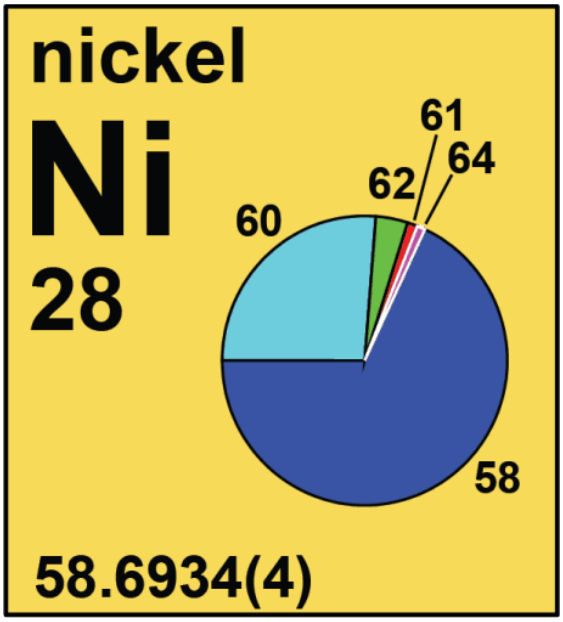
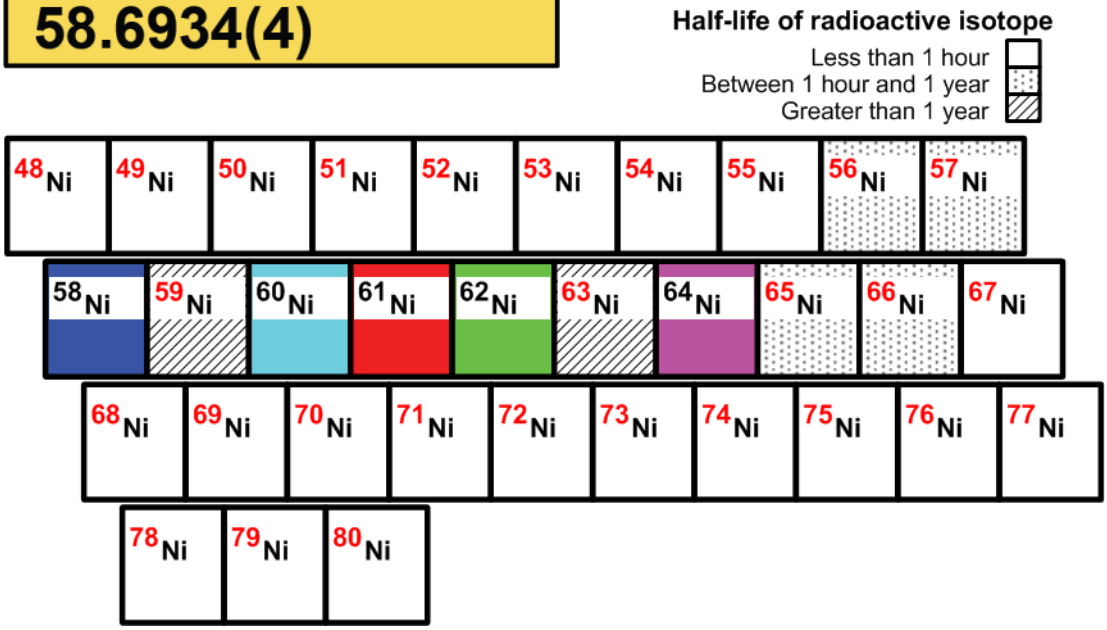


Stable isotope	Relative atomic mass	Mole fraction
^{58}Ni	57.935 342	0.680 769
^{60}Ni	59.930 786	0.262 231
^{61}Ni	60.931 056	0.011 399
^{62}Ni	61.928 345	0.036 345
^{64}Ni	63.927 967	0.009 256



Nickel isotopes in Earth/planetary science

Because molecules, atoms, and ions of the **stable isotopes** of nickel possess slightly different physical, chemical, and biological properties, they commonly will be **isotopically fractionated** during physical, chemical, and biological processes, giving rise to variations in **isotopic abundances** and in **atomic weights**. There are measureable variations in the isotopic abundances of nickel in terrestrial silicate rocks (Figure 1) [225].

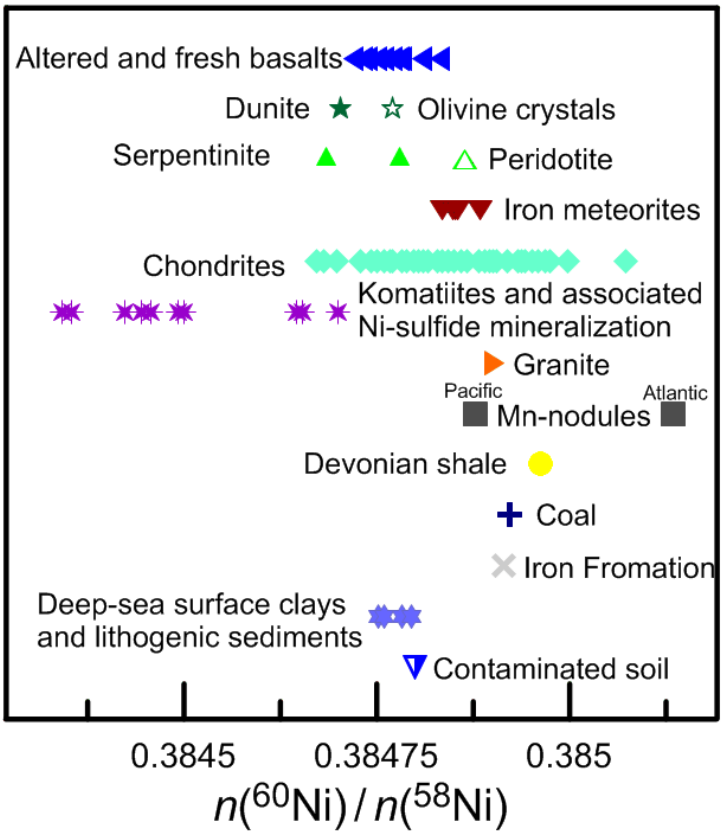


Fig. 1: Variation in **isotope-amount ratio** of nickel in terrestrial silicate rocks (modified from [225]).

Nickel isotopes in geochronology

Anomalies in ^{60}Ni abundance caused by decay of now extinct ^{60}Fe have been used to study the early history of our Solar System (see *Iron isotopes in Earth/planetary science*) [102-104]. ^{59}Ni is a **cosmogenic** **radionuclide** with a **half-life** of 76,000 years. Decay of ^{59}Ni has been used to assess the terrestrial age of meteorites and to determine abundances of extraterrestrial dust in ice and sediment [102-104].

Nickel isotopes in industry

^{63}Ni is produced from stable ^{62}Ni and is a beta-emitting radionuclide that serves as an **electron** source together with ^{55}Fe in **electron-capture detectors**. Electron-capture detectors are used as thickness gauges or as detectors for organic **analytes** in **gas chromatography** (Figure 2) [102-104]. ^{63}Ni is also used to ionize substances in ion mobility spectrometry–the basis of the instrument used in airports to screen passengers for drugs and bombs [226]. ^{63}Ni is also used as a fluorescence-inducing source in elemental analysis by **X-ray fluorescence spectroscopy** and in miniaturized long-lived **nuclear batteries**. Until the mid-1980s, nuclear batteries were used in pacemakers, but then they were replaced by long-lasting lithium batteries [102-104, 227].

Fig. 2: Shimadzu GC-8A **Gas Chromatograph** (GC) with an **Electron-Capture Detector** (ECD). (Image Source: The Reston Chlorofluorocarbon Laboratory, U.S. Geological Survey) [228, 229].

Nickel isotopes used as a source of radioactive isotope(s)

^{61}Ni is used as a radiation target for production of the **radioactive isotope** ^{61}Cu, which emits **positrons** for **positron emission tomography** (PET) applications using the ^{61}Ni (p, n) ^{61}Cu reaction [90, 102-104, 230]. ^{64}Ni is used as a radiation target for production of ^{64}Cu, which is used in **radioimmunotherapy** by attaching it to an antibody for delivery of cytotoxic radiation (toxic to living cells) to a target cell via the ^{64}Ni (p, n) ^{64}Cu reaction [90, 102-104, 230]. ^{60}Ni is used for the production of ^{57}Co, which is used as a reference source for **gamma cameras** that are used in **nuclear medicine** via the ^{60}Ni (p, ^{4}He) ^{57}Co reaction [90, 102-104, 230].

Glossary

alpha particle – a positively charged nuclear particle identical with the nucleus of a helium atom consisting of two **protons** and two **neutrons**.

analyte – chemical substances or materials undergoing analysis. [return]

atomic number (*Z*) – The number of protons in the nucleus of an atom.

atomic weight (relative mean atomic mass) – the sum of the products of the relative atomic mass and the **mole fraction** of each stable and long-lived **radioactive isotope** of that **element** in the sample. The symbol of the atomic weight of element E is $A_r(\mathrm{E})$, and the symbol of the atomic weight of an atom (**isotope**) of element E having mass number A is $A_r({}^{A}\mathrm{E})$. Because relative atomic masses are scaled (expressed relative) to one-twelfth the mass of a carbon-12 atom, atomic weights are dimensionless. [return]

cosmogenic – produced by the interaction of Earth materials (soil, rock, and atmosphere) and meteorites with high-energy **cosmic rays**, resulting in **protons** and **neutrons** being expelled from an atom (termed cosmic ray **spallation**). [return]

cosmic rays – extremely high-energy radiation, mainly originating outside the Solar System, consisting of one or more charged particles, such as **protons**, **alpha particles**, and larger atomic nuclei.

CT scan (X-ray computed tomography or X-ray CT, computerized axial tomography scan or CAT scan) – a computerized tomography (CT) scan combines a series of **X-ray** images taken from different angles and uses computer processing to create cross-sectional images, or slices, of the bones, blood vessels and soft tissues inside your body [702].

electron – elementary particle of matter with a negative electric charge and a rest mass of about 9.109×10^{-31} kg. [return]

electron-capture detector (ECD) – an apparatus for detecting trace amounts of atoms and molecules (such as halogens, organometallic compounds, nitriles, or nitro compounds). The ECD uses an **electron** emitter (commonly the **radioactive isotope** ${}^{63}\mathrm{Ni}$) to produce a current in the detector. Any electron-absorbing compound in the carrier gas reduces the current and is thus detected. [return]

element (**chemical element**) – a species of atoms; all atoms with the same number of **protons** in the atomic nucleus. A pure chemical substance composed of atoms with the same number of protons in the atomic nucleus [703].

gamma camera (scintillation camera or Anger camera) – instrument used to track the distribution in body tissue of **radioactive isotopes** (**tracers**) that emit **gamma radiation** (high energy photons), a technique known as **scintigraphy**. [return]

gamma rays (gamma radiation) – a stream of high-energy electromagnetic radiation given off by an atomic nucleus undergoing **radioactive decay**. The energies of gamma rays are higher than those of **X-rays**; thus, gamma rays have greater penetrating power.

gas chromatography (GC) – a common technique for separating compounds that can be vaporized in a gas used as the moving carrier medium (commonly helium or nitrogen) in order to determine the purity or determine the relative fractions of components in the sample. [return]

half-life (radioactive) – the time interval that it takes for the total number of atoms of any **radioactive isotope** to decay and leave only one-half of the original number of atoms. [return]

isotope – one of two or more species of atoms of a given **element** (having the same number of **protons** in the nucleus) with different atomic masses (different number of **neutrons** in the nucleus). The atom can either be a **stable isotope** or a **radioactive isotope**.

isotopic abundance (mole fraction or amount fraction) – the amount (symbol n) of a given isotope (atom) in a sample divided by the total amount of all stable and long-lived **radioactive isotopes** of the chemical **element** in the sample. [return]

isotope-amount ratio (r) – amount (symbol n) of an **isotope** divided by the amount of another isotope of the chemical **element** in the same system [706]. [return]

isotopic fractionation (stable-isotope fractionation) – preferential enrichment of one **isotope** of an **element** over another, owing to slight variations in their physical, chemical, or biological properties [706]. [return]

isotopically labeled (compound) – a mixture of an isotopically unmodified compound with one or more analogous isotopically substituted compound(s) [703].

neutron – an elementary particle with no net charge and a rest mass of about 1.675×10^{-27} kg, slightly more than that of the **proton**. All atoms contain neutrons in their nucleus except for protium (^{1}H).

nuclear battery – a device that uses **radioactive decay** to generate electricity. [return]

nuclear medicine – the branch of medicine that deals with the use of **radiopharmaceuticals** to diagnose and treat disease. [return]

positron – the antimatter counterpart of the **electron**, with a mass identical to that of the electron and an equal but opposite (positive) charge. [return]

positron emission tomography (PET) scan – an imaging technique that is used to observe metabolic activity within the body. The system detects pairs of **gamma rays** emitted indirectly by a radioactive isotope used as a tracer, which emits **positrons** and which is introduced into the body on a biologically-active molecule. Three-dimensional images of the concentration of the

radioactive isotope within the body are then constructed by computer analysis. The imaging often is performed with an **X-ray CT scan** in the same instrument. [return]

proton – an elementary particle having a rest mass of about 1.673×10^{-27} kg, slightly less than that of a **neutron**, and a positive electric charge equal and opposite to that of the **electron**. The number of protons in the nucleus of an atom is the **atomic number**.

radioactive decay – the process by which unstable (or radioactive) **isotopes** lose energy by emitting alpha particles (helium nuclei), beta particles (positive or negative **electrons**), **gamma radiation**, **neutrons** or **protons** to reach a final stable energy state.

radioactive isotope (radioisotope) – an atom for which **radioactive decay** has been experimentally measured (also see **half-life**). [return]

radioimmunotherapy (RIT) – a combination of radiation therapy and immunotherapy used to treat non-Hodgkin B-cell lymphoma and other types of cancer. RIT uses engineered monoclonal antibodies **isotopically labeled** with a radionuclide to deliver radiation toxic to living cells to a target cell. [return]

radiolabeled – a mixture of an isotopically unmodified compound with one or more analogous radioactive isotopically substituted compound(s).

radionuclide – a nuclide that is radioactive [703]. [return]

radiopharmaceutical – **radiolabeled** compound used for diagnostic or therapeutic purposes.

spallation – a process in which fragments of a solid (spall) are ejected from the solid due to impact or stress. In nuclear physics, spallation is the process in which a nucleus of a heavy element emits a large number of nucleons (isotopes) as a result of being hit by a high-energy particle (e.g., a cosmic ray), resulting is a substantial loss of its atomic weight.

stable isotope – an atom for which no radioactive decay has ever been experimentally measured. [return]

tracer - substance used for tracking purposes.

X-rays – electromagnetic radiation with a wavelength ranging from 0.01 to 10 nanometers—shorter than those of UV rays and typically longer than those of gamma rays.

X-ray fluorescence (XRF) spectroscopy – the branch of science concerned with the investigation and measurement of characteristic “secondary” (or fluorescent) X-ray spectra produced when a material has been bombarding with high-energy X-rays or gamma rays—widely used for elemental analysis and chemical analysis. [return]

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