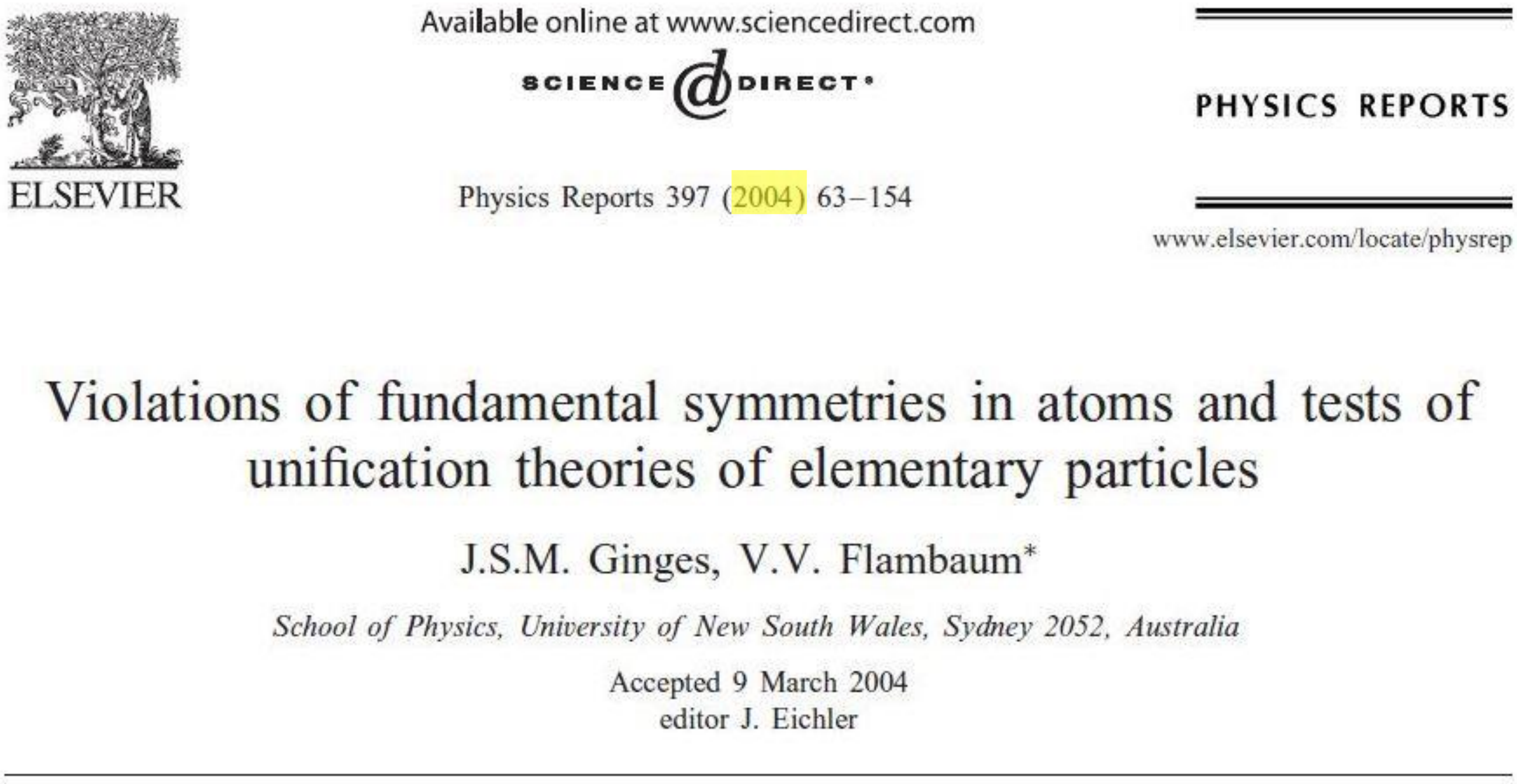

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Violations of fundamental symmetries in atoms and tests of unification theories of elementary particles

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The success of the standard electroweak model of elementary particles is extraordinary.

It has been tested in physical processes covering a range in momentum transfer exceeding ten orders of magnitude. It correctly predicted the existence of new particles such as the neutral Z boson.

However, the standard model fails to provide a deep explanation for the physics that it describes. For example,

why are there three generations of fermions?
What determines their masses and the masses of gauge bosons?
What is the origin of CP violation?
The Higgs boson (which gives masses to the particles in the standard model) **has not yet been found. (nel 2004 !!!!)**
The standard model is unable to explain Big Bang baryogenesis which is believed to arise as a consequence of CP violation.

It is widely believed that the standard model is a low-energy manifestation of a more complete theory (perhaps one that unifies the four forces). Many well-motivated extensions to the standard model have been proposed, such as supersymmetric, technicolour, and left-right symmetric models, and these give predictions for physical phenomena that differ from those of the standard model.

Some searches for new physics beyond the standard model are performed at high-energy and medium-energy particle colliders where new processes or particles would be seen directly.

However, a very sensitive probe can be carried out at low energies through precision studies of quantities that can be described by the standard model. The new physics is manifested indirectly through a deviation of the measured values from the standard model predictions.

These tests exploit the fact that low-energy phenomena are especially sensitive to new physics that is manifested in the violations of fundamental symmetries, in particular P (parity) and T (time-reversal), that occur in the weak interaction. The deviations from the standard model, or the effects themselves, may be very small.

To this end, exquisitely precise measurements and calculations are required.

More than 20 years ago atomic experiments played an important role in the verification of the standard model. While the first evidence for neutral weak currents (existence of the neutral Z boson) was discovered in neutrino scattering, the fact that neutral currents violate parity was first established
in atomic experiments and only later observed in high-energy electron scattering [5].

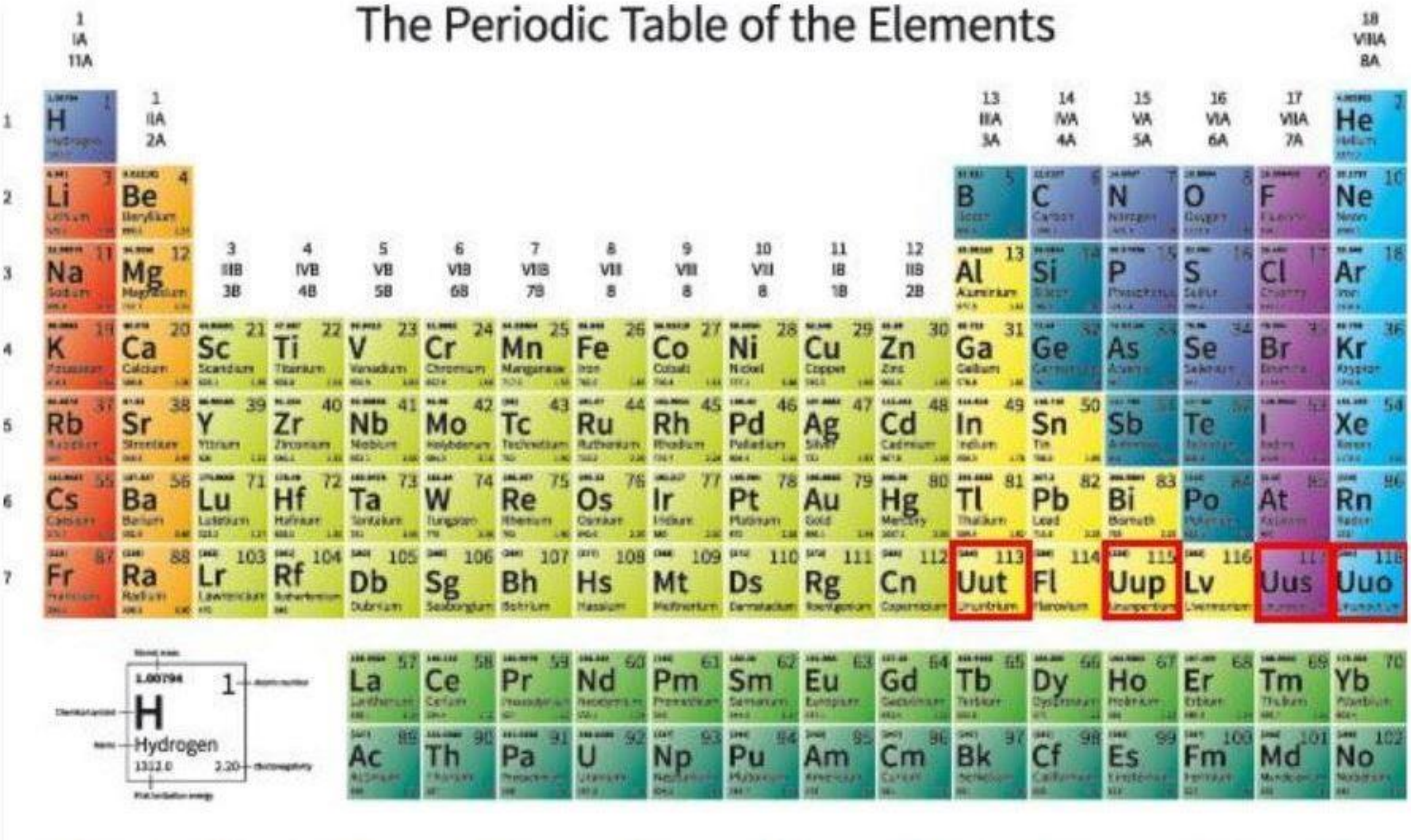
Atomic physics plays a major role in the search for possible physics beyond the standard model.

Precision atomic and high-energy experiments have different sensitivities to models of new physics and so they provide complementary tests. In fact the energies probed in atomic measurements exceed
those currently accessible at high-energy facilities. For example, the most precise measurement of parity non conservation (PNC) in the cesium atom sets a lower bound on an extra Z boson popular in many extensions of the standard model that is tighter than the bound set directly at the Tevatron

Also, the null measurements of electric dipole moments (EDMs) in atoms (an EDM is
a P- and T-violating quantity) place severe restrictions on new sources of CP-violation which arise naturally in models beyond the standard model such as supersymmetry. (Assuming CPT invariance, CP-violation is accompanied by T-violation.) Such limits on new physics have not been set by the detection of CP-violation in the neutral K [6] and B [7] mesons (see, e.g., Ref. [8] for a review of CP violation in these systems).
Let us note that while new physics would bring a relatively small correction to a very small signal in atomic parity violation, in atomic EDMs the standard model value is suppressed and is many orders of magnitude below the value expected from new theories.

Therefore, detection of an EDM would be unambiguous evidence of new physics.

it is now (2004) firmly established that the **cesium** measurement is in excellent agreement with the standard model;

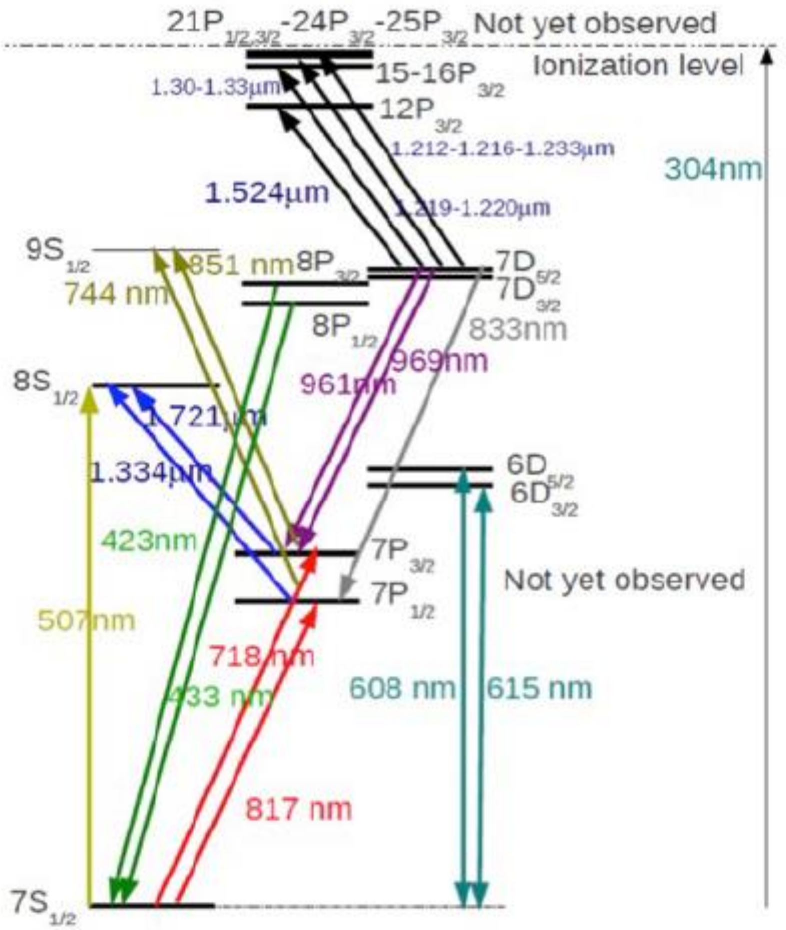


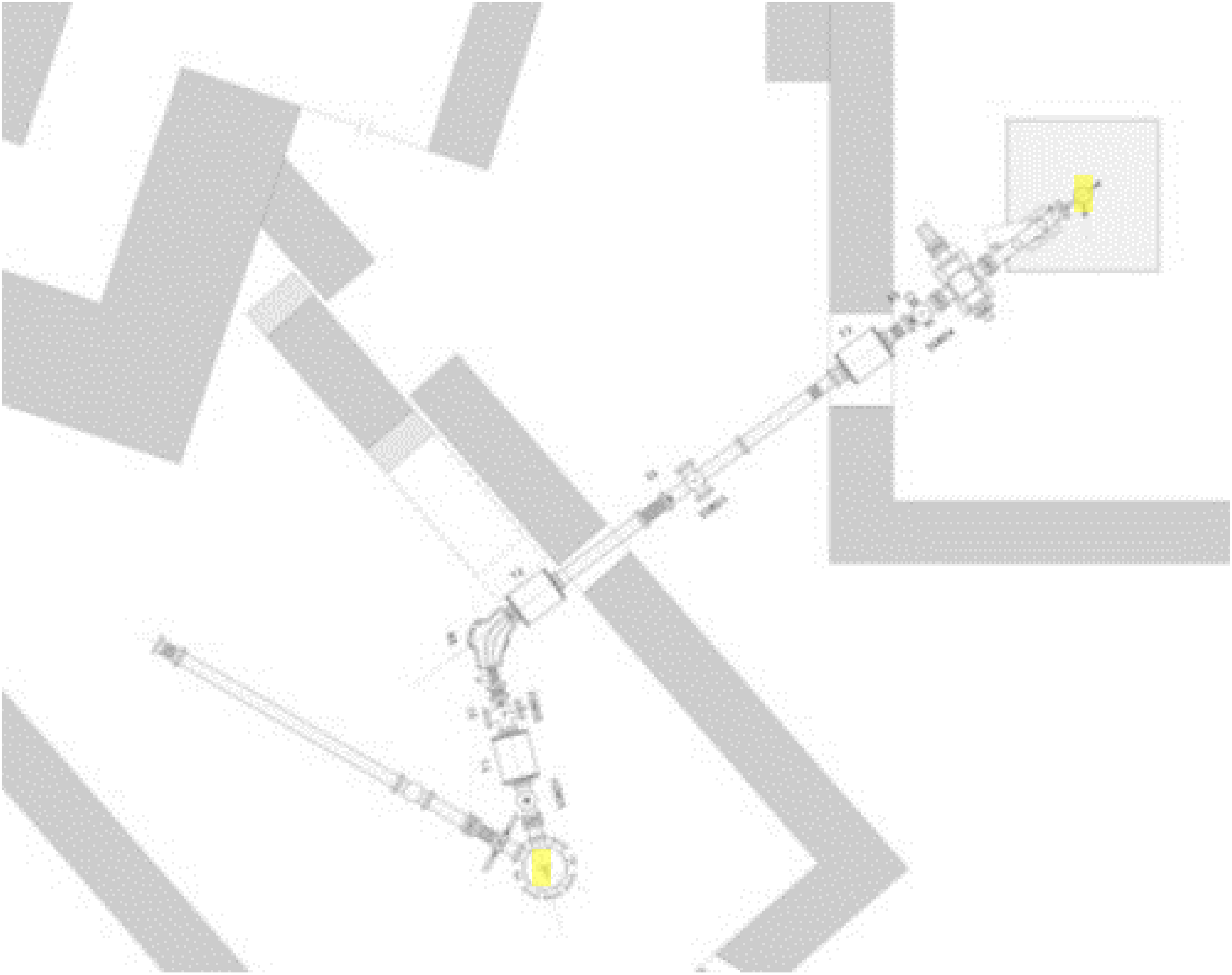
The Periodic Table of the Elements

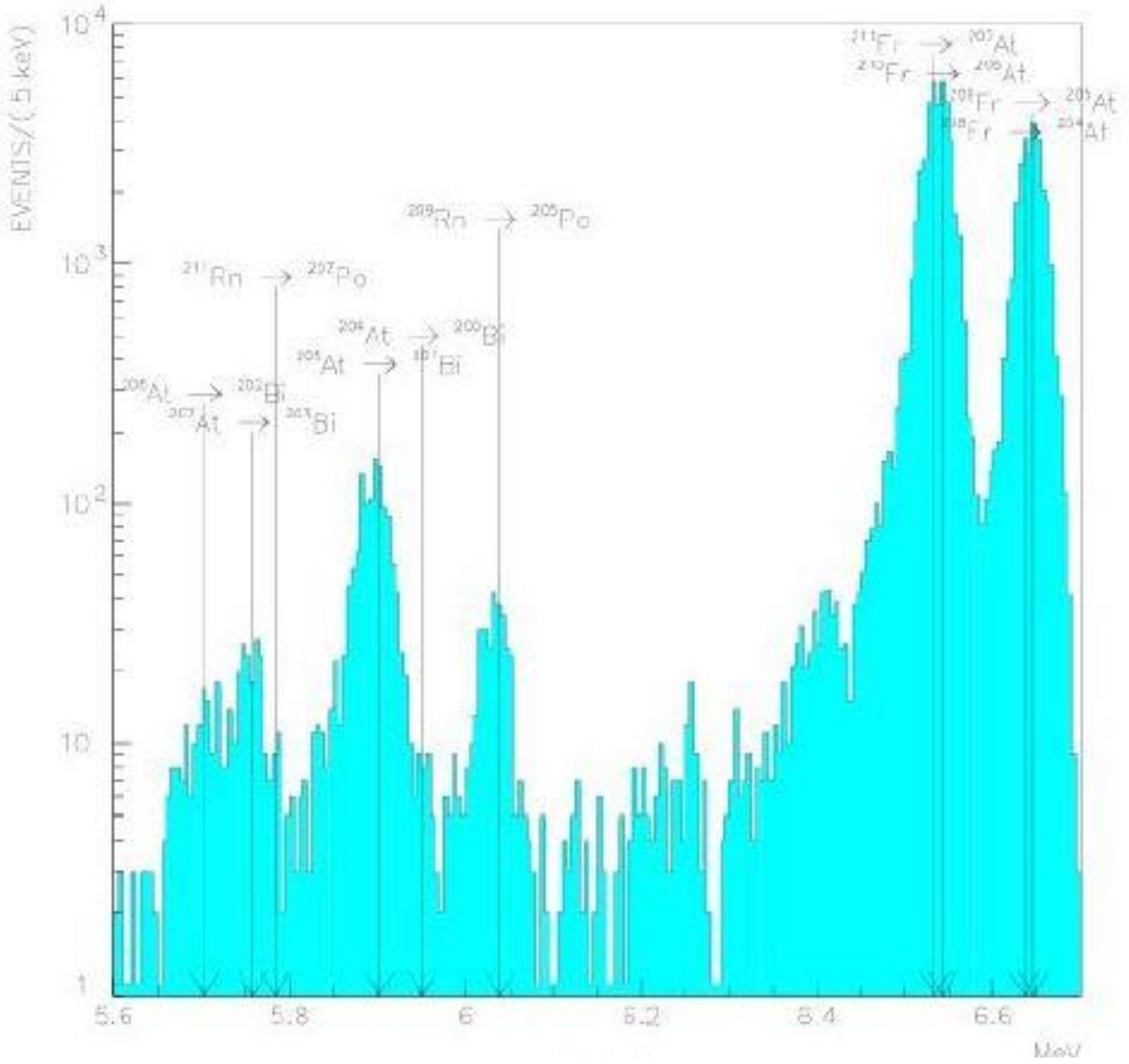
	1 IA 11A	1 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	Lu 71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	Lr 103	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Uut 113	Fl 114	Uup 115	Lv 116	Uus 117	Uuo 118
					La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70
					Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102

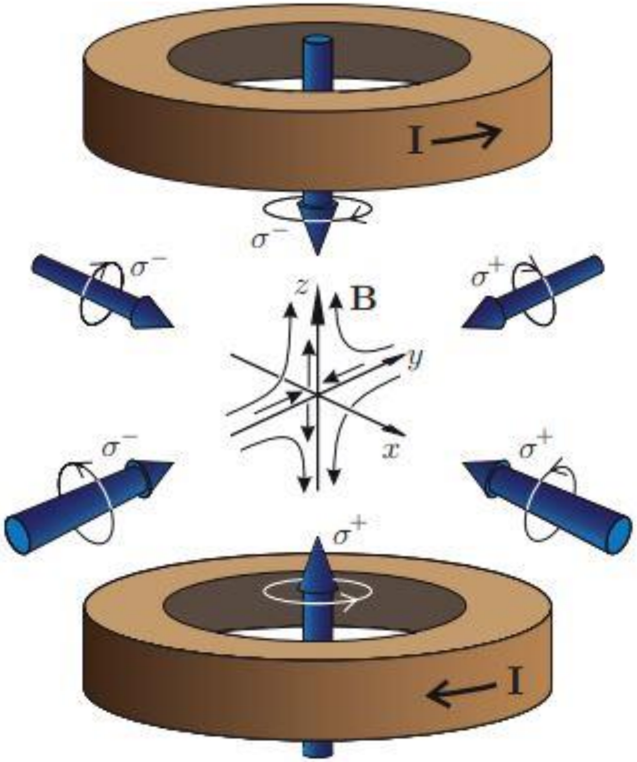
^{207}Fr		87	120	206.99695(5)	14.8(1) s	α (95%)	^{203}At	9/2−	
						β^+ (5%)	^{207}Rn		
^{208}Fr		87	121	207.99714(5)	59.1(3) s	α (90%)	^{204}At	7+	
						β^+ (10%)	^{208}Rn		
^{209}Fr		87	122	208.995954(16)	50.0(3) s	α (89%)	^{205}At	9/2−	
						β^+ (11%)	^{209}Rn		
^{210}Fr		87	123	209.996408(24)	3.18(6) min	α (60%)	^{206}At	6+	
						β^+ (40%)	^{210}Rn		
^{211}Fr		87	124	210.995537(23)	3.10(2) min	α (80%)	^{207}At	9/2−	
						β^+ (20%)	^{211}Rn		
^{212}Fr		87	125	211.996202(28)	20.0(6) min	β^+ (57%)	^{212}Rn	5+	
						α (43%)	^{208}At		
^{213}Fr		87	126	212.996189(8)	34.6(3) s	α (99.45%)	^{209}At	9/2−	
						β^+ (.55%)	^{213}Rn		
^{214}Fr		87	127	213.998971(9)	5.0(2) ms	α	^{210}At	(1−)	
^{214m1}Fr		123(6) keV			3.35(5) ms	α	^{210}At	(8−)	
^{214m2}Fr		638(6) keV			103(4) ns			(11+)	
^{214m3}Fr		6477+Y keV			108(7) ns			(33+)	
^{215}Fr		87	128	215.000341(8)	86(5) ns	α	^{211}At	9/2−	
^{216}Fr		87	129	216.003198(15)	0.70(2) μs	α	^{212}At	(1−)	
						β^+ (2×10^{-7}%)	^{216}Rn		
^{217}Fr		87	130	217.004632(7)	16.8(19) μs	α	^{213}At	9/2−	
^{218}Fr		87	131	218.007578(5)	1.0(6) ms	α	^{214}At	1−	
^{218m1}Fr		86(4) keV			22.0(5) ms	α	^{214}At		
						IT (rare)	^{218}Fr		

96																					Cm232 ~1 M	Cm233 -1 M
95																					Am231 -10 S	Am232 79 S
94																			Pu228 -0.2 S	Pu229 >2 US	Pu230 -200 S	Pu231 8.6 M
93																	Np225 >2 US	Np226 35 MS	Np227 0.51 S	Np228 61.4 S	Np229 4.0 M	Np230 4.6 M
92											U218 1.5 MS	U219 42 US	U220 -60 NS	U221 -0.7 US	U222 1.0 US	U223 55 US	U224 0.9 MS	U225 60 MS	U226 0.35 S	U227 1.1 M	U228 9.1 M	U229 58 M
91						Pa212 5.1 MS	Pa213 5.3 MS	Pa214 17 MS	Pa215 15 MS	Pa216 105 MS	Pa217 2.3 MS	Pa218 0.11 MS	Pa219 53 NS	Pa220 0.78 US	Pa221 4.9 US	Pa222 3.3 MS	Pa223 5 MS	Pa224 0.85 S	Pa225 1.7 S	Pa226 1.8 M	Pa227 38.3 M	Pa228 22 H
90				Th209 3.8 MS	Th210 9 MS	Th211 37 MS	Th212 30 MS	Th213 140 MS	Th214 100 MS	Th215 1.2 S	Th216 0.028 S	Th217 0.252 MS	Th218 109 NS	Th219 1.05 US	Th220 9.7 US	Th221 1.68 MS	Th222 2.8 MS	Th223 0.60 S	Th224 1.05 S	Th225 8.72 M	Th226 30.57 M	Th227 18.72 D
89		Ac206 33 MS	Ac207 27 MS	Ac208 95 MS	Ac209 0.10 S	Ac210 0.35 S	Ac211 0.25 S	Ac212 0.93 S	Ac213 0.80 S	Ac214 8.2 S	Ac215 0.17 S	Ac216 -0.33 MS	Ac217 69 NS	Ac218 1.08 US	Ac219 11.8 US	Ac220 26.4 MS	Ac221 52 MS	Ac222 5.0 S	Ac223 2.10 M	Ac224 2.78 H	Ac225 10.0 D	Ac226 29.37 H
88	Ra204 59 MS	Ra205 0.21 S	Ra206 0.24 S	Ra207 1.3 S	Ra208 1.3 S	Ra209 4.6 S	Ra210 3.7 S	Ra211 13 S	Ra212 13.0 S	Ra213 2.74 M	Ra214 2.46 S	Ra215 1.59 MS	Ra216 182 NS	Ra217 1.6 US	Ra218 25.6 US	Ra219 10 MS	Ra220 18 MS	Ra221 28 S	Ra222 38.0 S	Ra223 11.435 D	Ra224 3.66 D	Ra225 14.9 D
87	Fr203 0.55 S	Fr204 1.7 S	Fr205 3.85 S	Fr206 -16 S	Fr207 14.8 S	Fr208 59.1 S	Fr209 50.0 S	Fr210 3.18 M	Fr211 3.10 M	Fr212 20.0 M	Fr213 34.6 S	Fr214 5.0 MS	Fr215 86 NS	Fr216 0.70 US	Fr217 22 US	Fr218 1.0 MS	Fr219 20 MS	Fr220 27.4 S	Fr221 4.9 M	Fr222 14.2 M	Fr223 22.00 M	Fr224 3.33 M
86	Rn202 10.0 S	Rn203 42 S	Rn204 1.17 M	Rn205 2.8 M	Rn206 5.67 M	Rn207 9.25 M	Rn208 24.35 M	Rn209 28.5 M	Rn210 2.4 H	Rn211 14.6 H	Rn212 23.9 M	Rn213 25.0 MS	Rn214 0.27 US	Rn215 2.30 US	Rn216 45 US	Rn217 0.54 MS	Rn218 35 MS	Rn219 3.96 S	Rn220 55.6 S	Rn221 25.7 M	Rn222 3.8235 D	Rn223 23.2 M
85	At201 89 S	At202 184 S	At203 7.4 M	At204 9.2 M	At205 26.2 M	At206 30.6 M	At207 1.80 H	At208 1.63 H	At209 5.41 H	At210 8.1 H	At211 7.214 H	At212 0.314 S	At213 125 NS	At214 558 NS	At215 0.10 MS	At216 0.30 MS	At217 32.3 MS	At218 1.5 S	At219 56 S	At220 3.71 M	At221 2.3 M	At222 54 S
84	Po200 10.9 M	Po201 15.3 M	Po202 44.7 M	Po203 36.7 M	Po204 3.53 H	Po205 1.66 H	Po206 8.8 D	Po207 5.80 H	Po208 2.898 Y	Po209 102 Y	Po210 138.376 D	Po211 0.516 S	Po212 0.299 US	Po213 3.65 US	Po214 164.3 US	Po215 1.781 MS	Po216 0.145 S	Po217 1.47 S	Po218 3.10 M	Po219 -2 M		
83	Bi199 27 M	Bi200 36.4 M	Bi201 108 M	Bi202 1.72 H	Bi203 11.76 H	Bi204 11.22 H	Bi205 15.31 D	Bi206 6.243 D	Bi207 31.55 Y	Bi208 368000 Y	Bi209 100	Bi210 5.013 D	Bi211 2.14 M	Bi212 60.55 M	Bi213 45.59 M	Bi214 19.9 M	Bi215 7.6 M	Bi216 2.17 M	Bi217 97 S			
82	Pb198 2.40 H	Pb199 90 M	Pb200 21.5 H	Pb201 9.33 H	Pb202 52 500 Y	Pb203 51.873 H	Pb204 1.4	Pb205 15300000 Y	Pb206 24.1	Pb207 22.1	Pb208 52.4	Pb209 3.253 H	Pb210 22.3 Y	Pb211 36.1 M	Pb212 10.64 H	Pb213 10.2 M	Pb214 26.8 M					
81	Tl197 2.84 H	Tl198 5.3 H	Tl199 7.42 H	Tl200 26.1 H	Tl201 72.912 H	Tl202 12.23 D	Tl203 29.524	Tl204 3.78 Y	Tl205 70.476	Tl206 4.200 M	Tl207 4.77 M	Tl208 3.053 M	Tl209 2.161 M	Tl210 1.30 M								
80	Hg196 0.15	Hg197 64.14 H	Hg198 9.97	Hg199 16.87	Hg200 23.10	Hg201 13.18	Hg202 29.86	Hg203 46.612 D	Hg204 6.87	Hg205 5.2 M	Hg206 8.15 M	Hg207 2.9 M	Hg208 41 M									


21P 1/2,3/2 -24P 3/2 -25P 3/2 Not yet observed
Ionization level
15-16P 3/2
1.30-1.33µm
12P 3/2
1.212-1.216-1.233µm
304nm
1.524µm
1.219-1.220µm
9S 1/2
851 nm
8P 3/2
7D 5/2
7D 3/2
744 nm
8P 1/2
833nm
969nm
8S 1/2
961nm
1.721µm
6D 5/2
1.334µm
6D 3/2
423nm
7P 3/2
Not yet observed
7P 1/2
507nm
718 nm
433 nm
608 nm
615 nm
817 nm
7S 1/2




EVENTS/(5 keV)
10^4
10^3
10^2
10
1
5.6
5.8
6
6.2
6.4
6.6
MeV
^{211}Fr → ^{207}At
^{210}Fr → ^{206}At
^{209}Fr → ^{205}At
^{208}Fr → ^{204}At
^{209}Rn → ^{205}Po
^{211}Rn → ^{207}Po
^{204}At → ^{200}Bi
^{205}At → ^{201}Bi
^{206}At → ^{202}Bi
^{207}At → ^{203}Bi


I
σ⁻
σ⁻
σ⁺
z
B
y
x
σ⁻
σ⁺
σ⁺
I

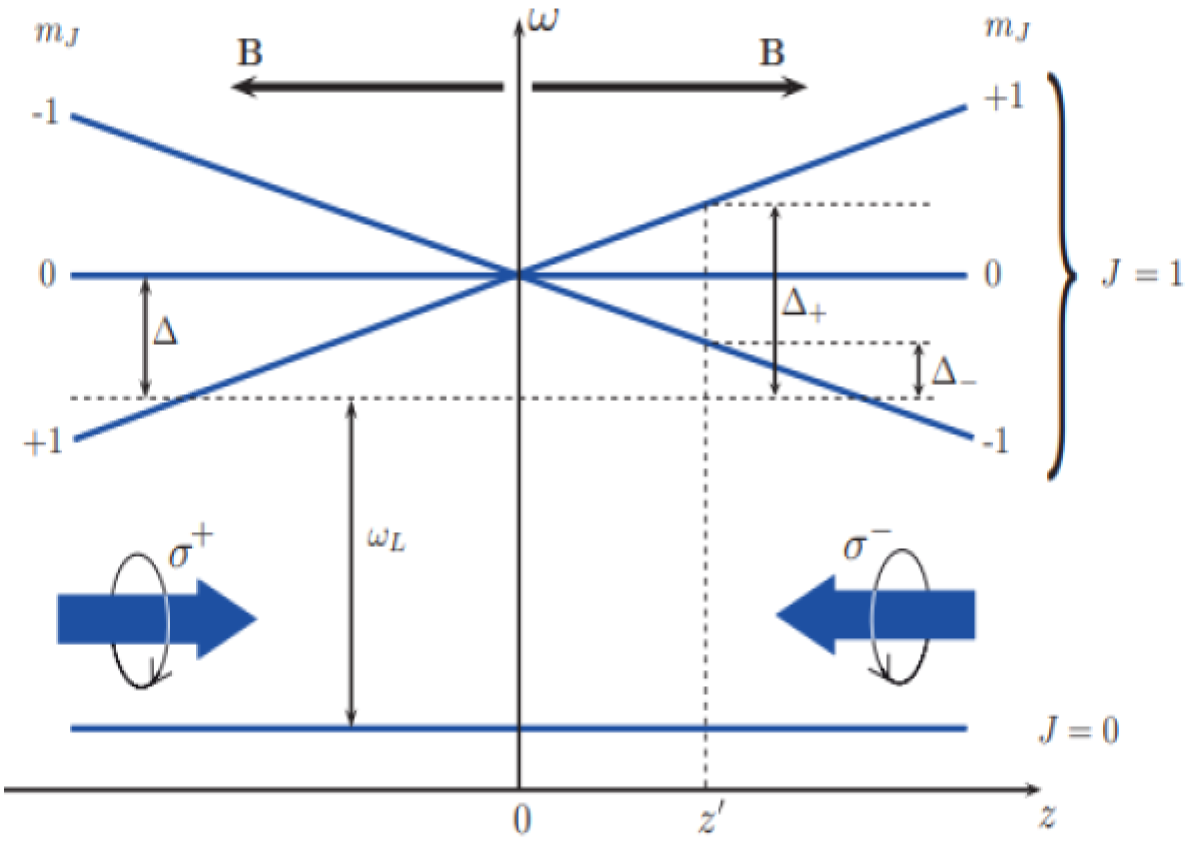


Figure 1.5. Meccanismo di funzionamento di una trappola magneto-ottica monodimensionale su una transizione $J = 0 \rightarrow J = 1$. L'illustrazione non è in scala; lo spostamento Zeeman è molto minore dell'energia della transizione ottica. [6]