

NUCLEAR AND PARTICLE PHYSICS



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Nuclear and Particle Physics

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Prelude to Nuclear and Particle Physics

In this course I shall discuss nuclear and particle physics on a somewhat phenomenological level. The mathematical sophistication shall be rather limited, with an emphasis on the physics and on symmetry aspects.

Course text:

- W.E. Burcham and M. Jobes, Nuclear and Particle Physics, Addison Wesley Longman Ltd, Harlow, 1995.

Supplementary references

- B.R. Martin and G. Shaw, Particle Physics, John Wiley and sons, Chichester, 1996. A solid book on particle physics, slightly more advanced than this course.
- G.D. Coughlan and J.E. Dodd, The ideas of particle physics, Cambridge University Press, 1991. A more hand waving but more exciting introduction to particle physics. Reasonably up to date.
- N.G. Cooper and G.B. West (eds.), Particle Physics: A Los Alamos Primer, Cambridge University Press, 1988. A bit less up to date, but very exciting and challenging book.
- R. C. Fernow, Introduction to experimental Particle Physics, Cambridge University Press. 1986. A good source for experimental techniques and technology. A bit too advanced for the course.
- F. Halzen and A.D. Martin, Quarks and Leptons: An introductory Course in particle physics, John Wiley and Sons, New York, 1984. A graduate level text book.
- F.E. Close, An introduction to Quarks and Partons, Academic Press, London, 1979. Another highly recommendable graduate text.
- The particle adventure: . A very nice—but slightly low level—introduction to particle physics.

Thumbnail: Simulated Large Hadron Collider CMS particle detector data depicting a Higgs boson produced by colliding protons decaying into hadron jets and electrons (CC BY-SA 3.0; CERN).

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CHAPTER OVERVIEW

1: A History of Particle Physics

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Thumbnail: A diagram summarizing the tree-level interactions between elementary particles described in the Standard Model. Vertices (darkened circles) represent types of particles, and edges (blue arcs) connecting them represent interactions that can take place. The organization of the diagram is as follows: the top row of vertices (leptons and quarks) are the matter particles; the second row of vertices (photon, W/Z , gluons) are the force mediating particles; and the bottom row is the Higgs boson. (Public Domain; TriTertButoxy).

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1.1: Nobel Prizes in Particle Physics

1903	BECQUEREL, ANTOINE HENRI, France, École Polytechnique, Paris, b. 1852, d. 1908:	"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity";
	CURIE, PIERRE, France, cole municipale de physique et de chimie industrielles, (Municipal School of Industrial Physics and Chemistry), Paris, b. 1859, d. 1906; and his wife CURIE, MARIE, née SKŁODOWSKA, France, b. 1867 (in Warsaw, Poland), d. 1934:	"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"
1922	BOHR, NIELS, Denmark, Copenhagen University, b. 1885, d. 1962:	"for his services in the investigation of the structure of atoms and of the radiation emanating from them"
1927	COMPTON, ARTHUR HOLLY, U.S.A., University of Chicago b. 1892, d. 1962:	"for his discovery of the effect named after him";
	and WILSON, CHARLES THOMSON REES, Great Britain, Cambridge University, b. 1869 (in Glencorse, Scotland), d. 1959:	"for his method of making the paths of electrically charged particles visible by condensation of vapour"
1932	HEISENBERG, WERNER, Germany, Leipzig University, b. 1901, d. 1976:	"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen"
	SCHRÖDINGER, ERWIN, Austria, Berlin University, Germany, b. 1887, d. 1961; and DIRAC, PAUL ADRIEN MAURICE, Great Britain, Cambridge University, b. 1902, d. 1984:	"for the discovery of new productive forms of atomic theory"
1935	CHADWICK, Sir JAMES, Great Britain, Liverpool University, b. 1891, d. 1974:	"for the discovery of the neutron"
1936	HESS, VICTOR FRANZ, Austria, Innsbruck University, b. 1883, d. 1964:	"for his discovery of cosmic radiation"; and
	ANDERSON, CARL DAVID, U.S.A., California Institute of Technology, Pasadena, CA, b. 1905, d. 1991:	"for his discovery of the positron"
1938	FERMI, ENRICO, Italy, Rome University, b. 1901, d. 1954:	"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"
1939	LAWRENCE, ERNEST ORLANDO, U.S.A., University of California, Berkeley, CA, b. 1901, d. 1958:	"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

1943	STERN, OTTO, U.S.A., Carnegie Institute of Technology, Pittsburg, PA, b. 1888 (in Sorau, then Germany), d. 1969:	"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"
1944	RABI, ISIDOR ISAAC, U.S.A., Columbia University, New York, NY, b. 1898, (in Rymanow, then Austria-Hungary) d. 1988:	"for his resonance method for recording the magnetic properties of atomic nuclei"
1945	PAULI, WOLFGANG, Austria, Princeton University, NJ, U.S.A., b. 1900, d. 1958:	"for the discovery of the Exclusion Principle, also called the Pauli Principle"
1948	BLACKETT, Lord PATRICK MAYNARD STUART, Great Britain, Victoria University, Manchester, b. 1897, d. 1974:	"for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation"
1949	YUKAWA, HIDEKI, Japan, Kyoto Imperial University and Columbia University, New York, NY, U.S.A., b. 1907, d. 1981:	"for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"
1950	POWELL, CECIL FRANK, Great Britain, Bristol University, b. 1903, d. 1969:	"for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method"
1951	COCKCROFT, Sir JOHN DOUGLAS, Great Britain, Atomic Energy Research Establishment, Harwell, Didcot, Berks., b. 1897, d. 1967; and WALTON, ERNEST THOMAS SINTON, Ireland, Dublin University, b. 1903, d. 1995:	"for their pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles"
1955	LAMB, WILLIS EUGENE, U.S.A., Stanford University, Stanford, CA, b. 1913:	"for his discoveries concerning the fine structure of the hydrogen spectrum"; and
	KUSCH, POLYKARP, U.S.A., Columbia University, New York, NY, b. 1911 (in Blankenburg, then Germany), d. 1993:	"for his precision determination of the magnetic moment of the electron"
1957	YANG, CHEN NING, China, Institute for Advanced Study, Princeton, NJ, U.S.A., b. 1922; and LEE, TSUNG-DAO, China, Columbia University, New York, NY, U.S.A., b. 1926:	"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"
1959	SEGRÉ, EMILIO GINO, U.S.A., University of California, Berkeley, CA, b. 1905 (in Tivoli, Italy), d. 1989; and CHAMBERLAIN, OWEN, U.S.A., University of California, Berkeley, CA, b. 1920:	"for their discovery of the antiproton"
1960	GLASER, DONALD A., U.S.A., University of California, Berkeley, CA, b. 1926:	"for the invention of the bubble chamber"

1961	HOFSTADTER, ROBERT, U.S.A., Stanford University, Stanford, CA, b. 1915, d. 1990:	"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"; and
	MÖSSBAUER, RUDOLF LUDWIG, Germany, Technische Hochschule, Munich, and California Institute of Technology, Pasadena, CA, U.S.A., b. 1929:	"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"
1963	WIGNER, EUGENE P., U.S.A., Princeton University, Princeton, NJ, b. 1902 (in Budapest, Hungary), d. 1995:	"for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles";
	GOEPPERT-MAYER, MARIA, U.S.A., University of California, La Jolla, CA, b. 1906 (in Kattowitz, then Germany), d. 1972; and JENSEN, J. HANS D., Germany, University of Heidelberg, b. 1907, d. 1973:	"for their discoveries concerning nuclear shell structure"
1965	TOMONAGA, SIN-ITIRO, Japan, Tokyo, University of Education, Tokyo, b. 1906, d. 1979;	"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"
	SCHWINGER, JULIAN, U.S.A., Harvard University, Cambridge, MA, b. 1918, d. 1994; and FEYNMAN, RICHARD P., U.S.A., California Institute of Technology, Pasadena, CA, b. 1918, d. 1988:	
1967	BETHE, HANS ALBRECHT, U.S.A., Cornell University, Ithaca, NY, b. 1906 (in Strasbourg, then Germany):	"for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"
1968	ALVAREZ, LUIS W., U.S.A., University of California, Berkeley, CA, b. 1911, d. 1988:	"for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using hydrogen bubble chamber and data analysis"
1969	GELL-MANN, MURRAY, U.S.A., California Institute of Technology, Pasadena, CA, b. 1929:	"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

1975	BOHR, AAGE, Denmark, Niels Bohr Institute, Copenhagen, b. 1922; MOTTELSON, BEN, Denmark, Nordita, Copenhagen, b. 1926 (in Chicago, U.S.A.); and RAINWATER, JAMES, U.S.A., Columbia University, New York, NY, b. 1917, d. 1986:	"for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection"
1976	RICHTER, BURTON, U.S.A., Stanford Linear Accelerator Center, Stanford, CA, b. 1931; TING, SAMUEL C. C., U.S.A., Massachusetts Institute of Technology (MIT), Cambridge, MA, (European Center for Nuclear Research, Geneva, Switzerland), b. 1936:	"for their pioneering work in the discovery of a heavy elementary particle of a new kind"
1979	GLASHOW, SHELDON L., U.S.A., Lyman Laboratory, Harvard University, Cambridge, MA, b. 1932; SALAM, ABDUS, Pakistan, International Centre for Theoretical Physics, Trieste, and Imperial College of Science and Technology, London, Great Britain, b. 1926, d. 1996; and WEINBERG, STEVEN, U.S.A., Harvard University, Cambridge, MA, b. 1933:	"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including inter alia the prediction of the weak neutral current"
1980	CRONIN, JAMES, W., U.S.A., University of Chicago, Chicago, IL, b. 1931; and FITCH, VAL L., U.S.A., Princeton University, Princeton, NJ, b. 1923:	"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"
1983	CHANDRASEKHAR, SUBRAMANYAN, U.S.A., University of Chicago, Chicago, IL, b. 1910 (in Lahore, India), d. 1995: FOWLER, WILLIAM A., U.S.A., California Institute of Technology, Pasadena, CA, b. 1911, d. 1995:	"for his theoretical studies of the physical processes of importance to the structure and evolution of the stars" "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"
1984	RUBBIA, CARLO, Italy, CERN, Geneva, Switzerland, b. 1934; and VAN DER MEER, SIMON, the Netherlands, CERN, Geneva, Switzerland, b. 1925:	"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

1988	LEDERMAN, LEON M., U.S.A., Fermi National Accelerator Laboratory, Batavia, IL, b. 1922; SCHWARTZ, MELVIN, U.S.A., Digital Pathways, Inc., Mountain View, CA, b. 1932; and STEINBERGER, JACK, U.S.A., CERN, Geneva, Switzerland, b. 1921 (in Bad Kissingen, FRG):	”for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino”
1990	FRIEDMAN, JEROME I., U.S.A., Massachusetts Institute of Technology, Cambridge, MA, b. 1930; KENDALL, HENRY W., U.S.A., Massachusetts Institute of Technology, Cambridge, MA, b. 1926; and TAYLOR, RICHARD E., Canada, Stanford University, Stanford, CA, U.S.A., b. 1929:	”for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics”
1992	CHARPAK, GEORGES, France, École Supérieure de Physique et Chimie, Paris and CERN, Geneva, Switzerland, b. 1924 (in Poland):	”for his invention and development of particle detectors, in particular the multiwire proportional chamber”
1995		”for pioneering experimental contributions to lepton physics”
	PERL, MARTIN L., U.S.A., Stanford University, Stanford, CA, U.S.A., b. 1927, REINES, FREDERICK, U.S.A., University of California at Irvine, Irvine, CA, U.S.A., b. 1918, d. 1998:	”for the discovery of the tau lepton” ”for the detection of the neutrino”

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1.2: A Timeline of Particle Physics

Year	Experiment	Theory
1927	β decay discovered	
1928		Paul Dirac: Wave equation for electron
1930		Wolfgang Pauli suggests existence of neutrino
1931	Positron discovered	
1931		Paul Dirac realises that positrons are part of his equation
1931	Chadwick discovers neutron	
1933/4		Fermi introduces theory for β decay
1933/4		Hideki Yukawa discusses nuclear binding in terms of pions
1937	μ discovered in cosmic rays	
1938	Baryon number conservation	
1946		μ is not Yukawa's particle
1947	π^+ discovered in cosmic rays	
1946-50		Tomonaga, Schwinger and Feynman develop QED
1948	First artificial π 's	
1949	K^+ discovered	
1950	$\pi^0 \rightarrow \gamma\gamma$	
1951	"V-particles" Λ^0 and K^0	
1952	Δ : excited state of nucleon	
1954		Yang and Mills: Gauge theories
1956		Lee and Yang: Weak force might break parity!
1956	CS Wu and Ambler: Yes it does.	
1961		Eightfold way as organising principle
1962	ν_μ and ν_e	
1964		Quarks (Gell-man and Zweig) u, d, s
1964		Fourth quark suggested (c)
1965		Colour charge all particles are colour neutral!
1967		Glashow-Salam-Weinberg unification of electromagnetic and weak interactions. Predict Higgs boson.
1968-69	DIS at SLAC constituents of proton seen!	

Year	Experiment	Theory
1973		QCD as the theory of coloured interactions. Gluons.
1973		Asymptotic freedom
1974	J/ψ ($c\bar{c}$) meson	
1976	D^0 meson ($\bar{u}c$) confirms theory.	
1976	τ lepton!	
1977	b (bottom quark). Where is top?	
1978	Parity violating neutral weak interaction seen	
1979	Gluon signature at PETRA	
1983	$W^\pm$ and Z^0 seen at CERN	
1989	SLAC suggests only three generations of (light!) neutrinos	
1995	t (top) at 175 GeV mass	
1997	New physics at HERA (200 GeV)	

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1.3: Earliest Stages

The early part of the 20th century saw the development of quantum theory and nuclear physics, of which particle physics detached itself around 1950. By the late 1920's one knew about the existence of the atomic nucleus, the electron and the proton. I shall start this history in 1927, the year in which the new quantum theory was introduced. In that year β decay was discovered as well: Some elements emit electrons with a continuous spectrum of energy. Energy conservation doesn't allow for this possibility (nuclear levels are discrete!). This led to the realisation, in 1929, by Wolfgang Pauli that one needs an additional particle to carry away the remaining energy and momentum. This was called a neutrino (small neutron) by Fermi, who also developed the first theoretical model of the process in 1933 for the decay of the neutron

$$n \rightarrow p + e^- + \bar{\nu}_e$$

which had been discovered in 1931.

In 1928 Paul Dirac combined quantum mechanics and relativity in an equation for the electron. This equation had some more solutions than required, which were not well understood. Only in 1931 Dirac realised that these solutions are physical: they describe the positron, a positively charged electron, which is the *antiparticle* of the electron. This particle was discovered in the same year, and I would say that particle physics starts there.

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1.4: Fission and Fusion

Fission of radioactive elements was already well established in the early part of the century, and activation by neutrons, to generate more unstable isotopes, was investigated before fission of natural isotopes was seen. The inverse process, fusion, was understood somewhat later, and Niels Bohr developed a model describing the nucleus as a fluid drop. This model - the collective model - was further developed by his son Aage Bohr and Ben Mottelson. A very different model of the nucleus, the shell model, was designed by Maria Goeppert-Mayer and Hans Jensen in 1952, concentrating on individual nucleons. The dichotomy between a description as individual particles and as a collective whole characterises much of “low-energy” nuclear physics.

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1.5: Low-Energy Nuclear Physics

The field of low-energy nuclear physics, which concentrates mainly on structure of and low-energy reaction on nuclei, has become one of the smaller parts of nuclear physics (apart from in the UK). Notable results have included better understanding of the nuclear medium, high-spin physics, super deformation and halo nuclei. Current experimental interest is in those nuclei near the “drip lines” which are of astrophysical importance, as well as of other interest.

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1.6: Medium-energy Nuclear Physics

Medium energy nuclear physics is interested in the response of a nucleus to probes at such energies that we can no longer consider nucleons to be elementary particles. Most modern experiments are done by electron scattering, and concentrate on the role of QCD (see below) in nuclei, the structure of mesons in nuclei and other complicated questions.

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1.7: High-Energy Nuclear Physics

This is not a very well-defined field, since particle physicists are also working here. It is mainly concerned with ultra-relativistic scattering of nuclei from each other, addressing questions about the quark-gluon plasma. It should be nuclear physics, since we consider “dirty” systems of many particles, which are what nuclear physicists are good at.

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1.8: Mesons, Leptons and Neutrinos

In 1934 Yukawa introduces a new particle, the pion (π), which can be used to describe nuclear binding. He estimates it's mass at 200 electron masses. In 1937 such a particle is first seen in cosmic rays. It is later realised that it interacts too weakly to be the pion and is actually a lepton (electron-like particle) called the μ . The π is found (in cosmic rays) and is the progenitor of the μ 's that were seen before:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The next year artificial pions are produced in an accelerator, and in 1950 the neutral pion is found,

$$\pi^0 \rightarrow \gamma\gamma.$$

This is an example of the conservation of electric charge. Already in 1938 Stuckelberg had found that there are other conserved quantities: the number of baryons (n and p and ...) is also conserved!

After a serious break in the work during the latter part of WWII, activity resumed again. The theory of electrons and positrons interacting through the electromagnetic field (photons) was tackled seriously, and with important contributions of (amongst others) Tomonaga, Schwinger and Feynman was developed into a highly accurate tool to describe hyperfine structure.

Experimental activity also resumed. Cosmic rays still provided an important source of extremely energetic particles, and in 1947 a "strange" particle (K^+) was discovered through its very peculiar decay pattern. Balloon experiments led to additional discoveries: So-called V particles were found, which were neutral particles, identified as the Λ^0 and K^0 . It was realised that a new conserved quantity had been found. It was called strangeness.

The technological development around WWII led to an explosion in the use of accelerators, and more and more particles were found. A few of the important ones are the antiproton, which was first seen in 1955, and the Δ , a very peculiar excited state of the nucleon, that comes in four charge states Δ^{++} , Δ^+ , Δ^0 , Δ^- .

Theory was developing rapidly as well. A few highlights: In 1954 Yang and Mills develop the concept of gauged Yang-Mills fields. It looked like a mathematical game at the time, but it proved to be the key tool in developing what is now called "the standard model".

In 1956 Yang and Lee make the revolutionary suggestion that parity is not necessarily conserved in the weak interactions. In the same year "madam" CS Wu and Alder show experimentally that this is true: God is weakly left-handed!

In 1957 Schwinger, Bludman and Glashow suggest that all weak interactions (radioactive decay) are mediated by the charged bosons $W^\pm$. In 1961 Gell-Mann and Ne'eman introduce the "eightfold way": a mathematical taxonomy to organise the particle zoo.

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1.9: The sub-structure of the nucleon (Quantum Chromodynamics)

In 1964 Gell-Mann and Zweig introduce the idea of quarks: particles with spin 1/2 and fractional charges. They are called up, down and strange and have charges $2/3, -1/3, -1/3$ times the electron charge.

Since it was found (in 1962) that electrons and muons are each accompanied by their own neutrino, it is proposed to organise the quarks in multiplets as well:

$$\begin{array}{ccc} e & \nu_e & (u, d) \\ \mu & \nu_\mu & (s, c) \end{array}$$

This requires a fourth quark, which is called charm.

In 1965 Greenberg, Han and Nambu explain why we can't see quarks: quarks carry color charge, and all observe particles must have color charge 0. Mesons have a quark and an antiquark, and baryons must be build from three quarks through its peculiar symmetry.

The first evidence of quarks is found (1969) in an experiment at SLAC, where small pips inside the proton are seen. This gives additional impetus to develop a theory that incorporates some of the ideas already found: this is called QCD. It is shown that even though quarks and gluons (the building blocks of the theory) exist, they cannot be created as free particles. At very high energies (very short distances) it is found that they behave more and more like real free particles. This explains the SLAC experiment, and is called asymptotic freedom.

The J/ψ meson is discovered in 1974, and proves to be the $c\bar{c}$ bound state. Other mesons are discovered ($D0, \bar{u}c$) and agree with QCD.

In 1976 a third lepton, a heavy electron, is discovered (τ). This was unexpected! A matching quark (b for bottom or beauty) is found in 1977. Where is its partner, the top? It will only be found in 1995, and has a mass of $175 \text{ GeV}/c^2$ (similar to a lead nucleus...)! Together with the conclusion that there are no further light neutrinos (and one might hope no quarks and charged leptons) this closes a chapter in particle physics.

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1.10: The W^+ , W^- , and Z bosons

On the other side a electro-weak interaction is developed by Weinberg and Salam. A few years later 't Hooft shows that it is a well-posed theory. This predicts the existence of three extremely heavy bosons that mediate the weak force: the Z^0 and the $W^\pm$. These have been found in 1983. There is one more particle predicted by these theories: the Higgs particle. Must be very heavy!

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1.11: GUTS, Supersymmetry, and Supergravity

This is not the end of the story. The standard model is surprisingly inelegant, and contains way to many parameters for theorists to be happy. There is a dark mass problem in astrophysics – most of the mass in the universe is not seen! This all leads to the idea of an underlying theory. Many different ideas have been developed, but experiment will have the last word! It might already be getting some signals: researchers at DESY see a new signal in a region of particle that are 200 GeV heavy – it might be noise, but it could well be significant!

There are several ideas floating around: one is the grand-unified theory, where we try to combine all the disparate forces in nature in one big theoretical frame. Not unrelated is the idea of supersymmetries: For every “boson” we have a “fermion”. There are some indications that such theories may actually be able to make useful predictions.

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1.12: Extraterrestrial Particle Physics

One of the problems is that it is difficult to see how we can actually build a microscope that can look at a small enough scale, i.e., how we can build an accelerator that will be able to accelerate particles to high enough energies? The answer is simple – and has been more or less the same through the years: Look at the cosmos. Processes on an astrophysical scale can have amazing energies.

Balloon experiments

One of the most used techniques is to use balloons to send up some instrumentation. Once the atmosphere is no longer the perturbing factor it normally is, one can then try to detect interesting physics. A problem is the relatively limited payload that can be carried by a balloon.

Ground based systems

These days people concentrate on those rare, extremely high energy processes (of about 10^{29} eV), where the effect of the atmosphere actually helps detection. The trick is to look at showers of (lower-energy) particles created when such a high-energy particle travels through the earth's atmosphere.

Dark matter

One of the interesting cosmological questions is whether we live in an open or closed universe. From various measurements we seem to get conflicting indications about the mass density of (parts of) the universe. It seems that the ratio of luminous to non-luminous matter is rather small. Where is all that “dark mass”: Mini-Jupiter's, small planetoids, dust, or new particles....

(Solar) Neutrinos

The neutrino is a very interesting particle. Even though we believe that we understand the nuclear physics of the sun, the number of neutrinos emitted from the sun seems to anomalously small. Unfortunately this is very hard to measure, and one needs quite a few different experiments to disentangle the physics behind these processes. Such experiments are coming on line in the next few years. These can also look at neutrinos coming from other astrophysical sources, such as supernovas, and enhance our understanding of those processes. Current indications from Kamiokande are that neutrinos do have mass, but oscillation problems still need to be resolved.

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CHAPTER OVERVIEW

2: Experimental Tools

In this chapter we shall concentrate on the experimental tools used in nuclear and particle physics. Mainly the present ones, but it is hard to avoid discussing some of the history.

[2.1: Accelerators](#)

[2.2: Targets](#)

[2.3: Main Experimental Facilities](#)

[2.4: Detectors](#)

Thumbnail: A sketch of a cyclotron.

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