PHYSNET

MISN-0-255

FUNDAMENTAL FORCES AND ELEMENTARY PARTICLE CLASSIFICATION

neutron
photon
tau's neutrino
eta
electron's neutrino
lambda
muon
omega
electron
pion
proton
xi
Kaon
muon's neutrino

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FUNDAMENTAL FORCES AND ELEMENTARY PARTICLE CLASSIFICATION

by

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Input Skills:

1. Vocabulary: conservation of energy (MISN-0-21) or (MISN-0-416); momentum (MISN-0-15) or (MISN-0-413); charge, Coulomb force (MISN-0-114) or (MISN-0-419); gravitation (MISN-0-101); energy levels (MISN-0-215); photons, quanta (MISN-0-212).

Output Skills (Knowledge):

K1. Vocabulary: antiparticle, baryon, electromagnetic interaction, elementary particle, fundamental forces, hadron, lepton, muon, meson, neutrino, nucleon, pair annihilation, pair production, strong interaction, weak interaction.

K2. State the four fundamental forces of nature.

K3. List seven known elementary particles that do not take part in the strong interaction.

Output Skills (Problem Solving):

S1. Determine, from the nature of the particles involved in a given reaction, whether the reaction goes via the strong, electromagnetic, or weak interaction.

Post-Options:

1. "Conservation Laws for Elementary Particles" (MISN-0-256).
2. "Elementary Particle Interaction Times, Ranges, Cross Sections" (MISN-0-266).

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1. Introduction

1a. The Fundamental Constituents of Matter. The fundamental constituents of matter are called "elementary particles." What do we mean when we refer to a particle as an elementary particle? In the 19th century you would have meant the atoms of the chemical elements. These were thought to be the "basic building blocks," the ultimate indivisible subdivision of matter. But, as the studies of the early 20th century revealed, the atom is divisible, it does have internal structure, therefore it's not an elementary entity. These revelations led to the modified view that the fundamental constituents of matter were those things of which the atoms were made: the various kinds of nuclei (of which there was a different one for each different atom), the electron, and the photon.

1b. The Photon is a Constituent of Matter. The photon is the quantum of electromagnetic field and must be included among the elementary particles. This particle is observed when the constituents of an atom, arrayed in one of the excited atomic states, "rearrange themselves" into a state of lower total energy. The force field which determines which "arrangements" are possible in a given atom is the electromagnetic field. Upon rearrangement, when the system undergoes a transition from an excited state to a state of lower energy, a quantum of the field, a photon, carries away the excess energy (see Fig. 1).

1c. The Nucleus Has Internal Structure. The picture became both simplified and complicated around 1930 when it was discovered that the nucleus was not elementary; it has internal structure. It became simpler because it seemed that the number of elementary particles was reduced. All nuclei are composed of various combinations of neutrons and protons, collectively called "nucleons." So instead of there being hundreds of "fundamental nuclei," there are only two nucleons which were the fundamental constituents of nuclei.

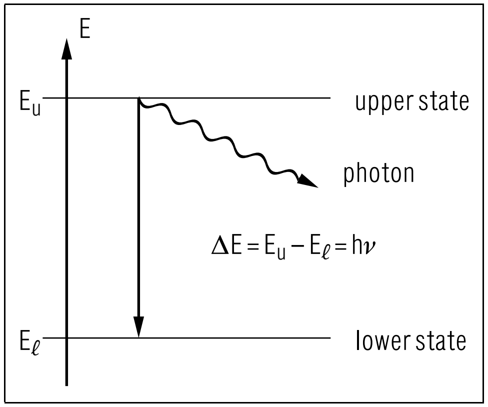

Figure 1. The transition of an atom from an excited state to the ground state, with the accompanying production of a photon.

2. The Fundemental Forces

2a. The Electromagnetic Interaction. The single basic force responsible for the structure of the atom is the "electromagnetic interaction." This single force field, together with the laws of quantum mechanics which, through the Schrödinger equation and the Pauli principle, tell you how the particles behave under the action of this force field, determines completely all chemical and biological properties of all matter. The prevailing viewpoint before the 1920's is illustrated in Table 1.

Table 1. The pre-1920 view of elementary particles and fundamental forces.

Elementary Particles	Interaction Forces
Nuclei (proton, helium, iron ...) electron photon	Electromagnetic

2b. The Strong Interaction. With the discovery of the internal structure of the nucleus, however, the situation became complicated because a new fundamental force field, the "strong interaction,"[1] hitherto unobserved in any macroscopic experience, was needed to explain how the nucleons were held together in a nucleus. The strong interaction is so-called because it apparently is stronger at short distances than the

[1] The current view of the basic strong interaction goes another stage beyond what is discussed here. There is now strong evidence that the proton, for example, has a substructure. The particles that make up the proton, called quarks, are held together by a more basic strong interaction, called "quantum chromodynamics," with mediating quanta called "gluons" [see "SU(3) and the Quark Model," MISN-0-282].

electromagnetic interaction. After all, it keeps protons together inside the nucleus in spite of the repulsive Coulomb force. To explain theoretically the properties of the nucleus you need to deal not only with the formidable Schrodinger equation (which is impossible to solve exactly for a many-particle system even if you do know exactly the properties of the force field involved, as you do in atomic problems) but you also need to deal with a force field whose detailed properties are unknown. Much of nuclear physics deals with the reverse problem: how to infer, from the properties of the myriad nuclei, what is the nature of the force field that is responsible for holding these systems together.

2c. The Weak Interaction. In addition to the strong interaction that is necessary to hold together the constituents of the nucleus, there is a "weak interaction," different from both the strong interaction and the electromagnetic interaction, which causes certain elementary particles to radioactively decay to other elementary particles. As an example of a decay via the weak interaction, the neutron decays to a proton with the emission of an electron and a massless particle called a "neutrino."

2d. The Gravitational Interaction. The fourth and weakest fundamental force is the "gravitational interaction." All of the elementary particles, including the massless photon and the neutrino, take part in the gravitational interaction. However, on the elementary particles scale the gravitational interaction is negligible compared with the other forces.

3. Elementary Particles

3a. Elementary Particles Circa 1930. By the 1930's physicists recognized four elementary particles and four fundamental forces (see Table 2). The interactions that the particles take part in are shown after the particle name. Note that only the neutron and proton take part in the strong interaction.[2] Thus, one might have ventured to say in the 1930's that the number of elementary particles was remarkably few. Furthermore these particles, interacting via the four fundamental forces were the components of all matter in the universe and that all phenomena in the universe could, in principle, be explained in terms of these particles and interactions. However, there were large gaps of knowledge to be filled in this picture before full understanding was achieved. First of all, the "quanta" of the strong interaction needed to be identified.[3]

[2]The neutron takes part in the electromagnetic interaction because it has a magnetic dipole moment.

Table 2. Elementary particles and the fields with which they interact, as viewed in the 1930's. The fields are denoted: S = Strong, E = Electromagnetic, W = Weak, and G = Gravitational.

Elementary Particles	**Interacting Fields**
Neutron	S, E, W, G
Proton	S, E, W, G
Electron	E, W, G
Photon	E, G

3b. Baryons, Mesons, and Leptons. When, in the late 1940's, what was thought to be these quanta were discovered, it turned out to be only the beginning. Over the years, not only did a complex spectrum of quanta of various masses appear, called "mesons," there also was discovered a spectrum of heavier strongly interacting particles, called "baryons." The "ground state" of this baryon spectrum is the familiar proton, and the first excited state is the neutron. The particles in these two spectra, all of which take part in the strong interaction, are collectively called "hadrons." The study of the properties of these hadrons and the search for what these properties tell about the nature of the strong interaction, occupies a significant part of what is called "high energy physics." An important step in unraveling the mysteries of hadronic physics is devising intelligent schemes for classifying these large numbers of hadrons.[4] A third spectrum of particles, called "leptons," or "light particles," do not participate in the strong interaction. The members of this class includes the electron, the muon (a heavy version of the electron) and neutrinos corresponding to the electron and the muon.

3c. Intrinsic Properties of the Elementary Particles. The intrinsic properties of the elementary particles are their mass, charge, spin, and magnetic moments. These properties are listed in Table 3 for the elementary particles we will encounter.

[3]Just as the quantum of the electromagnetic interaction is the photon, there was thought to be a corresponding quantum associated with the strong interaction.

[4]You may recall from chemistry that the classification of the elements in the periodic table of the elements played an important role in uncovering the structure of atoms.

Table 3. Intrinsic Properties of Elementary Particles. Mass in MeV/c^2, charge in units of e, spin in units of $\hbar$.

Family	**Particle**	**Symbol**	**Mass**	**Charge**	**Spin**
	photon	γ	0	0	1
LEPTONS	electron's neutrino	ν_e	0	0	1/2
	muon's neutrino	ν_μ	0	0	1/2
	tau's neutrino	ν_τ	0	0	1/2
	electron	e	0.511	−1	1/2
	muon	μ	105.66	−1	1/2
	tau	τ	1784.2	−1	1/2
HADRONS:					
mesons	pion	π^0	134.96	0	0
		π^+	139.57	+1	0
		π^-	139.57	−1	0
	Kaon	K^+	493.8	+1	0
		K^-	493.8	−1	0
		K^0	493.8	0	0
	eta	η	548.8	0	0
baryons	proton	p	938.26	+1	1/2
	neutron	n	939.55	0	1/2
	lambda	Λ^0	1115.6	0	1/2
	sigma	Σ^+	1189.4	+1	1/2
		Σ^0	1192.5	0	1/2
		Σ^-	1197.4	−1	1/2
	xi	Ξ^0	1315	0	1/2
		Ξ^-	1321.3	−1	1/2
	omega	Ω^-	1673	−1	3/2

3d. Pair Production and Annihilation. For every particle listed in Table 3 there is an "antiparticle" with the same mass but opposite charge. An antiparticle is symbolized by the particle symbol with a bar over it e.g. $\bar{p}$ is an antiproton. Exceptions to this nomenclature rule include the chargeless photon and π° meson, which are their own antiparticles, and the electron, whose antiparticle is given the special name of "positron" with the symbol e^+. A particle and its antiparticle may be created spontaneously out of energy in a process called "pair production." To conserve momentum, such a particle-antiparticle pair must have equal and opposite momenta. The energy required for such a process is equal to the rest

energy of both particles plus their total kinetic energy. When a particle and an antiparticle combine, they destroy each other in a process called "pair annihilation." The total energy of the pair (rest energy plus kinetic) is converted into two or more photons of equivalent energy. At least two photons must be created to conserve momentum in the process.

3e. Particle Decay. The majority of the particles in Table 3 have finite lifetimes and decay radioactively to some other state or group of particles with a characteristic mean life.[5] Most particles that decay have more than one final state, or "decay mode," available, although frequently one decay mode is dominant. The only particles which appear to be stable against decay are the photon, the electron, both neutrinos (ν_e and ν_μ) and the proton.[6]

4. Elementary Particle Reactions

4a. Introduction. What factors determine which one of the three fundamental interactions is responsible for a given reaction among elementary particles? Why, for example, does the Δ^+ always decay via the strong interaction, the π^+ always via the weak interaction, and the π^0 always via the electromagnetic interaction? Why does the reaction

$$\pi^- + \mathrm{p} \Rightarrow \pi^0 + \mathrm{n}$$

(where p and n are the proton and neutron) go via the strong interaction and not the weak interaction? The answer to all of these questions is that it depends upon which particles, on both sides of the reaction equation, are involved in the reaction. Some reactions involve more than one interaction. An example of this is

$$\gamma + \mathrm{p} \Rightarrow \pi^+ + \mathrm{n}$$

which requires the intervention of both the electromagnetic and strong interactions for it to take place. Most simple reactions, however, take place via a single interaction, and we'll restrict our concerns to one-interaction reactions.

4b. Conservation Laws Restrict Reactions. Conservation laws have been deduced for various classes of reactions and form a means of determining which interaction is responsible for any particular reaction.

[5]See "Exponential Decay: Observation, Derivation," MISN-0-311.
[6]See "Conservation Laws for Elementary Particles Reactions" (MISN-0-256).

If you consider a reaction and write down the reaction equation, the reaction will go if all appropriate conservation laws are satisfied. Energy, momentum, and charge must be conserved in any reaction.

4c. The Strong Interaction Takes Precedence. Any reaction will go via the strong interaction (hereafter denoted SI) unless at least one of the particles involved does not take part in the SI. Most of the 200 or so elementary particles, are hadrons – particles which interact via SI. A reaction involving hadrons such as

$$\pi^- + \mathrm{p} \Rightarrow \pi^0 + \mathrm{n}$$

may go via the weak interaction (hereafter denoted WI) as well as the SI. However, the SI is so much more likely (by a factor of 10^{13}) that the reaction has never been observed to go via the WI. In fact, there are only nine particles which do not interact strongly: these are the electron and its antiparticle, the positron, the muons, (μ and $\bar{\mu}$), the electron's neutrinos (ν_e and $\bar{\nu}_\mathrm{e}$), the muon's neutrinos (ν_μ and $\bar{\nu}_\mu$), and the photon.

4d. Leptons Indicate Weak Interaction. The first eight non-hadronic particles are the leptons, and their presence in a reaction signals the participation of the weak interaction. Note that these consist of 4 particles and their antiparticles. For example, consider the pion decay reaction:

$$\pi^- \Rightarrow \mu^- + \bar{\nu}_\mu$$

where $\bar{\nu}_\mu$ is the muon's antineutrino. The pion is a hadron but the reaction products are leptons, so the reaction can not go via SI. Furthermore, the presence of one of the four neutrinos or antineutrinos assures that the reaction goes via WI and not the electromagnetic interaction. The neutrinos are unique in that they only interact via WI.

4e. Photons Indicate Electromagnetic Interaction. Similarly, if you notice that a photon is involved in an reaction, then you can be assured that the reaction involves the electromagnetic interaction. Note also, that all of the particles currently known take part in the WI except the photon. More about the classification of these particles can be found in the text and assigned readings.

Acknowledgments

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Glossary

- **antiparticle**: a counterpart of a given particle with the same mass but opposite charge and magnetic moment.
- **baryon**: a family, or spectrum of heavy particles, the ground state of which is the proton.
- **electromagnetic interaction**: an interaction between elementary particles mediated by the exchange of a photon.
- **elementary particle**: a fundamental constituent of matter.
- **fundamental forces**: four basic physical interactions between elementary particles which include strong, electromagnetic, weak, and gravitational interactions.
- **hadron**: any particle which may participate in the strong interaction, i.e., a baryon or a meson.
- **lepton**: a family of "light particles" which as a class, together with the photon, does not interact strongly. Members of the lepton family include the electron and its neutrino, the muon and its neutrino, and the antiparticles of each of the above particles.
- **meson**: a family of intermediate mass particles which mediate the strong interaction between baryons.
- **muon**: a lepton which is identical to an electron, except that it is roughly 200 times more massive.
- **neutrino**: a virtually massless lepton which comes in two varieties (an electron's neutrino and a muon's neutrino).
- **nucleon**: a constituent of the nucleus, i.e., a proton or a neutron.
- **pair annihilation**: the conversion of a particle-antiparticle pair into two or more photons.
- **pair production**: the creation of a particle-antiparticle pair out of energy.

- **strong interaction**: an interaction between elementary particles mediated by the exchange of a meson between two baryons or two mesons.
- **weak interaction**: a fundamental interaction between elementary particles that is weaker than the strong and electromagnetic interaction. This interaction is responsible for the radioactive decay of many of the elementary particles.

MODEL EXAM

1. See Output Skills K1-K3 in this module's *ID Sheet*. One or more of these skills may be on the actual exam.
2. An antiproton, $\overline{\mathrm{p}}$, and a proton, p, may "annihilate" via the strong interaction. The products resulting from the annihilation must carry off the energy, net charge, momentum, etc., that the p and $\overline{\mathrm{p}}$ had to begin with. Many possible final states of reaction products exist.

   a. For the three possible annihilation reactions considered below, which interaction is responsible for each reaction?

      i) $\mathrm{p} + \overline{\mathrm{p}} \Rightarrow \nu_{\mathrm{e}} + \bar{\nu}_{\mathrm{e}}$

      ii) $\mathrm{p} + \overline{\mathrm{p}} \Rightarrow \pi^- + \pi^+$

      iii) $\mathrm{p} + \overline{\mathrm{p}} \Rightarrow \gamma + \gamma$

   b. Which one of these reactions is most likely to happen and which is least likely?

Brief Answers:

1. See this module's *text*.
2. a. i) weak interaction

      ii) strong interaction

      iii) electromagnetic interaction

   b. most likely: $\mathrm{p} + \overline{\mathrm{p}} \Rightarrow \pi^- + \pi^+$

      least likely: $\mathrm{p} + \overline{\mathrm{p}} \Rightarrow \nu_{\mathrm{e}} + \bar{\nu}_{\mathrm{e}}$