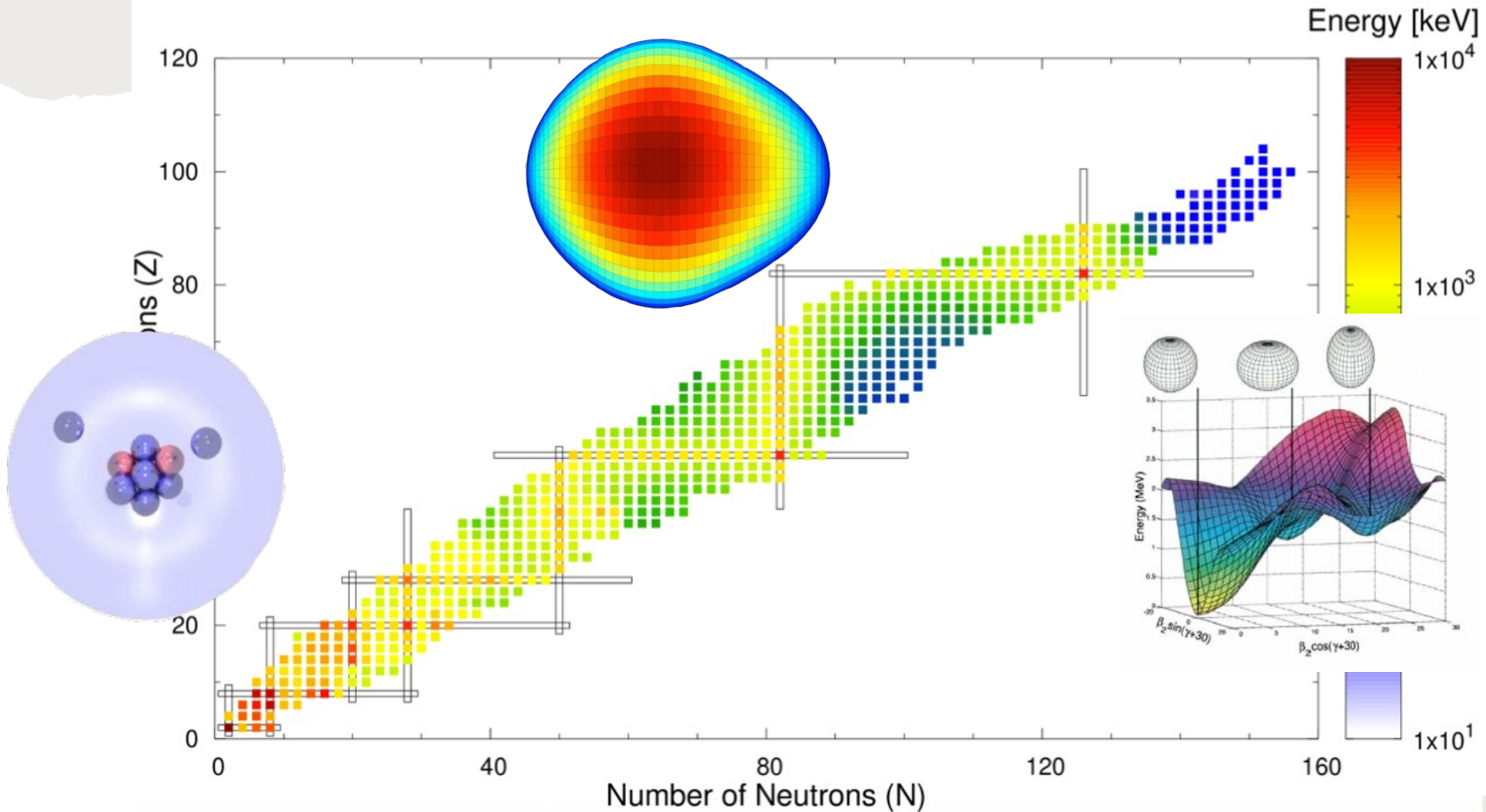
L'interazione spin-orbita deriva dal fatto che lo spin di una particella risente del moto della particella stessa.

Questa interazione ha l'effetto di abbassare i livelli  $j = \ell + \frac{1}{2}$  di alcune shell


I conti tornano!



# Lo shell model oggi





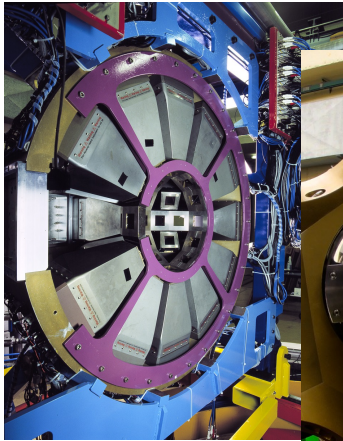


*Neutron number  
34 makes exotic  
calcium-54 isotopes  
doubly magic*


**PAGE 207**

# MAGIC MOMENTS

# Il viaggio continua...







Grazie per  
l'attenzione