The Project Physics Course

Resource Book **B**

A Supplemental Unit

Discoveries in Physics

Resource Book

Supplemental Unit **B**

Discoveries in Physics

by

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Table of Contents

NOTES ON THE TEXT

ANSWERS TO END-OF-CHAPTER QUESTIONS

NOTES ON THE TEXT

PROLOGUE

How *do* scientific discoveries occur? How *do* scientists go about solving problems? The four examples in this unit are quite different. Their careful study should lessen any faith in a naive idea that there is THE scientific method. Note the questions raised in the text about the conditions and timing of scientific discoveries. Class discussions centering on these questions will emphasize the major points in this unit.

CHAPTER 1

The film loop "Kepler's Laws" and the transparencies T-17, "Orbit Parameters," and T-18, "Motion Under a Central Force" may be useful for a review of planetary motion.

Page 6. Notice that Herschel was engaged in a systematic count of the stars visible in his telescope. Also, he was alert to unusual objects that moved into his field of view.

Page 7. Notice also that Johann Bode, whose name appears later for another reason, used the orbit computed by Lexell as the basis for searching old records that did contain earlier positions observed for Uranus. Often careful records can be searched for results unanticipated by the recorder.

Page 8. A variety of possible explanations were postulated to account for the scandalous deviations of Uranus' position from those predicted by Bouvard. Discussion of these possibilities, and others that students may propose, illustrate the initial qualitative screening of ideas and proposals within scientific work. Only after the possibility of an outer perturbing planet was fairly well accepted would anyone undertake the difficult task of trying to predict its position.

Page 12. The offering of a prize by the University of Göttingen was a fairly common means of attracting able men to work on a problem. Now such prizes are rarely, if ever, offered; they are not needed.

Page 12. Despite the prize for a mathematical prediction of the planet's position, both Adams and Leverrier had difficulties getting anyone to search near their predicted positions. Galle, having at hand the unpublished star map of that region, had an advantage over the British observers. The systematic approach used by the British observers would have been, indeed had already been, successful; but was costly in terms of time for observing and reducing the records.

Page 14. Bode's law for the spacing of the planetary orbits deserves a note here. Like Kepler, Bode sought a pattern among the orbits. Despite the "forced fit" for Mercury, Bode's pattern fits fairly well. Since neither the mass nor solar distance of the suspected planet was known, both Adams and Leverrier assumed a solar distance by extrapolating Bode's law. As appears later, neither Neptune nor Pluto are near the solar distances predicted by Bode's law.

NOTES ON THE EXPERIMENT, PAGE 22

The method of graphical iteration, used by Newton in Proposition 1 of the *Principia* and reproduced as Article 10 in Reader 2, was used in Experiment 21 (Experiment II-9 in the revised *Student Handbook*) to develop an orbit for a "comet." If your students have not done Experiment 21, sufficient details are given here so they can proceed on this more complex analysis. The approach uses the idea of repeated blows toward a center of force at regular intervals. By vector addition the continued inertial motion in a straight line is combined with the effects of the accelerations to yield a new velocity vector and displacement for the next iteration interval. If two large masses are simultaneously attracting a small body in motion, as in this problem, the two attractions can be combined by vector addition, as in Figures 1b, 2a, and 2b of the text.

The initial conditions of the masses: their relative positions and their velocities, are arbitrary. However, for this experiment, which must yield quantities which can be graphed by a student, the initial conditions are rather critical. Many trial conditions resulted in orbits which threw the small planet out of the planetary system.

The scale of the diagram is important. If it is too small, the vector additions are very difficult to make accurately. If it is too large, the graph becomes unwieldy. Since the large planet is for convenience put initially into a circular orbit at 4 AU from the sun, it moves at a uniform rate in the circular orbit unperturbed by the small planet. The data for the two initial orbits are:

	Planet	
	Large	Small
Orbital radius, R, in AU	4.0	3.1
Period, T, in days (365 × R 3/2)	2920.0	1990.0
60/T. fractional period per iteration interval	0.0205	0.0301
Degrees per 60 days (360 × 60/T)	7.40	10.84
Speed in AU/60 days	0.516	0.586
Scaled speed/60 days	1.29 inches *3.28 cm*	1.47 *3.72*

The graphs for the values of the displacement as a function of *R* should be drawn with some care. By assuming a mass for the large planet of 1/100 of the sun's mass, the relation between the two accelerating effects at the same distance are 1:10;

$$\frac{F_{\text{planet}}}{F_{\text{sun}}} = \frac{\dfrac{G M_p}{R^2_p}}{G\dfrac{M_s}{R^2_s}}, \quad \text{since } m_p = \frac{M_s}{100},$$

then $\dfrac{F_p}{F_s} = \dfrac{M_s}{100 R_p^2} X \dfrac{R_s^2}{M_s}$

When $F_p = F_s$, $10 R_p = R_s$.

Values for these graphs are given in inches and *centimeters* for graphing the *R* vs *F* curves in either set of units. Graph paper subdivided in 1/20 inch or 1/10 cm units is easy to use and leads to higher accuracy.

Predicted unperturbed positions for the small planet are important to emphasize the effects of the perturbations caused by the large planet. Selection of the starting places, as indicated in Figure 4 of the text is important. However, some brave students may wish to choose other starting places; or, if they enjoy doing the experiment as outlined in the text, they may make a second analysis with different starting conditions. Twenty iteration steps are recommended because that carries the small planet through sizable orbital changes to a point where the perturbations of the large planet become negligible. The remainder of the new orbit can be approximated from the positions given for S 21, S 25, S 28, S 29, and the approximate positions of perihelion and aphelion. Note that the angles to these positions are to be laid off *clockwise* from the sun-small planet line through the starting position, S 1.

Our plot gave the following answers to the questions at the end of the experiment:

1. Average distance of the small planet from sun (the semi-major axis of the new orbit) as 2.25 AU.

2. The new period is 3.35 years ($2.25^{3/2}$).

3. The eccentricity is about 0.45; $e = c/a = 1/2.25$.

4. This is a temporary orbit for the small planet. The large planet will continue to attract it and intermittently change its orbit. This occurs for the orbits of the asteroids and short-period comets which come near Jupiter every few cycles.

5. The small planet will come fairly close to the large planet after only 6 years. This is an example of the "chase problem" discussed in Unit 2 of the text. There the frequency, *f*, of close approaches, is given by $f_{SL} = f_S - f_L$. In terms of the periods, *T*, this is $1/T_{SL} = 1/T_S - 1/T_L$, which upon substituting the periods becomes $1/T_{SL} = 1/3.35 - 1/8$, or 0.173. Hence T_{SL} is about 5.8 years until another close approach. Small perturbations will continually modify the orbit of the small planet slightly.

6. After point S 3, the small planet would slow down and fall behind the predicted positions. Compare the perturbed and the unperturbed positions on the plot.

7. On the plot between S 1 and S 4 the small planet is being accelerated, just as Uranus was by Neptune before 1822. Between points S 4 and S 15 the small planet is retarded in its motion and is pulled outward toward the large planet. Its orbit is drastically changed. After point S 15 the effect of the large planet diminishes rapidly as the small planet moves along its new orbit.

CHAPTER 2

Page 33. Technological developments allowing much lower pressures in evacuated tubes permitted new experiments on the current-carrying characteristics of gases at low pressures. The gas discharge tubes (Plücker tubes) used in the lab as the source of gaseous spectra have relatively high pressure. The discovery of the strange greenish glow in discharge tubes was followed by a wide variety of experimentation. This is typical—mapping the territory of the phenomenon, finding the conditions which were stable, and those which influenced the newly found phenomenon.

Page 34. Even as new experimental results were being found, possible explanations were proposed. In this case only two possibilities were proposed; either the rays were electromagnetic, or they were corpuscular.

Page 36. Now Schuster proposes a modification of Crooke's particle proposal, perhaps the particles are charged fragments of molecules. The role of analogy is worth noting. His analysis for the derivation of q/m is simple and both B and R can be measured rather accurately. His estimation of v at least bracketed the range for q/m. Transparency T-32 "Magnetic Fields and Moving Charges" could be used here for review.

Page 38. The work of Hertz illustrates how, as with Schuster and later Thomson, a basic assumption shapes the nature of the experimental questions. As is observed later, the mounting of the collecting can outside rather than inside the evacuated tube was an unfortunate choice by Hertz. Notice also the technical difficulties of Hertz: electric field too weak, and the high conductivity of the residual gas.

Perhaps here is a useful place to emphasize the point that any experimental set-up will always give *some* results, even if it is "no reaction." Many assumptions go into the design of an experiment and the selection of the instruments to be used from those available. The interpretation of the experiment depends upon what the inquirer expected. In many instances later results reveal that because unexpected factors were operating, the experimenter came to unjustified conclusions.

Page 41. Refer to Experiment 43, "The Photoelectric Effect." (Experiment V-1 in the revised *Student Handbook.*)

Page 41. Three possible explanations existed for the value of 1840 for q/m. Perhaps students would wish to examine the three and propose their reasons for agreeing with Thomson that the size, and probably the mass, of the cathode ray particle was very small, although it carried the same charge as a hydrogen ion.

Page 41. The discoveries of photoelectricity and x rays, occurred during studies of cathode rays. The discovery of radioactivity by Becquerel occurred during a study of x rays. Thus the investigations of cathode rays led to several new lines of evidence about atomic behavior and structure. Neither the scientific nor the applied consequences of the cathode ray studies could have been anticipated.

Page 42. This special page provides more details about the procedure used by Thomson in 1897 to extend Schuster's analysis. The magnetic and electrical forces are applied simultaneously and balanced to produce a straight beam from which v could be derived.

Page 43. Reference could be made to Experiments 41 "The Charge-to-Mass Ratio for an Electron," and to Experiment 42 "Measurement of Elementary Charge." (Experiments V-3 and V-4 in the revised *Student Handbook.*)

Reference to Experiment 44 "Spectroscopy" (Experiment V-6 in the revised *Student Handbook*) would remind students of their experiences with line spectra.

Film loop "Rutherford Scattering" is related to the development of the ideas.

CHAPTER 3

Teaching Aids likely to be useful with this chapter are:

Transparencies	T-42	Radioactive Disintegration Series
	T-43	Radioactivity Decay Curves
	T-44	Radioactivity Displacement Rules
	T-46	Chart of Nuclides
	T-47	Nuclear Equations

Film loop "Collisions with an Unknown Object" and reference to Experiment 46 "Range of α, β, and γ Particles," and Experiment 47 (C) "Measurement of a Half-Life." (Experiments VI-2 and VI-3 in the revised *Student Handbook).*

The film "People and Particles" is especially appropriate to show in conjunction with Chapters 3 and 4 of this Supplementary Unit.

The film "The World of Enrico Fermi" is also appropriate for showing with Chapter 4.

Page 47. As the text makes clear, the discovery of nuclear fission could have been made at any time between 1934 and 1939, but it was not. The experimental evidence was inconclusive, but the possibility of an atom breaking into two medium sized parts was almost unimaginable.

Page 48. The behavior of atoms which captured a neutron of low energy (a slow neutron) seemed to be well known. One beta particle emission resulted in a stable daughter nucleus.

Page 50. Again, the experiments of Irene Joliet-Curie and Paul Savitch, of Hahn and Strassmann, of Braun, Preiswerk and Scherrer, and of Droste illustrate the difficulties of experimental work and the influences of assumptions upon the equipmental design.

Page 54. In line with the comment above, note the caution in the statement by Hahn and Strassmann: "A series of strange coincidences may, perhaps, have led to these results."

Page 54. Meitner and Frisch benefited from some theoretical suggestions by Bohr about atomic nuclei being like liquid drops, an unusual but highly important analogy. The suggestion by Hahn and Strassmann that uranium hit by neutrons might actually split into two major parts with the release of great energy, plus the calculations by Meitner and Frisch were enough to open a whole new line of interpretations and experimentation. What had been confusing could now be interpreted. This illustrates well the generative power of a new idea.

Page 57. The self-imposed decision to stop publishing papers about nuclear fission was remarkable. As early as 1940, nuclear scientists realized the enormous military potential of a fission weapon. They wished to contribute no information to the enemy who probably would attempt to develop such a weapon. Stopping publication was a dramatic example of the social concern of these scientists.

CHAPTER 4

Page 63. This chapter stresses the faith physicists have put in the general conservation laws. To save them, a new particle was "invented."

Page 65. The peculiar continuous energy spectra of beta rays having all energies up to some maximum appeared to violate the conservation laws for energy and momentum.

Page 67. Pauli proposed a new particle with certain properties, a "might be like this." Fermi used the new quantum mechanics to develop a theory about the particle and to explain the beta ray spectrum and the missing momentum.

Thus an idea proposed by one man was elaborated by another.

Page 68. While an experiment to detect neutrinos had been proposed, its application had to wait until 1956 when newly developed nuclear reactors would produce a sufficient supply of beta decays. Very sensitive scintillation counters and complex computer circuitry were also essential in detecting reactions and ruling out events having other causes. Problem 4.11 illustrates the mathematics of the analysis. You may wish to discuss with the students the diversity of complex apparatus and the theoretical assumptions which lay between the supposed production of neutrons by neutrinos Eq. 4.3, on page 69, and the conclusion that the predicted events had actually occurred.

Page 72. Problem 4.10 illustrates the calculation of recoil energy, which is rarely above 100 eV. The sketch in the margin of the text, page 72, illustrates the vector analysis for momentum conservation when the nucleus recoils upon emission of a beta ray and perhaps also a neutrino.

Page 73. The experiment by Davis is one of the relatively few examples of a significant conclusion from a negative observation. His experimental design and operative care were so great that the *absence* of evidence for argon 37 was accepted as evidence *for* the existence of antineutrinos.

Page 75. The equations for the Danby and Lederman experiment are:

$$\text{(a)}\quad \nu_\pi + P \rightarrow e^-, \qquad \text{if } \nu_\pi \equiv \nu_\beta \qquad (4.7)$$

or

$$\text{(b)}\quad \nu_\beta + P \rightarrow \mu \qquad (4.8)$$

Since no electrons were produced, but about 50 muons were recorded, the reaction of equation (b) seems to be occurring, while that of equation (a) is not.

Page 78. The acceptance of neutrinos which have such very small capture cross-sections has led to changes in the mechanism considered possible within stars. Thus the theory to account for supernovae has been reexamined. Probably the detection of neutrinos from relatively nearby supernova, such as that which formed the Crab nebula in Taurus in 1054 AD, is a task unlikely to be undertaken because of the size and cost of the equipment.

ANSWERS TO END-OF-CHAPTER QUESTIONS

CHAPTER 1

1.1 The discovery of Uranus was an accident in the sense that Herschel, when he found it, was not looking for a new planet.

Accidental aspect of the discovery of Neptune: The elements of Neptune's orbit, as calculated by Adams and by Leverrier, were in error, but happened to predict the position of the planet precisely enough for it to be found. The errors in the elements were shown by later calculations when more complete data were available for the positions of Neptune.

Accidental aspects of the discovery of Pluto:

(a) Faintness of Pluto's image on the 1919 plates, so that it was overlooked at that time.

(b) The perturbations of Uranus which were thought to have been caused by Pluto may not, in fact, have really been due to Pluto (which turned out to have a very small mass). Nevertheless, they led to "predictions" which led Tombaugh to find Pluto.

1.2 In what way or ways was the time ripe for the work of Adams and of Leverrier? (a) Uranus had been observed long enough for the residuals of its motion, particularly since its conjunction with Neptune in 1820, to be large enough to be a major problem. (b) Since the publication of Newton's *Principia* in 1685, many mathematicians, astronomers, and physicists had worked out highly ingenious techniques for deriving orbits and computing the perturbing effects acting between planets. Thus, the analytical tools were available.

1.3 The maximum force exerted on Uranus by Neptune is 14% of that exerted by Saturn, and 9% of that exerted by Jupiter. (It is approximately 15 times that [at the least] exerted by Pluto on Uranus. One says "at the least" because the mass of Pluto is not well known, but is certainly no more than that of the Earth.)

		Avg. Solar Dist.	Least Dist. Uranus
Jupiter mass	318 earth's	5.2 AU	13.9
Saturn mass	95 earth's	9.6	9.5
Uranus mass	15 earth's	19.1	0
Neptune mass	18 earth's	30.1	11.0

Relative Max. forces on Uranus by Neptune =

$$\frac{18}{11.0^2} = .149$$

$$\text{Jupiter}\left(\frac{318}{13.9^2}\right) = 1.64$$

$$\text{Saturn}\ \frac{95}{9.5^2} = 1.05$$

$$\text{Force on Uranus by}\ \frac{\text{Neptune}}{\text{Jupiter}} = \frac{0.149}{1.64} = 0.091$$

$$\frac{\text{Neptune}}{\text{Saturn}} = \frac{0.149}{1.05} = 0.142$$

1.4 The gaps in the periods of asteroids occur at certain fractions of the period of Jupiter, at what are called resonant periods. Evidently the repetition of similar perturbations at frequent conjunctions changes the asteroid orbits to ones which are non-resonant which the asteroids then follow for longer intervals.

1.5 See Table at the bottom of the page.

1.6 Angular Diameter of Neptune

$= (28 \times 10^3)/29.1\ \text{AU})\ (93 \times 10^6\ \text{mi/AU}) =$
$1.04 \times 10^{-5}\ \text{rad}\ (206{,}265\ ''/\text{rad}) =$
2.1 seconds of arc

1.7 Student's discussion including perhaps clear statement of premises which seem possible, knowledge of available data, concern for predicting new observations, background of the writer, etc.

1.5

(1) Planet	(2) Relative diameter	(3) Dist. from sun, A.U.	(4) $(\text{Diam.})^2$ rel. area	(5) $(\text{Dist.})^2$	(6) $\frac{(\text{Area})}{(\text{Dist.})^2}$	(7)* Relative Brightness
Mars	0.52	1.52	0.27	2.30	0.117	0.475
Jupiter	10.97	5.2	120.	27.0	4.45	0.238
Saturn	9.03	9.6	82.	92.0	0.89	0.012,1
Uranus	3.72	19.6	13.8	384	0.36	0.000,104
Neptune	3.38	30.1	11.4	910	0.0125	0.000,014,7
Pluto	0.45 ?	39.5	0.21	1600	0.00013	0.000,000,086

* On the assumption that all planets reflect the same fraction of incident light.

CHAPTER 2

2.1 Evidence that cathode rays are not electromagnetic waves:

(a) They are deflected by magnetic fields. Electromagnetic waves are not. For example, a flashlight beam is not deflected when it is sent between the poles of a strong magnet. Radio and light waves are not deflected by the earth's magnetic field, which, though weak, extends very far into space. Gamma rays are not bent by strong magnetic fields, while alpha and beta rays are.

(b) They convey electric charge, as shown by the experiments of Perrin and Thomson. Electromagnetic waves do not convey charge.

(c) Cathode rays are deflected by strong electric fields, as shown by Thomson's experiments and, of course, by many modern cathode ray oscilloscopes. Electromagnetic waves are not deflected by electric fields.

2.2 At the time of J. J. Thomson's experiments there was little direct information about the actual size of the electron's charge compared to that of the hydrogen ion. The cathode ray experiments suggested that the *ratio* of the charge to the mass of the cathode ray particles was about 1800 times the corresponding ratio for hydrogen ions. One needed evidence for the comparative masses of electrons and ions in order to make use of the ratio measurements. Thomson suggested that Lenard's experiments indicated that the size (and presumably the mass) of cathode ray particles (i.e., electrons) was much smaller than that of atoms. Further, the Zeeman effect indicated that electrons are contained within atoms, and therefore, must be smaller than atoms (or ions). As the view developed that ionization was the result of adding or subtracting electrons from neutral atoms, then of course the equivalence of the charges followed automatically.

2.3 The time was ripe for the discovery of the electron in the 1890's because

(a) The technology needed was available:
(1) Good vacuum pumps.
(2) Well-developed glassblowing techniques, including methods for making metal-to-glass seals for electrodes. (This was not mentioned as such in the text, but was implied for the work of Perrin, Thomson, etc.)
(3) Circuits for the production of high voltages and instruments for the measurement of very weak currents were available.
(4) Spectroscopic techniques of good resolving power (for Zeeman effect measurements).

(b) Many scientists at the time were interested in the problems raised by investigations in the conductivity of gases under low pressure, and of the optical spectra produced by such gases.

(c) The controversy over the nature of cathode rays stimulated interest in the field.

2.4 (a) Where the effects of the electric and magnetic fields cancel, we have

$$qE = qvB, \qquad \text{or} \qquad v = \frac{E}{B}, \text{ and}$$

$$\text{since } E = \frac{V}{d}, v = \frac{V}{Bd};$$

$$\text{so } v = \frac{200 \text{ volts}}{1.0 \times 10^{-3} \dfrac{\text{N}}{\text{amp}\cdot\text{m}} \times 0.01 \text{ m}}$$

$$= 2.0 \times 10^{7} \text{ m/sec}$$

$$\left(\frac{\text{volt}\cdot\text{amp}}{\text{N}} = \frac{\dfrac{\text{N}\cdot\text{m}}{\text{coul}}\cdot\dfrac{\text{coul}}{\text{sec}}}{\text{N}} = \frac{\text{m}}{\text{sec}}\right)$$

(b) When the magnetic field acts alone, a circular orbit results, and

$$qvB = \frac{mv^2}{R}, \qquad \text{or} \qquad \frac{q}{m} = \frac{v}{BR}$$

$$\frac{q}{m} = \frac{2.0 \times 10^{7} \dfrac{\text{m}}{\text{sec}}}{1.0 \times 10^{-3} \dfrac{\text{N}}{\text{amp}\cdot\text{m}} \times 0.114 \text{ m}}$$

$$= 1.8 \times 10^{11} \text{ coul/kg}$$

$$\left(\frac{\text{amp}\cdot\text{m}}{\text{N}\cdot\text{sec}} = \frac{\dfrac{\text{coul}}{\text{sec}}\cdot\text{m}}{\dfrac{\text{kg}\cdot\text{m}}{\text{sec}^2}\cdot\text{sec}} = \frac{\text{coul}}{\text{kg}}\right)$$

* The MKSA unit for B is N/amp. m and is now called the *tesla* (after the electrical engineer Nikola Tesla).

2.5 (a) Since $V = \Delta(PE)/q$ by definition, then $qV = \Delta(PE)$. Since the electrons start from rest, then $\Delta(PE)$ will equal their gain in kinetic energy, or $qV = \frac{1}{2}mv^2$. The value of v is then

$$v = \left(\frac{2qV}{m}\right)^{1/2}$$

Since $V = 5000$ volts, or 5000 joules/coulomb, $v = (2 \times 1.76 \times 10^{11} \times 5.0 \times 10^3)^{1/2} = 4.2 \times 10^7$ m/sec.

(b) $E = V/d = 3 \times 10^4$ volts/meter $= 3 \times 10^4$ newtons/coulomb.

(c) $F = 3 \times 10^4$ newtons/coulomb $\times$ 1.6×10^{-19} coulomb $= 4.8 \times 10^{-15}$ newtons.

(d) $a = 4.8 \times 10^{-15}$ n/9.1×10^{-31} kg $= 5.28 \times 10^{15}$ m/s^2.

(e) $t = 5 \times 10^{-2}$ m/4.2×10^7 m/sec $= 1.2 \times 10^{-9}$ sec.

(f) The final velocity in the vertical component, v_v, is given by $v_v = v_i + at + gt$. But v_i is zero since the electron enters horizontally. From (d) we have $a = 5.3 \times 10^{15}$ m/sec^2 and from (e) we have $t = 1.2 \times 10^{-9}$ sec. The value of $a + g$ is the same as that of a, for g of 9.8 m/sec^2 is negligible compared to a of 5.3×10^{15} m/sec^2.

Therefore, $v_v = 5.3 \times 10^{15}$ m/sec$^2 \times 1.2 \times 10^{-9}$ sec, or $v_v = 6.4 \times 10^6$ m/sec.

(g) The displacement in the vertical direction, d_y, is given by $d_y = \frac{1}{2}\, a_y t^2$. Values for a and for t were found in (d) and in (e). Therefore,

$d_y = \frac{1}{2}\ 5.3 \times 10^{15}$ m/sec$^2 \times (1.2 \times 10^{-9}$ sec$)^2$, or $d_y = 3.75 \times 10^{-3}$ m, or 0.375 cm

(h) The electron will have its original horizontal velocity component because there will have been no force acting on it in the horizontal direction. The ratio of its vertical velocity, as it leaves the deflecting plates, to its horizontal velocity will be $v_v/v_h = 6.4 \times 10^6/4/2 \times 10^7 = 0.15$. The vertical deflection when it hits the screen will then be (0.15) (30 cm) = 4.5 cm

(i) If magnetic force (Bqv) is to equal electric force (Eq), then $Bqv = Eq$, giving $B = E/v = 3 \times 10^4/4.2 \times 10^7 = 7.1 \times 10^{-4}$ webers/m^2

2.6 (a) Paper is typically 0.15 millimeter thick—about 50 times thicker than Lenard's foils. (Student might like to measure, for comparison, the thickness of household aluminum foil.)

(b) The volume of a gram-atom of aluminum would be about 10 cm^3. It would contain 6×10^{23} atoms. Each atom would therefore occupy about 1.7×10^{-23} cm^3. One edge of a cube with that volume would be the cube root of the volume, or 2.6×10^{-8} cm

(c) Number of layers = (thickness of foil)/(thickness of a single layer) = 12,000.

2.7 The probability for surviving through 150 mean-free-paths would be $(\frac{1}{2})^{150} = 1.4 \times 10^{-45}$, (log p = 150 log ($\frac{1}{2}$) = 150 (−0.30) = −45).

2.8 A meter reading of 0.50 milliamp is equivalent to 0.50×10^{-3} coul. of charge passing in 1 second.

(a) Since the average current for 40 pulses per second is 0.50×10^{-3} coul., the charge per pulse is 1/40 of that amount, or 1.25×10^{-5} coul.

(b) Since the charge on one electron is 1.6×10^{-19} coul., the number of electrons per pulse is

$$\frac{1.25 \times 10^{-5}\ \text{coul}}{1.6 \times 10^{-19}\ \text{coul/electron}},\ \text{or } 7.8 \times 10^{13}\ \text{electrons.}$$

(c) The energy per second equals the power. Since the current is 0.50 milliamp and the potential difference is 20,000 volts, the power is

0.50×10^{-3} amps $\times$ 2.0×10^4 volts, which is 1.0×10^1 or 10 watts.

This amount of power will heat a small light bulb, so the foil is likely to be heated considerably.

2.9 Most important was the development of the mercury high-vacuum pump. The experimentation could not have been carried out without: development of glass-working techniques, high voltage generators, creation and control of magnetic and electric field, and the electrometer.

2.10

(a) **Waves**

1. Produced greenish glow in tube at end opposite cathode (negative plate)
   Produced chemical reactions like ultraviolet light
   Produced by any metal serving as the cathode
2. Behaved like light (light is polarized in a magnetic field)
3. Molecular mean free path in tube only about 0.6 cm
4. No Doppler shift of spectral lines, therefore not a moving source
5. Hertz: Current separated from glow of beam
   No deflection in electric field
   Beam penetrated thin foils
   No charge on collector outside tube

(b) **Particles**

1. Beam bent by a magnetic field
2. Crookes: Beam heats foils and moves vanes
3. Schuster assumed particles with mass, then from $q/m = v/BR$ estimated q/m as less than 10^{10} coul/kg
4. Perrin and Thomson: Charge on collector inside tube
   Negative charge was deflected magnetically into collector
   Beam deflected by electric field
   Remeasured q/m for beam and results consistent with those from photoelectric experiments and also for beta particles in radioactive experiments
   Zeeman splitting required same value of q/m

2.11

Evidence	**Arguments and Conclusions**
Schuster: Beam bends in magnetic field as though it had a negative charge, q	If beam consists of negatively charged particles, they must have some mass m Then $q/m = v/BR$ (measured B and R and estimated v) Obtained maximum and minimum values for q/m
Perrin and Thomson: Beam deflected in electric field	Established both electric and magnetic field of known strength From $F_{el} = F_{mag}$ derived v Solved $q/m = v/BR$
From electrolysis value of q/m known for hydrogen ion	Found $q/m = 1/1840$ of charge to mass ratio of hydrogen ion
Thomson: Molecular mean free path in tube about one cm	Particle must be very small

2.11 (continued)

Evidence	**Arguments and Conclusions**
Edison: Hot filaments release charged particles	All the charged particles in these experiments were equivalent ("electrons")
Hertz: Charged particles from illuminated metals (photoelectric effect)	
Zeeman: Spectral lines split when source is in magnetic field	Theory requires Thomson's value of q/m Electrons are components of all atoms
Millikan: Oil drop experiment	Derived smallest charge on oil droplets, value of q, thus of m

CHAPTER 3

3.1 Experiments of critical importance in the discovery of fission:

(a) The discovery of the neutron (Bothe, Becker, Chadwick).

(b) The experiments of Fermi and his collaborators using neutrons to make radioactive isotopes, leading to the discovery of "transuranic elements."

(c) The work of Hahn, Meitner, and others extending the experiments of Fermi's group, leading to the discovery of many "transuranic isotopes," and the problems of "triple isomerism" and "inheritability of isomerism."

(d) Curie and Savitch's discovery of the 3.5 hour activity of "actinium," which led to the work of Hahn and Strassmann.

(e) Intensified work by Hahn and Strassmann on the chemistry of the 3.5 hour activity and related isotopes, culminated in the chemical labeling of some of the activities produced by neutron bombardment of uranium as lanthanum and barium. This led to the tentative suggestion that fission was occurring.

(f) Frisch and Meitner's hypothesis that uranium was, in fact, undergoing nuclear fission, and to Frisch's (and others') experiments showing that fission products emerged with the appropriate amount of kinetic energy.

(Note: there were, of course, other important experiments which served to provide clues—sometimes misleading clues—and hence motivation for further research, but which were not themselves in the direct line as shown above.)

3.2 Glossary created by student.

3.3 There is no obvious set of "right answers" to this question. Students will no doubt wish to consider such questions as whether a 1930 discovery of nuclear fission would have influenced the work and the demise of the League of Nations; whether Britain and France and the United States would have awakened to the Nazi menace sooner; whether there might have been noticeable economic effects of a possible development of nuclear energy for peaceful purposes on the course of the Depression; and the like. If, on the other hand, the discovery had not been made until 1950, there are interesting questions as to how and when the war against Japan would have ended; how postwar American politics would have developed without (a) the false security provided from 1945 through 1947 by the concept of "The Atomic Secret," or (b) without the jolting fright provided by the first Russian atomic explosion in 1947.

3.4 One distinction which may be helpful is that between scientific discoveries, on the one hand, and their technological applications, on the other. While discoveries such as that of nuclear fission are, of course, strongly dependent on the state of technological developments, the actual discoveries themselves in many cases could not have been anticipated or made to occur earlier by deliberate choice by society. The concept of nuclear fission was simply too bizarre to be entertained seriously until the chemical evidence for barium and lanthanum in the products was overwhelming. An exceptionally brilliant physicist might have conceived the idea earlier, but he could not have been told to do so. A government *might* have decided to marshal a big research effort, which would have accelerated the discovery, but there was no apparent reason for a government to spend money, and scientists' time, on the problem of the transuranic elements in the mid-1930's. Once a discovery is made, a government or corporation may decide to invest large resources on its application to practical problems. And a government or corporation may set up laboratories and support scientists, in the hope that new discoveries will occur, which may then be applied to technological problems. One may even make shrewd guesses as to some (but not all) of the areas in which exciting discoveries may emerge. Discoveries in the non-predictable areas sometimes have the most far-reaching consequences.

3.5 Neptune was clearly looked for and then found. Nuclear fission, on the other hand, was not expected. The electron is not so easily categorized: the discovery of cathode rays was a surprise, but the experiments which showed their properties were certainly planned.

3.6 Energy released per atom = 208 MeV.

U235	235.04393	La 139	138.9061
n	+ 1.00867	Mo 95	94.9057
	236.05260	2 n	2.0173
	−235.8291	7 e^-	—
	0.2235		235.8291

931 MeV × 0.2235 = 208 MeV.

3.7 The energy would be about 150 MeV. This does not agree exactly with the answer to problem 6 because of the roughness of the approximations made in this problem, particularly the assumption that $R = 2 \times 10^{-14}$ meters.

The total kinetic energy after the fragments fly apart equals the work necessary to move them from a great distance to a separation of only 2×10^{-14} m. Consequently,

$$\text{work} = \frac{kQ_1Q_2}{R}$$

$$= \frac{9 \times 10^9 \frac{\text{nm}^2}{\text{coul}^2} \times 54 \times 1.6 \times 10^{-19}\ \text{coul} \times 38 \times 1.6 \times 10^{-19}\ \text{coul}}{2 \times 10^{-14}\ \text{m}}$$

$= 2.36 \times 10^{-11}$ nm. Since 1 eV $= 1.6 \times 10^{-19}$ joul,

the total energy in eV is $\frac{2.36 \times 10^{-11}\ \text{nm}}{1.6 \times 10^{-19}\ \text{nm/eV}} = 1.48 \times 10^8$ eV

$= 148$ MeV.

3.8 Students should be urged to solve the problem algebraically first, and then to substitute numerical values. If m_1, v_1 and E_1 are the mass, velocity, and kinetic energy of the first particle, and m_2, v_2 and E_2 those of the second, then $E_1/E_2 = \frac{1}{2}m_1v_1^2/\frac{1}{2}m_2v_2^2$. Then $E_1/E_2 = m_1v_1v_1/m_2v_2v_2 = v_1/v_2 = m_2/m_1$ (since $m_1v_1 = m_2v_2$). Hence for Sr^{95} (particle 1) and Xe^{138} (particle 2), $E_1/E_2 = 1.45$. Since $E_1 + E_2 = E_0$ (the total energy), E_2 will be 41% of E_0 and E_1 will be 59% of E_0.

3.9 An alpha particle of initial energy 4 MeV would produce about 130,000 ion pairs while coming to rest:

$\frac{4 \times 10^6\ \text{eV}}{30\ \text{eV}} = 1.3 \times 10^5$ ion pairs, or 130,000 ion pairs.

A 100 MeV-fission fragment would produce about 3.3 million ion pairs:

$$\frac{100 \times 10^6\ \text{eV}}{30\ \text{eV}} = 3.3 \times 10^6 \text{ ion pairs}$$

If the negative ions in the latter case were collected, the pulse would contain about 5.4×10^{-13} coulomb:

$$3.3 \times 10^6 \times 1.6 \times 10^{-19}\ \text{c} = 5.3 \times 10^{-13}\ \text{c}$$

If the pulse lasts 0.001 second, the current would be 5.4×10^{-10} ampere:

Average current $= 5.3 \times 10^{-13}/10^{-3} = 5.3 \times 10^{-10}$ amp.

While this is a very small current by ordinary standards (the current in a light bulb is of the order of one ampere), it can be amplified and detected fairly easily.

3.10 (a) If small amounts of a barium salt to serve as a carrier are dissolved in solutions containing the neutron-bombarded uranium, and then precipitated out of solution by the addition of appropriate reagents, the precipitate is found to contain radioactive material. Before the concept of fission was taken seriously, this radioactive material was naturally thought to be an isotope of that element near uranium in the periodic table which had chemical properties like those of barium—i.e., radium. Radium itself could not be used as the carrier because it was radioactive, and its activity would mask the activity of the unknown material.

(b) The prevailing opinion about twofold emission of alpha particles by neutron-bombarded uranium was that it was (1) unlikely, but (2) the only conceivable mechanism by which uranium could be converted to radium. At least two groups of physicists tried to detect the emission of alpha particles under these circumstances.

(c) In 1938 nuclear isomerism had been known to exist for only a year. The apparent triple isomerism—and inheritable isomerism, at that—of the bombardment products seemed strange, but the experimental "facts" seemed to demand such explanations.

CHAPTER 4

4.1 One can think of radioactive decay as a process in which a nucleus changes from an unstable arrangement of its constituents to a more stable arrangement, either by emitting a particle or by emitting a gamma ray. If a given isotope, in the decay process, always emits alpha particles or gamma rays with a very specific amount of energy, the implication is strong that the "unstable arrangement" for all such atoms is somehow alike, at least as far as energy content is concerned—and likewise the "more stable arrangement" to which each one decays. A crude analogy might be as follows: if stones dropped from a bridge all hit the water with the same kinetic energy, one would be safe in assuming that they all came from the same level. If they hit the water with a continuous spectrum of energies, one would have to assume (a) that they were dropped from an infinite variety of levels, or (b) that they were slowed down, in the course of dropping, by some unknown mechanism.

4.2 (a) The total energy released is identical irrespective of whether the alpha or the beta particle is emitted first. Evidently one specific energy state in the Po-218 is related to another specific energy state when the nucleus has become Bi-214.

(b) In no cases of beta decay does the nucleus lose more energy than maximum observed in the beta-ray spectrum.

4.3 (a) The shape of the continuous beta ray spectrum, and (b) the dependence on the half-life of an isotope upon the energy of the beta-rays.

4.4 The neutrino is almost incapable of disturbing atoms or molecules through which it is traveling. Particles can be detected only by causing ionization or some other change in the detector. The neutrino is almost incapable of causing such disturbances because it has little or no mass, no electric charge, and little or no magnetic moment, etc. Reines and Cowan were able to detect the very rare interactions which occurred when they used a very intense source of neutrinos and very sensitive detectors with large numbers of "target" nuclei.

4.5 Reines and Cowan succeeded in catching neutrinos, as it were. A crude analogy: one could show that energy disappeared into a radio transmitting station, and be fairly well convinced that Maxwell's theory of electricity and magnetism could account for that disappearance by postulating the radiating of energy in the form of electromagnetic waves. But one would still like to be able—as Hertz was able to do—to show that these waves could actually be received.

4.6 (a) Neutrinos, produced in positron emission from nuclei, or in negative electron capture by nuclei. (b) Anti-neutrinos, produced in ordinary (e.g., negative) beta emission from nuclei. (c) the muon neutrino and (d) the muon anti-neutrino, produced together with muons in the decay of pi mesons. The necessity for "ordinary" neutrinos and anti-neutrinos to be different was shown by the Davis experiment. (Sec. 4.8) That "ordinary" neutrinos are different from those associated with muons has been shown by the experiments of Danby and Lederman, and by others. (Sec. 4.10)

4.7 Neutrinos might account for stellar supernovae by providing an understandable mechanism for the sudden release of large amounts of energy from the interior regions of a star, permitting it to collapse and then explode. Additional evidence for or against such a theory is likely to come from further theoretical investigations (a) of conditions inside stars thought to be capable of becoming supernovae, and (b) of the cross-sections for the required processes, such as neutrino production by high energy gamma rays. It is not very likely that ten thousand ton detectors will be built and then maintained in readiness for a hundred years or so, for actual observations.

4.8 $7.83 + 3.26 = 11.09$ MeV., and $5.61 + 5.48 = 11.09$ MeV.

4.9 $(1/4)\ (3.26) + 7.83 = 8.64$ MeV. $5.61 + (1/4)\ (5.48) = 6.98$ MeV.

4.10 P_ν = momentum of neutrino = P_n momentum of nucleus

$P_\nu = \frac{E_\nu}{c}$, where E_ν = energy of neutrino
c = velocity of light

but $P_\nu = P_n = mv$, where m = mass of nucleus
and v = recoil velocity of nucleus

then, $mv = \frac{E_\nu}{c}$, and $v = \frac{E_\nu}{mc}$.

However, $E_n = \frac{1}{2} mv^2$, where E_n = energy of nucleus

$$\text{or } E_n = \tfrac{1}{2}\, m \left(\frac{E_\nu}{mc}\right)^2 = \frac{E_\nu^2}{2\, mc^2}.$$

For m, mass of the nucleus, we can substitute $m = Am_0$, where A is the atomic weight of the nucleus and m_0 is the mass of one atomic weight unit.

$$\text{Then } E_n = \frac{E^2_\nu}{2 \times 7\ (m_0c^2)},\ \text{but } m_0c^2 = 931 \text{ MeV},$$

$$\text{so} \quad E_n = \frac{(0.86)^2}{14 \times 931} = 5.7 \times 10^{-5} \text{ MeV}$$
$$= 57 \text{ eV}.$$

4.11 In the text it was stated that 50 interactions were observed during the passage of 10^{14} neutrinos through the spark chamber, so $(N_r/N_\nu) = 50 \times 10^{-14}$. Substitution of the constants of the apparatus gives a cross section $\sigma = 3.6 \times 10^{-38}$ cm^2/atom. (Note: A = 27 grams/gram-atom, D = 2.7 grams/cm^3, L = 90 inches = 229 cm, and $N_0 = 6 \times 10^{23}$ atoms/gram-atom.)

The neon gas may be neglected because the number of neon nuclei in the beam is much smaller than the number of aluminum nuclei.

4.12 The id, ego, and superego are qualitative concepts not having any physical attributes. However, the gene and atom and the neutrino do have physical attributes which allow their study through physical reactions.

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