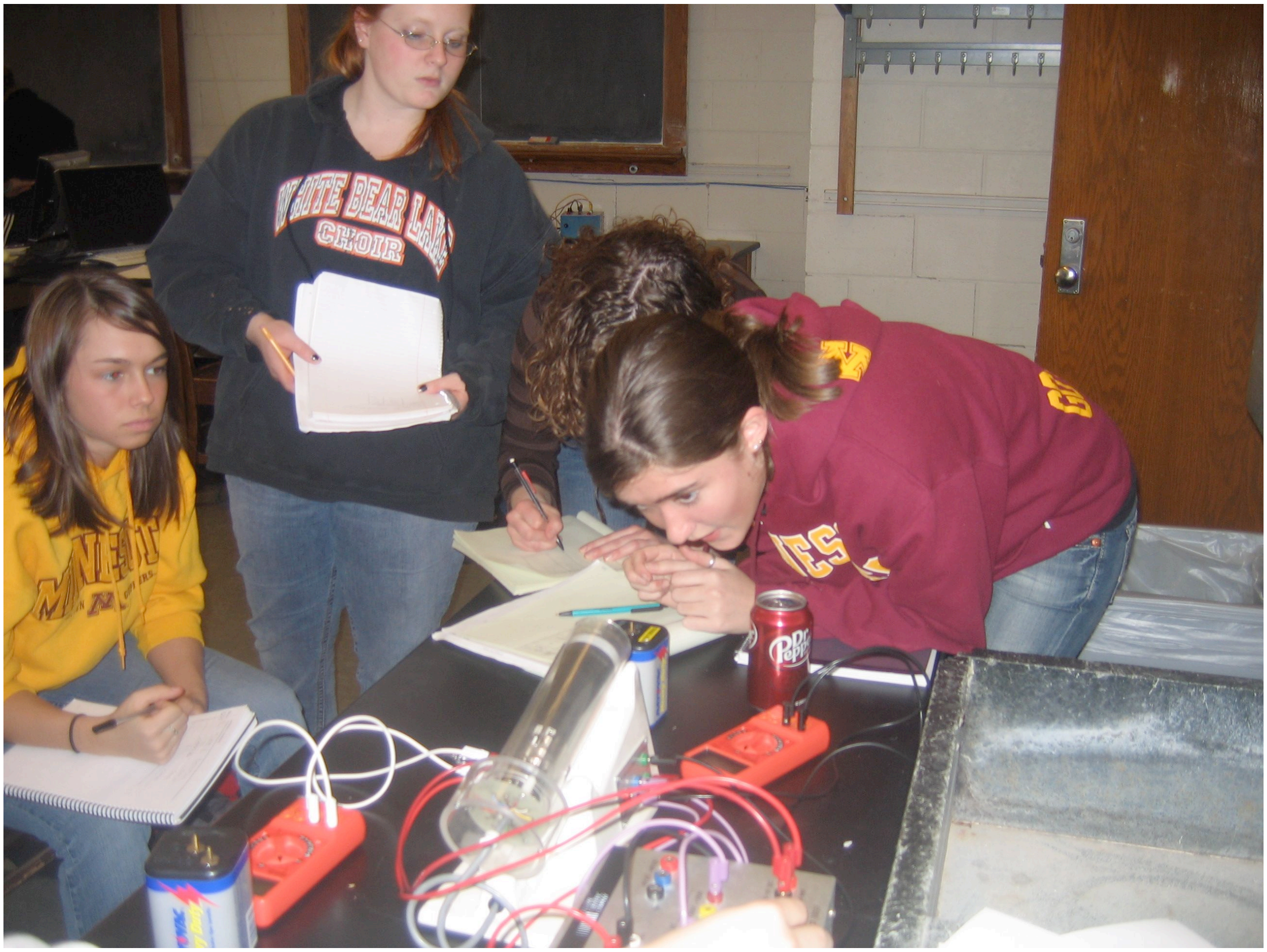

College Ready Physics Standards: A Look to the Future

Patricia Heller
Physics Education Research Group
Department of Curriculum and Instruction
University of Minnesota

Gay Stewart
Department of Physics
University of Arkansas

STANDARD 2
CONSERVATION PRINCIPLES

The interaction of one object with another object is governed by a few conservation principles. These principles are considered fundamental because they apply to interactions at all time and size scales and cannot be derived from other theories.

All interactions, at all size and time scales, are governed by conservation principles. A quantity is "conserved" when the total quantity does not change as the universe evolves. Therefore in an open system, any change in the quantity represents a transfer of the quantity into or out of the system. Mass and energy are conserved separately at the macro (human) time and size scales. The conservation of charge, mass-energy, and linear momentum are fundamental principles of science because they apply to interactions at all size and time scales and they cannot be derived from other theories. All scientific theories must be consistent with these conservation principles.

CLARIFICATION. The physics standards use the conservation principle❖ (sometimes called the continuity principle) as a central idea to organize and understand the interactions between objects and systems. The conservation principle for a quantity is: The total change of the quantity (Q) within a system (ΔQ_{system}) is equal to the quantity transferred out of the system subtracted from the quantity transferred into the system ($Q_{in} - Q_{out}$).

Objective 2.1:Conservation of Mass, Energy, and Charge (Grades 5-8 & 9-12)

Students understand that at the macro (human) and atomic scales, mass and energy are conserved separately for all types of interactions and defined systems (open or closed). Charge is always conserved at all scales.

Objective 2.2: Conservation of Linear Momentum (Grades 9-12)

Students understand that at the macro (human) scale, linear momentum is conserved for all types of interactions and defined systems (open or closed).

Objective 2.3: Nuclear Interactions and the Conservation of Mass-Energy (Grades 9-12)

Students understand that nuclear interactions result in product particle(s) with less mass than the original particle(s); the missing mass appears as an energy transfer out the system. Mass-energy is conserved at all size and time scales, for all types of interactions, and for all defined systems (open or closed).

❖ Underlined words and phrases are defined in the glossary.

OBJECTIVE 2.1
CONSERVATION OF MASS, ENERGY AND CHARGE (Grades 5-8 and Grades 9-12)

Students understand that at the macro (human) and atomic scale, mass and energy are conserved separately for all types of interactions and defined systems (open or closed). Charge is always conserved at all scales.

Clarification. The physics standards use the conservation principle (sometimes called the continuity principle) as a central idea to organize and understand the interactions between objects and systems. For students in grades 5 - 8, the conservation of mass principle is addressed. For students in grades 9 - 12, both the conservation of charge and conservation of energy are addressed (when no mass is converted to energy). The general principle of the conservation of mass–energy is introduced in Objective.2.3.

Elementary Foundations

By the end of grade 4, students know that:

1. No matter how parts of an object are assembled, the mass of the whole object is always the same as the sum of the parts; and when an object is broken into parts, the parts have the same total mass as the original object. [BSL 4D/E2*]

2. Objects and substances may move from place to place, but they never appear out of nowhere and never just disappear. [BSL 4D/E8**] It is helpful to keep track of where objects and substances come from and where they go. [BSL 11C/P2]

3. The number of objects in a group can stay the same even as some enter or leave, as long as each one that leaves is replaced by another one that is entering. [BSL 11C/E5**]

4. Water can be a liquid or a solid and can go back and forth from one form to the other. If water is turned into ice and then the ice is allowed to melt, the amount of water is the same as it was before freezing.

Grades 5 - 8

Clarification. See Instructional Guidance for Standard 2 (page 89) for a clarification of the conservation principle and how the principle can be introduced in the early middle-school grades.

RELATED OBJECTIVE: Heating and Cooling Interactions and Energy (4.5)

BOUNDARY.† *Quantities students measure include, but are not limited to, the number of identical objects, length, perimeter, surface area, mass, volume, and density. The mass changes that students investigate should include both open and closed systems and a wide range of different types of interactions.*

ESSENTIAL KNOWLEDGE❋

Students reason with and apply the following concepts in the learning outcomes:

M.2.1.1 Scientists find it useful to compare a new idea about a system, process, or event with something that is familiar. The thing that is familiar is called an analogue model of the system, process, or event. [Same as in Objective 1.3]

M.2.1.2 A quantity is "conserved" when the total change of the quantity within a defined system and time interval is equal to the total transfer of the quantity into or out of the system during the defined time interval.

total quantity change within system = total quantity transferred into or out of system

† For further background and instructional guidance for each objective, including restrictions in the scope of the content for the learning outcomes, see Instructional Guidance for Standard 2, page 89.

❋ For further clarification of the essential knowledge statements and learning outcomes for each objective, see the objective *Table of Common Student Conceptual Difficulties* in Instructional Guidance for Standard 2.

ESSENTIAL KNOWLEDGE (5-8), continued

a. A change in a quantity in a defined system is the value of the quantity before the event (Start Quantity) subtracted from the value of the quantity after an event (End Quantity):

change of quantity within system = End Quantity – Start Quantity.

b. The total transfer of a quantity into or out of a defined system is the value of the quantity transferred out of the system (Quantity Out) subtracted from the value of the quantity transferred into the system (Quantity In):

total transfer of quantity = Quantity In – Quantity Out.

M.2.1.3 A system may stay the same because nothing is influencing it or the influences on it are balanced. [BSL 11C/M2]

M.2.1.4 Most quantities, like surface area, perimeter, volume and density are not conserved for all types of interactions. Mass is ***always*** conserved for all interactions,[1] and for both closed and open systems.

End Mass – Start Mass = Mass In – Mass Out[2]

Start Mass = End Mass + Mass Out – Mass In

End Mass = Start Mass + Mass In – Mass Out

M.2.1.5 When energy is transferred into or out of a system without a transfer of materials, there is no change in mass of the system within measurement errors.

M.2.1.6 The small-particle model of physical and chemical interactions is consistent with the conservation of mass principle. According to this model, during physical interactions atoms and molecules are rearranged, but the atoms do not change. During chemical reactions, the number and kinds of atoms in the reactants are the same as the number and kinds of atoms in the products – the atoms do not change.

LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Analyze and solve different word problems involving the conservation of identical objects by drawing a picture of the situation, writing a mathematical sentence for the conservation principle, and solving for the unknown quantity.

- Give real world examples of systems when mass is transferred into or out of the defined system, and when the rate of mass transfer into the system is the same as the rate of mass transfer out of the system (dynamic equilibrium).

- <u>Investigate</u> changes within a systems and transfers into and/or out of the system for different quantities (e.g., mass, volume, surface area, density), for different physical and chemical interactions, and different <u>defined systems</u> and time intervals. (a) Gather and record data on the quantity before and after a physical or chemical interaction, and the amount of the quantity transferred into and/o out of a system during the interaction. (b) Make a <u>claim</u> about whether the quantity is conserved or not conserved. Justification is based on the <u>evidence</u> and the conservation principle.

- Construct <u>analogue models</u> of the conservation of quantities from everyday life. <u>Explain</u> how the model is the same and different from the conservation of mass principle.

- Give examples of evidence supporting the conclusion that surface area, volume, and density are sometimes conserved and sometimes not conserved, while mass is conserved in all of the examples.

- Give examples of evidence supporting the conclusion that the transfer of energy into or out of an object/system (without a transfer of materials) does not change the mass of the system within the measurement errors.

[1] Nuclear interactions are excluded.

[2] Research indicates that different middle-school students tend to prefer one or two of three ways of representing a mathematical sentence for conservation. At this level, it is not important which way students prefer to reason with the conservation of mass principle.

LEARNING OUTCOMES (5-8), continued

- Predict whether the mass of a defined system will decrease, stay the same, or increase for different physical and chemical interactions, and justify using the conservation of mass principle.

- Calculate the end mass of a defined system after different physical and chemical interactions, and justify by using the conservation of mass principle.

Grades 9 - 12

Clarification. In these standards, the approach to energy and energy conservation is the same as in the new AP Physics B courses: there is only *one* conservation of energy equation and all other energy equations are special cases (e.g., conservation of mechanical energy, the first law of thermodynamics).[3]

RELATED OBJECTIVES: Interactions and Models of the Nucleus (1.3), Contact Interactions and Energy (4.1); Electric Current Interactions and Energy (4.2); Mechanical Wave Interactions and Energy (4.3); Radiant Energy Interactions (4.4); Heating and Cooling Interactions and Energy (4.5); and Potential Energy and Fields (5.2).

***BOUNDARY*.*[†]* *This is not a stand-alone objective*.** *The specific methods of energy storage and methods of energy transfer needed to apply the conservation of energy principle are in the five objectives of Standard 4 and in Objective 5.1.*

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes: [SSCS, page 152]

H.2.1.1 For all types of interactions (except nuclear reactions) and for all systems (open and closed), energy is always conserved. The mathematical form of the conservation of energy principle is the same as the conservation of mass principle: total energy change within system (ΔE_{system}) is equal to the total energy transfer into or out of system (E_{in} - E_{out}):

$$\Delta E_{system} = E_{in} - E_{out}$$

where (ΔE_{system}) is the change in one or more methods of energy storage within a system, and E_{in} and E_{out}) are one or more methods of energy transfer into or out of a system.

H.2.1.2 The energy terms in the conservation of energy principle depend on the defined system and defined time interval. For any event or process, the terms in the conservation of energy equation will be different for different defined systems and time intervals.

H.2.1.3 For all types of interactions covered in this standards document (except nuclear interactions), mass and energy are always conserved separately.

H.2.1.4 Many events and processes involve multiple interactions occurring simultaneously and/or chains of interactions. When the details of the multiple transfers of energy are unknown or not of interest in a problem, the term "transformation" can be used (i.e., the initial form of energy is "transformed" into the final form of energy within the defined closed system). For radiant energy transfers into or out of a system, this description is often extended to include the transformation of radiant energy (electromagnetic waves or photons) into the final form(s) of energy within the system (e.g., chemical energy or thermal energy).

H.2.1.5 Charge is always conserved for all types of interactions (including nuclear interactions). The total change of charge within a system (Δq_{system}) is equal to the total charge transferred into or out of the system ($q_{in} - q_{out}$). This can be mathematically represented by:

$$\Delta q_{system} = q_{in} - q_{out}$$

H.2.1.6 The conservation of charge, mass, and energy principles are examples of fundamental principles of science because they cannot be derived from other theories—all scientific theories must be consistent with these principles.

[3] A similar approach is described in a series of four articles in *The Physics Teacher* by John Jewett Jr. (2008a; 2008b; 2008c; 2008d).

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Construct analogue models of the conservation of energy principle. Explain how each model is the same and different from the conservation of energy equation. Choose and justify which model (if any) is best for the purpose of making sense of (understanding) the conservation of energy equation.
- Analyze different problems involving multiple interactions (e.g., contact, electric circuit, mechanical wave, radiant energy, thermal, and/or gravitational interactions):
  - ♦ Select a system and time interval to solve the problem. Identify the interactions of the defined system with other systems. Identification is based on the defining characteristics of interactions and on information from the problem.
  - ♦ Determine and represent, with an energy diagram, the type and direction of energy transfers across the system boundary, as well as energy changes within the system.
  - ♦ Make claims about which terms in the conservation of energy equation are applicable, are zero or not applicable, or are too small to be measurable. Justify the claims based on knowledge of methods of energy storage and methods of energy transfer.
  - ♦ Write the conservation of energy equation for the problem.
  - ♦ Predict what would happen to a given energy term (increase, stay the same, decrease) in the conservation of energy equation under different conditions for the problem. Justification is based on the terms in the conservation of energy equation.
- Describe, using energy diagrams, the energy changes within a system and the transfer of energy into and out of a system, for different defined systems or time intervals of the same event. [SSCS, page 152]
- Explain why an energy description of an event for a given system can differ for different time intervals, and why an energy description of an event for a given time interval can differ for different systems of interest. [SSCS, page 152]
- Describe the same event in terms of energy transfers and energy transformations. Description is based on an energy diagram and the conservation of energy principle. [SSCS, page 152]
- Give examples of problem situations in which the conservation of charge must be used or assumed to solve the problem. (See Objective 3.5)
- Explain why the conservation of mass, charge, and energy are fundamental principles of science.

Objective 2.2
Conservation of Linear Momentum (Grades 9 - 12)

Students understand that at the macro (human) scale, linear momentum is conserved for all types of interactions and defined systems (open or closed).

Clarification. Conservation of linear momentum is a fundamental principle of physics. This objective, which is limited to one dimension, provides a strong foundation for extending the content and skills to two- and three-dimensional linear momentum and angular momentum in an introductory college physics course. The objective can be introduced prior to, or after the introduction of Newton's laws (see Objective.3.2).

Related Objective: Forces and Changing Motion (3.2)

BOUNDARY.† Problems are limited to motion in one dimension. A full discussion of collisions also requires conservation of energy, but collisions can be approached from the point of view of conservation of momentum, and energy can be discussed at a later time.

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes: [SSCS, page 154]

H.2.2.1 All moving objects can be described by a quantity of motion called linear momentum. Momentum (p) for objects with mass is a vector quantity that depends on the mass of the object (increasing with increasing mass), the velocity of the object (increasing with increasing velocity), and is in the direction the object is moving ($p=mv$). There is no standard unit of momentum; the units are those of the product of mass and velocity, kg·m/sec.

H.2.2.2 The conservation of linear momentum states that the total momentum change within a system is equal to the total momentum transfer into or out of the system. This can be mathematically represented by:

$$\Delta p_{system} = p_{in} - p_{out}.$$

The conservation of linear momentum is a fundamental principle of science because it cannot be derived from other theories. -- all scientific theories must be consistent with this principle.

H.2.2.3 Linear momentum is always conserved for all types of interactions at all scales, and for both closed and open systems. For any system impulse — the total momentum transfer into or out of the system — is equal to the change in momentum for the system. This transfer is the result of interaction(s) with other systems outside the system boundary and can be mathematically represented by:

$$\Delta p_{system} = p_f - p_i = F_{ave}\Delta t,$$

where F_{ave} is the vector sum of the *external forces* (net external force).

H.2.2.4 Any combination of force and time could be used to produce the transfer of linear momentum (impulse) necessary for a given change of momentum of an object. The smaller the force, the longer the time interval over which the force acts; the larger the force, the shorter the time interval. Consequently, impulse is an important consideration in a number of real-world applications.

H.2.2.5 The linear momentum of the system is constant in a system where the interactions across the system boundary may be neglected because they are insignificant compared to the interactions within the system, or because the time interval is very short.

H.2.2.6 Newton's second and third laws of motion are a direct result of the conservation of linear momentum principle applied to cases of constant mass:

*[**BOUNDARY:** For inertial frames of reference, Newton's first law of motion is a special case of Newton's second law of motion. The distinction between gravitational and inertial mass is not necessary for preparing students for college success.]*

a. The sum of external forces (net external force) acting on an object causes the object's momentum to change. The average force multiplied by the time interval is equal to the momentum change ($m\Delta v$).

$$\Sigma F_{external} = m(\Delta v/\Delta t) = ma$$

If there are no external forces acting on an object, the object's linear momentum (and therefore its motion) cannot change.

b. Interaction forces between two objects cannot change the total momentum of the objects, since these forces would exist even if the system were isolated. Consequently, when two objects interact, the force on one object is equal in magnitude but opposite in direction to the force on the second object. This is the origin of Newton's third law.

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective: [SSCS, page 153]

- Investigate the conservation of linear (one-dimensional) momentum for different problem situations involving open and closed systems and for different types of interactions (e.g., an automobile collision, a bat hitting a baseball, an object falling to the ground from rest).

LEARNING OUTCOMES (9-12), continued

- Select a system of interest and time interval.
- Predict the transfer of momentum into or out of a defined system during the interaction. Justification is based on the problem situation and the conservation of momentum principle.
- Determine and justify the observations or data needed to test the prediction.
- When appropriate, record and organize data, including estimates of measurement errors.
- .When appropriate, analyze the data for outliers, and represent the data on a momentum diagram.
- Make claims about the transfer of momentum into or out of a system. Claims are based on gathered data that can be used as evidence and the conservation of momentum principle.

- Predict qualitatively the change in direction of motion of two interacting objects. Justification is based on the initial conditions and on the relationship between the momenta of the two objects in a closed system.

- Explain when the external friction interaction may be ignored when using the conservation of linear momentum principle.

- Explain, using the conservation of linear momentum principle, how a process or design achieves a desired effect (e.g., reducing damage or injury, maximizing a force).

- Design or adapt a process to achieve a desired effect of increasing or decreasing the force applied to an object by using the conservation of linear momentum principle.

- Investigate qualitatively and make a claim about the changes in kinetic energy and linear momentum for a defined system of two objects in different problems involving inelastic collisions. Identify possible methods of energy transfer or transformation within the system to account for the "lost" kinetic energy, and construct energy and momentum diagrams. Justification is based on the conservation of energy and on the conservation of linear momentum. Explain where this energy has gone, and justify the explanation by using the conservation of energy principle and conservation of linear momentum principle.

  *[**BOUNDARY:** Students are not expected to use the coefficient of restitution.]*

- Explain and justify how the conservation of linear momentum can be used in the investigation of traffic accidents to determine, based on measurements of the final motions, the initial motions of the objects.

- Calculate, using the conservation of linear momentum principle, the final velocity in a two-object system for different problems involving totally inelastic collisions.

- Predict algebraically the average force, initial or final velocity, mass, or time interval in multistep word problems. Justification is based on the conservation of linear momentum principle.

- Predict algebraically the average force, the initial or final velocity, masses or time interval in different multistep word problems in which external forces can be neglected and the approximation that no energy is dissipated can be made. Justify the prediction by constructing momentum diagrams and by using the conservation of linear momentum principle.

- Predicts algebraically the relative size of the accelerations of two interacting objects in word problems by drawing a momentum diagram and using the mathematical representation for the relationship between the momenta of the two objects in a closed system.

- Explain why the conservation of linear momentum is a fundamental principle of science. Justification should include the example of Newton's laws derived from the conservation of linear momentum.

Objective 2.3
Nuclear Interactions and the Conservation of Mass-Energy (Grades 9 - 12)

Students understand that nuclear interactions result in product particle(s) with less mass than the original particle(s); the missing mass appears as an energy transfer out the system. Mass-energy is conserved at all size and time scales, for all types of interactions, and for all defined systems (open or closed).

Grades 9 - 12

Clarification. In grades 5 - 8, students are introduced to the small-particle model of matter, chemical interactions and the periodic table. In grades 9 - 12, students extend this knowledge to include atomic structure (i.e., protons, neutrons and electrons in Objective 1.3) and nuclear interactions, which serve as an introduction to the conservation of mass–energy.

Related Objective: Interactions and Atomic and Subatomic Models (1.3)

BOUNDARY.† *Nuclear interactions are limited to radioactive decay, fusion and fission – other interactions involving protons or neutrons are excluded.*

Essential Knowledge

Students reason with and apply the following concepts in the learning outcomes: [SSCS, 155-156]

H.2.3.1 The nuclear interaction between protons and neutrons is a non-electrical, attractive interaction-at-a-distance that binds them to form a stable nucleus. The nuclear force is much stronger than the electrical repulsive force between the protons for particle distances less than 10^{-15} meters, but it becomes very, very weak for larger distances. Consequently, neutrons have little effect on how an atom interacts with other atoms, yet the number of neutrons does affect the mass and stability of the nucleus.

H.2.3.2 Atoms with the same number of protons and a different number of neutrons are called isotopes. Most elements have more than one stable isotope. When an atom has an unstable nucleus, the unstable nucleus emits very fast-moving particles (e.g., alpha, beta, or positron). This process, called radioactive decay, results in nuclei of a different element being formed from the old one. Sometimes the emission of radiant energy (e.g., gamma rays) is part of this process. Atoms with an unstable nucleus are often called radioisotopes.

H.2.3.3 Radioisotopes have several medical applications. The particles and radiant energy emitted as a result of the unstable nucleus have high energy and can be detected. These characteristics allow radioisotopes to be used as tracers of biological processes and to kill biological materials (e.g., cancer cells).

H.2.3.4 Half-life is a measure of the rate of radioactive decay, or the amount of time it takes for half of a radioactive sample to decay to its products. For any radioisotope, the half-life is constant and unique and can be used to determine the age of the material.

H.2.3.5 When two smaller nuclei combine to produce one larger nucleus, the interaction is called nuclear fusion. The process of fusion is the source of energy for stars. Elements heavier than hydrogen continue to be created as a result of fusion reactions in the centers of stars. In the fusion process, the mass of the product is less than the mass of the reactants. The missing mass appears as energy. These energy changes are much greater than those that accompany chemical reactions.

H.2.3.6 When a large nucleus splits to produce two smaller nuclei, the interaction is called nuclear fission. In many fission reactions, energetic neutrons are also released, which can be absorbed by nearby nuclei, causing them to undergo fission. In the fission process, the mass of the product is less than the mass of the original nucleus. The missing mass appears as energy. These energy changes are much greater than those that accompany chemical reactions.

H.2.3.7 As predicted by Albert Einstein in his special theory of relativity, during nuclear interactions, the transfer of energy out of a system is directly proportional to the change in mass of the system. The mass–energy equivalence principle is $\Delta E = \Delta mc^2$, where c is the speed of light in a vacuum. A very small amount of mass is converted to a large amount of energy.

H.2.3.8 A more general conservation principle is a combination of the conservation of mass principle and conservation of energy principle, including the mass-energy equivalence principle. Mass–energy (ME) is always conserved for all types of interactions at all scales.

$$\Delta ME_{system} = ME_{in} - ME_{out},\quad \text{where ME is mass or energy.}$$

Except for nuclear interactions, the conversion of mass to energy is too small to be measurable.

H.2.3.9 Experiments to date indicate that the conservation of charge and the conservation of linear momentum also apply at all time and size scales for all types of interactions. The conservation principles of mass-energy, linear momentum, and charge cannot be derived from other theories. They are considered to be *fundamental* principles of science and all other theories must be consistent with these fundamental principles.

LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective: [SSCS, page 155]

- Explain why the nuclear interaction among the protons and neutrons in the nucleus of an atom does not play a role in everyday phenomena. Justify the explanation by using knowledge of electrical and nuclear forces.
- Compare and contrast alpha and beta radioactive decay, in terms of what happens to the nuclei. Contrast includes visual representations of the two processes.
- Compare and contrast nuclear fusion with nuclear fission, in terms of what happens to the nuclei. Contrast includes visual representations of the two processes.
- Predict the new element that is formed during the radioactive decay (alpha decay or beta decay) of a given isotope. Justify the prediction by using the periodic table and knowledge of radioactive decay.
- Explain why it is possible to get more energy out of fission and fusion reactions than out of chemical reactions involving the same amount of material. Justification is based on knowledge of mass–energy equivalence.
- Calculate the energy required to fuse two atoms in a fusion reaction and the energy released in a fission reaction, using the mass–energy equivalence principle in the conservation of energy equation and knowledge of fusion and fission reactions. Calculations are based on the atomic masses of the product particle(s) and the masses of the original particle(s) that interacted to produce them.
- Explain and justify why it can be appropriate to solve some problems by using the conservation of mass principle or the conservation of energy principle, rather than the conservation of mass–energy principle.
- Explain why Newton's laws of motion and Newton's law of gravitation are not considered to be fundamental principles of science.