SUBATOMIC PARTICLES, NUCLEAR STRUCTURE AND STABILITY

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Summary

This chapter provides elementary introduction to the Standard Model of fundamental particles and interactions to serve with background for the Theme Radiochemistry and Nuclear Chemistry (RC&NC). It also illustrates the stability and instability of the nucleus by presenting the systematics of stable nuclei as well as by explaining the

possible ways of reaching greater stability. Nuclear models are also explained in simple terms.

1. Introduction

This chapter is meant to be an easily digestible supplement to the Theme Radiochemistry and Nuclear Chemistry (RC&NC) on the topics subatomic particles, nuclear structure and nuclear stability.

The Standard Model treated first is not really part of what we call RC&NC, however it belongs to the general background of all nuclear science. Dealing with a rather abstract field in every sense (e.g. some particle physicists insist that there are no particles just fields), the treatment will be qualitative with emphasis on the "colorful" features.

Another interesting topic is the systematics of stable nuclides in nature. It is a really exciting area for chemists because simple classification principles lead to easily interpreted conclusions about the questions of stability and instability of nuclei giving important hints to certain features that some nuclear models possess.

The rest of the topics (nuclear structure, decay modes etc.) have also been touched in the "main" chapter (*Radiochemistry and Nuclear Chemistry*), however their treatment will be more detailed here.

2. Particles and Forces – the Standard Model in a Nutshell

After the discovery of the nucleons and with the aid of increasingly powerful accelerators, experimental physicists kept busily discovering new particles every week until it became clear that all of these particles could not be elementary. Enrico Fermi's comment on this was supposed to be: *"Had I foreseen that, I would have gone into botany!"* The solution to the problem came with the classification scheme of hadrons by the aid of the *quark concept* established by M. Gell-Mann in 1964 (Nobel Prize in physics, 1969). His ideas were based on the *symmetry principles* recognized by E.P. Wigner (Nobel Prize in physics, 1963) as early as 1927 (see: Appendix 1 in *Radiochemistry and Nuclear Chemistry*).

The brief summary of particle physics background we give in this section is based on the theory called the Standard Model. For more detail see the free site of the Contemporary Physics Education Project at http://www2.slac.stanford.edu/vvc/theory.html. For personal use or for teaching purposes one can also load down a very informative 2006 poster and its printable parts from the site http://www.cpepweb.org/cpep_sm_large.html.

2.1. The Origin of Nuclear Force

Figure 1 shows the artistic representation of the structure of a ^{4}He atom based on the Standard Model. The *nuclear force* that holds the nucleus together is only a residual of the *strong force* or *color force* which acts inside the nucleons between quarks and is mediated by gluons (not represented in the figure). The color force is never completely compensated at every point of the "surface" of a nucleon. Thus, if observed from close enough, the nucleon is not "neutral" as regards the *color charge*, and the locally uncompensated color charge makes it "sticky" thus attracting other nucleons nearby. The nuclear force that binds the nucleons to each other – being just a residual of color force – has a very *short range* in the order of the size of a nucleon (see Table 4). In chemistry, the "force" binding electrically neutral atoms together to form molecules can also be regarded as the residual of the electric force that is neutralized within atomic scale. And so is the attractive London force (dispersion force) between nonpolar molecules which is explained by fluctuations in the instantaneous distribution of the electrons. In contrast to the Coulomb force whose range is infinite, the interatomic/intermolecular "residual electric" forces are also short-range forces. In the case of molecules, the bonding electrons moving between the atoms can also be regarded as "force carriers", thus playing the same role as the (virtual) pions between neighboring nucleons (see the last row, shaded in yellow, in Table 3). The nuclear force acting between nucleons has another similarity with the bond between two atoms forming a molecule, namely, with decreasing internucleonic distance (at about 0.5 fm) the nuclear force becomes repulsive. That is, nucleons – same as atoms (or molecules) – cannot be easily squeezed into each other. Such behavior is the basis of the "incompressibility" of liquids. The recognition of this kind of similarity between internucleonic and interatomic forces led to the creation of the *liquid drop model* of the atomic nucleus, which had been successfully used for the explanation of many nuclear properties.

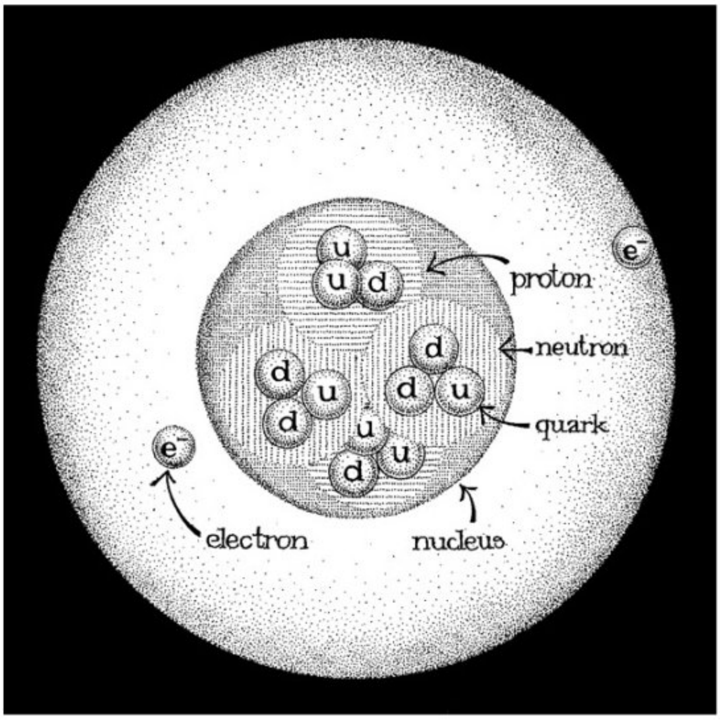

Figure 1: Artistic representation of the structure of a helium atom ^{4}He by "Iscsu" (an alias used by the Hungarian graphic artist István Molnár). Note that the actual

dimensions of the particles, the nucleus, and the atom are by far not in proportion with each other.

2.2. Classification of Particles and Forces

Tables 1 through 5 show some properties of a few particles, which are only representatives of the several hundred whose existence is proven by experiment. The data have been compiled from the Particle Data Group site http://pdg.lbl.gov/ (Particle Listings 2006). Data in Table 4 are mostly from the Standard Model Chart (copyright 1999 by the Contemporary Physics Education Project, http://particleadventure.org/frameless/chart.html).

Particles and their *antiparticles* have the same mass, and all of the generalized "charges" that characterize them (including *electric charge*, *strangeness*, *bottomness*, *topness*, *charm*, *baryon number*, *lepton number*, *color charge*, etc.) change to the opposite. Thus, the positron e^+, the antiparticle of the ordinary electron e (which is also called negatron e^- in this context), has positive electric charge. (Since the electron/negatron is a lepton having an assigned value of lepton number $L = +1$, its antiparticle, the positron, has $L = \text{-}1$. Since leptons are not baryons, the baryon number of e^- and e^+ is $B = 0$.) Similarly, the antiparticle of π^+ is π^- and vice versa. There are some "absolutely neutral" particles, such as π^0, which are identical with their antiparticles. Particles meeting their antiparticles may *annihilate* with each other, which means that the whole rest energy (mass) of the ensemble gets converted to "pure" energy, i.e. to photons, according to the equation $E_0 = mc^2$ (see: Appendix 2 in *Radiochemistry and Nuclear Chemistry*). Unless they bump into each other with high energy, e.g., in the proton-antiproton collider Tevatron, when they tend to produce further particles. On the other hand, if a particle is stable (e.g. the electron), so is its antiparticle (e.g. the positron) when left alone. Their apparent instability is just the consequence of the fact that – surrounded by ordinary matter – they are never left alone for very long and therefore annihilation takes place.

Particles – once all of them referred to as elementary – are classified according to different criteria.

One important aspect of classification is whether the *spin quantum number of the particle* (s) is a *half-integer* (i.e. 1/2, 3/2, 5/2…) as with *fermions*, or an *integer* (i.e. 0, 1, 2…) as with *bosons*. This may seem just a trifle, but has important implications. (In particle physics lingo, s is simply referred to as *spin*, because it gives the maximum observable projection of the spin vector $\boldsymbol{s}$ in units of $\hbar$, where $\hbar$ is the reduced Planck constant, i.e. the Planck constant h divided by 2π.)

Fermions – similarly to their well-known representative, the electron – are all subject to the *Pauli exclusion principle*, whereas bosons (such as the photon) are not.

The names themselves are mnemonics of statistics. Fermions obey *Fermi–Dirac statistics* (connected with the problem of placing n undistinguishable objects in N labeled boxes with storage capacity limited to one object only), whereas bosons obey

Bose–Einstein statistics (placing n undistinguishable objects in N labeled boxes with unlimited storage capacity).

Another important aspect is *complexity*. According to this, those particles that are considered nowadays as the ultimate building blocks of matter are called *fundamental particles* or, alternatively, *elementary particles*. These are thought of as lacking any internal structure and therefore point-like. Even the mass of them is sometimes far from being easily interpreted by anybody except particle physicists. (This is particularly true for quarks.)

The known elementary particles are divided in three classes. Two of them (the leptons and the quarks) are fermions with spin 1/2, whereas the elementary force carriers are bosons with spin 0, 1, 2, ….

Generation (flavor)	**Lepton**		**Rest energy ($E_0 = mc^2$), mass (m)**			**Charge**	**Found in year**
	Symbol	**Name**	E_0 **/MeV**	m/m_e	m **/u**	q/e	
1st	ν_e	electron neutrino	<0.000 002	$<4\times10^{-6}$	$<2\times10^{-9}$	0	1956
	e	electron	0.511	1	5.486×10^{-4}	–1	1897
2nd	ν_μ	muon neutrino	<0.19	<0.37	$<2\times10^{-4}$	0	1962
	μ	muon	106	207	0.11343	–1	1937
3rd	ν_τ	tau neutrino	<18.2	<35.6	<0.02	0	2000
	τ	tau lepton	1777	3477	1.908	–1	1974

Table 1**:** Leptons are the class of elementary fermions ($s = 1/2$) that are not affected by strong/color force (see Table 4). The upper limit for the mass of electron neutrino (actually antineutrino) also sets an upper limit for the mass of the lightest neutrino independent of flavor. Note that the antiparticle of the electron (i.e. the positron) remained undiscovered till 1932.

Leptons, one of the classes of fundamental particles consisting of six known members only (as well as their antiparticles which makes them 12 altogether), are listed in Table 1. Their name, coming from Greek (leptós ≈ small, slight), is obviously associated with the lightness of electron, the best and longest known representative of the group.

Leptons, in spite of their name, are not all really light. The tau lepton of the 3rd generation, e.g., is several thousand times heavier than the electron, the “prototype” of the group. In fact, the τ is almost as heavy as a whole hydrogen molecule, H_2.

The electron is the only “absolutely stable” member of this group in every sense. It is proven that its half-life is at least 3.2×10^{24} years, which is about 200 trillion times longer than the age of the Universe.

The stability of neutrinos is a more delicate question, because the representatives of the generations (i.e. different “flavors”, ν_e, ν_μ, ν_τ) can change into each other with some probability (*change of flavor*, *neutrino oscillation*). On the other hand, neutrino oscillation is considered as a proof that all neutrinos cannot be mass-less particles.

Generation (flavor)	Quark		Rest energy ($E_0 = mc^2$), mass (m)			Charge	Found in year
	Name	Mnemonic	E_0 /MeV	m / m_e	m /u	q / e	
1st	u	up	2	4	0.002	+2/3	1970
	d	down	5	10	0.005	–1/3	
2nd	c	charm	1020	2450	1.3	+2/3	1976
	s	strange	90	190	0.1	–1/3	1964
3rd	t	top (truth)	175 000	337 000	185	+2/3	1995
	b	bottom (beauty)	4500	8200	4.5	–1/3	1977

Table 2: Quarks (q) are the class of elementary fermions ($s = 1/2$) that are affected not only by strong/color force, but also by the rest of the fundamental forces (see Table 4). They are also the constituents of composite particles that give the “bulk” of the matter in and around us. The nucleons (N), e.g., are built from the two 1st generation quarks u and d. Note that the names of quarks are the symbols themselves according to IUPAP. What most people think are the names of quarks are actually mnemonics for the symbols. The interpretation of the masses is not at all straightforward, e.g., the masses of u and d are only tiny fractions of the nucleons they build up.

Quarks, a group of six also (as well as their antiparticles which makes them 12 altogether), are listed in Table 2. The name itself comes from literature, namely from James Joyce’s cultic book “Finnegans Wake” (http://www.trentu.ca/faculty/jjoyce/fw-383.htm), where a rhyme starting with the following lines can be read:

– Three quarks for Muster Mark!
Sure he hasn’t got much of a bark
And sure any he has it’s all beside the mark.
Note that Gell-Mann originally hypothesized only three quarks (u, d, s).

The distinctive feature of quarks is *confinement* meaning that they cannot be separated from each other and can only exist in twos or threes forming hadrons. Strangely enough for a chemist, the electric charge of quarks is 1/3 or 2/3 of *e*, the elementary charge (which does not appear to be elementary after all).

Force mediated by the boson	Boson		Rest energy ($E_0 = mc^2$), mass (m)			Charge	Found in year
	Symbol	Name	E_0 /MeV	m / m_e	m /u	q / e	
Electromagnetic	γ	photon	0	0	0	0	1905
Weak	W^-	W bosons	80 400	157 000	86	–1	1983
	W^+					+1	
	Z^0	Z boson	91 188	178 000	98	0	

Strong (color)	g	gluon	0	0	0	0	1970
Strong residual (nuclear)	$\pi^{\pm}$	pion	139.6	273.1	0.150	±1	1947
	π^{0}		135.0	264.1	0.145	0	1950

Table 3: Bosons are particles with integer spin ($s = 0,\ 1, \ldots$). Unshaded rows show elementary bosons (gauge bosons) which propagate the fundamental forces (Table 4) integrated into the Standard Model (SM). The yellowed row shows pions (π), which were hypothesized by Yukawa (1935) to mediate what is now called the residual strong force (nuclear force) which binds the nucleons (N) together. Pions are just a sample of the numerous types of mesons composed of one quark and an antiquark.

Force:	**Gravitational**	**Electroweak**		**Strong**	
Characteristics		Electromagnetic	Weak	Fundamental (color)	Residual (nuclear)
Acting on	mass-energy	electric charge	flavor ch.	color charge	residual color
Particles feeling it	all of them	electrically charged	leptons, q	q, g	hadrons
Known carriers		γ	W^{+}, W^{-}, Z^{0}	g	mesons
Range of force	∞	∞	~0.001 fm	∞	~1 fm
Dependence on distance *d*	decreasing ($\propto d^{-2}$)	decreasing ($\propto d^{-2}$)	steeply decreasing	does not decrease	steeply decreasing
Relative strength					
u–u at 0.001 fm	10^{-41}	1	0.8	25	
u–u at 0.01 fm	10^{-41}	1	0.0001	60	
p–p at 1 fm	10^{-36}	1	0.0000001		20

Table 4: Characteristics of the fundamental forces as well as of nuclear force. Weak force, in spite of its name, on short distance is much stronger than gravitational force. Its range, however, is very short, even shorter than that of the nuclear force. Its range is short because it is mediated by very massive particles (see Table 3). Note, e.g., that either “weight-class” of the carriers is heavier than a whole molecule of benzene, C_6H_6, which only weighs ~78 u. The column of the gravitational force is shaded gray to remind of its Janus-faced nature: under terrestrial conditions it has no effect whatsoever on nuclear processes, whereas on much larger scale it becomes a decisive factor in nucleosynthesis. Also, it is not integrated into the SM. The last yellowed column with the properties of nuclear force corresponds to the yellowed row in Table 3. The cells filled with a pattern of slanting lines are not applicable to the given force.

Elementary bosons, five of which are known to exist in all (*gauge bosons*), are *carriers of fundamental forces* (see Table 4). The photon (γ), their most familiar representative to a chemist, is the mediator of the electromagnetic force. They are listed together with some composite bosons (pions) in Table 3.

Hadrons are composite particles built directly from quarks. The name comes from Greek (hadrós ≈ thick, bulky). They have two types: *baryons* (from Greek barýs ≈ heavy) and *mesons* (from Greek mésos ≈ middle).

Mesons, consisting of an even number of fermions (i.e. one quark and one antiquark, $\mathrm{q\bar{q}}$) are bosons. (Note that 1/2 ± 1/2 is always an integer, namely either 0 or 1.) None of the mesons are stable. Even the charged pions ($\pi^{\pm}$) – hypothesized (as the mediators of the nuclear force between nucleons) by H. Yukawa (Nobel Prize in physics, 1949) 12 years before their actual discovery by C.F. Powell (Nobel Prize in physics, 1950) et al. – have a mere 18 ns for half-life. Some of the properties of pions are shown in the last row of Table 3. Their quark composition is as follows: π^{+} ($\mathrm{u\bar{d}}$), π^{-} ($\mathrm{\bar{u}d}$), π^{0} (mixed state from $\mathrm{u\bar{u}}$ and $\mathrm{d\bar{d}}$). The meson π^{0} is its own antiparticle.

Baryon		**Quark content**	**Rest energy ($E_0 = mc^2$), mass (m)**			**Charge**	**Found in year**
Symbol	**Name**		E_0 **/MeV**	m/m_e	m /**u**	q/e	
p	proton	u u d	938.3	1836.2	1.0073	+1	1919
$\mathrm{\bar{p}}$	antiproton	$\mathrm{\bar{u}\,\bar{u}\,\bar{d}}$				–1	1955
n	neutron	u d d	939.6	1838.7	1.0087	0	1932
$\mathrm{\bar{n}}$	antineutron	$\mathrm{\bar{u}\,\bar{d}\,\bar{d}}$				0	1957

Table 5: Barions, the “heavier” types of hadrons, are fermions. Only four examples are shown of the many that have been discovered: the nucleons ($s = 1/2$), because of their importance to chemists, as well as their antiparticles.

Baryons, consisting of an odd number of fermions (i.e. three quarks, qqq), are also fermions themselves. (Note that 1/2 ± 1/2 ± 1/2 cannot be an integer.) The antiparticles of baryons (antibaryons) are built from three antiquarks ($\mathrm{\bar{q}\,\bar{q}\,\bar{q}}$). Some examples of the huge variety of baryons are shown in Table 5.

Two of the baryons – the proton and the neutron – are known to every chemist as the building units of the atomic nucleus, called therefore together as *nucleons* N. The nucleons and their antiparticles – as their quark contents reveal – are different particles.

The proton is absolutely stable (and so is its antiparticle $\mathrm{\bar{p}}$). More strictly speaking: the half-life of the proton is certainly no shorter than 10^{32} a, which is more than a billion trillion times longer than the age of the Universe.

The free neutron, on the other hand, is an unstable particle with a half-life of only just a little longer than 10 min ($T_{1/2}$ = 614 s). This and the fact that there are a lot of stable nuclei in and around us containing neutrons helps to remember that the whole (e.g. the nucleus) is always more than just a simple collection of its parts (i.e. the $N + Z$ nucleons).

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Biographical Sketch

Sándor Nagy, the Honorary Theme Editor of Radiochemistry and Nuclear Chemistry, was born in Budapest, Hungary, in 1949. He received his MSc in chemistry from Eötvös Loránd University (ELTE), Budapest, in 1972. He got his Dr. Univ. degree from ELTE in 1975, where he had also studied applied mathematics for five years. He received his CSc (PhD) in nuclear chemistry from the Hungarian Academy of Sciences in 1996.

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