Astrophysical Radiative Processes

DRAFT

Alessandro Patruno

May 5, 2022

ISBN

Contents

3 Radioactive Decay

Beside atomic line transitions that occur when electrons jump between energy levels, atoms are also capable of emitting radiation via radioactive decay. The number of electrons in an atom defines the ion species, the number of protons defines the element and the number of neutrons define the isotope. Many isotopes display radioactivity, meaning that they will undergo beta-decay (also called β^-) with a neutron in the nucleus transforming into a proton and emitting an electron and an anti-neutrino:

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{3.1}$$

Sometimes the inverse reaction can occur when the nucleus absorbs an electron, the so-called inverse β decay (or β^+):

$$p + e^- \rightarrow n + \nu_e \tag{3.2}$$

Because the atomic species is defined by the number of protons, the β^-/β^+ decay induces a *transmutation* of one atomic species into another. This reaction does not entail the emission of a photon. However, the newly formed isotope might not be formed in its ground state, but in an excited state (either meta-stable or not). This occurs because protons and neutron in the nucleus occupy energy levels similar to what electrons do in the atomic electron orbitals. The nucleus can therefore undergo *gamma decay* by emitting the excess energy as a γ ray photon. This occurs either promptly, in a very short time of order 10^{-12}s or on a longer timescale of at least 2-3 orders of magnitude, when the daughter nucleus is created in a meta-stable state called nuclear isomer.

In either case the resulting decay produces the emission of a high energy photon, with energies that depend on the type of daughter nucleus and that typically range around 1 MeV.

For example, the most stable cobalt isotope is ${}^{59}_{27}\mathrm{Co}$, whereas ${}^{60}_{27}\mathrm{Co}$ is highly radioactive. This latter isotope decays via β decay into a nickel isotope ${}^{60}_{28}\mathrm{Ni}$ by emitting an energetic electron with kinetic energy of 0.31 MeV and an anti-neutrino. This nickel isotope is in an excited state and decays twice via gamma decay by emitting in succession a 1.17 MeV and a 1.33 MeV photon. This transmutation occurs 99.88% of the times, whereas in a small fraction of reaction there is a direct decay from ${}^{60}_{27}\mathrm{Co}$ to ${}^{60}_{28}\mathrm{Ni}$ with an emission of a 1.48 MeV

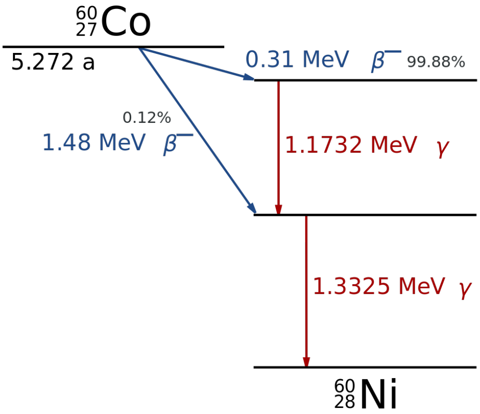

Figure 3.1: Caption

electron. This nickel isotope then does one gamma decay with emission of a single photon of 1.33 MeV energy (see Fig 3.1).

This gamma decay might therefore be an important source of gamma-ray photons whose observations might be important to trace the chemical composition of the universe and understand nucleosynthesis, supernovae and other astrophysical processes like planet formation.

3.1 Aluminium 26

Aluminium-26 is a radioactive isotope of the stable $^{27}_{13}$Al element. It is produced during supernova explosions and it is a fundamentally important radioisotope for our understanding of chemical abundances in the solar system, nuclear reactions in astrophysical environments and for the evolution of massive stars.

Aluminium 26 typically exists either in the ground state ($^{26}_{13}\mathrm{Al}^{g}$) or in a metastable form ($^{26}_{13}\mathrm{Al}^{m}$). The transition to a $^{26}_{12}$Mg occurs from the ground state of aluminium-26 via inverse beta decay with a typical half-life of 717,000 years. About 82% of the $^{26}_{12}$Mg atoms are created in an excited state that undergo rapid (0.49 picoseconds) gamma decay by emitting a characteristic gamma ray photon at 1.809 MeV.

This emission line has been detected by multiple gamma ray space observatories like the MeV Compton gamma-ray telescope COMPTEL aboard of the NASA Compton Gamma-Ray observatory (CGRO). A complete map of the

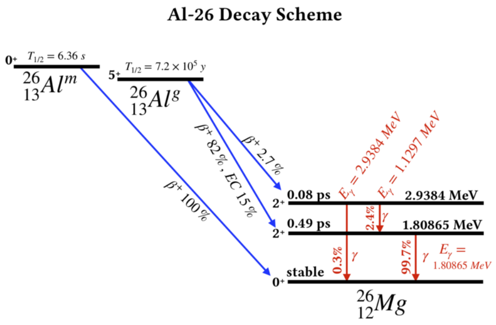

Figure 3.2: Caption

From these observations and further observations of the SPI (SPectrometer on Integral) aboard the INTEGRAL space observatory (Dehli et al. 2006), it was inferred that there are about $3M_\odot$ of Al-26 in the Milky Way. Since the half-life is so short (0.7 Myr), it must be replenished at a high rate in our galaxy. Formation mechanisms for aluminium-26 are related to core-collapse supernovae either in the pre-supernova phase or during the explosion. These pre-supernova phases occur in massive stars during core hydrogen burning and hydrostatic carbon/neon shell burning. Formation of aluminium-26 can also occur in the hydrogen-burning shell at the base of convective envelope of asymptotic giant branch (AGB) stars. In the explosive scenario, aluminium-26 is instead produced during C/Ne burning and possibly explosive oxygen/neon shell burning.

In either case, aluminium-26 is spread throughout the galaxy either from the ejecta in supernovae or by the strong winds in Wolf-Rayet and AGB stars.

The creation of aluminium-26 occurs mostly via the so-called manganese-aluminium cycle, that involves several inverse beta decays and proton captures (see Fig. 3.4).

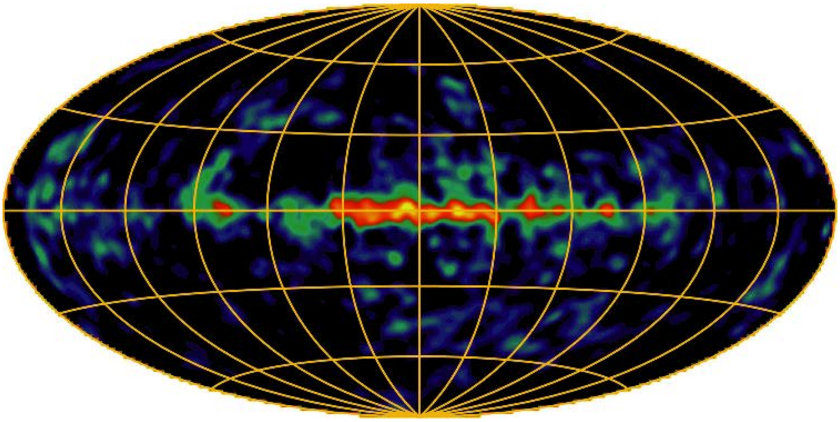

Figure 3.3: COMPTEL map of Aluminium-26 distributed in the Milky Way. The most prominent features are the galactic center region, the Carina and Vela regions (the two rightmost red regions in the map) and the Cygnus region on the left. These latter three are all intense star forming regions

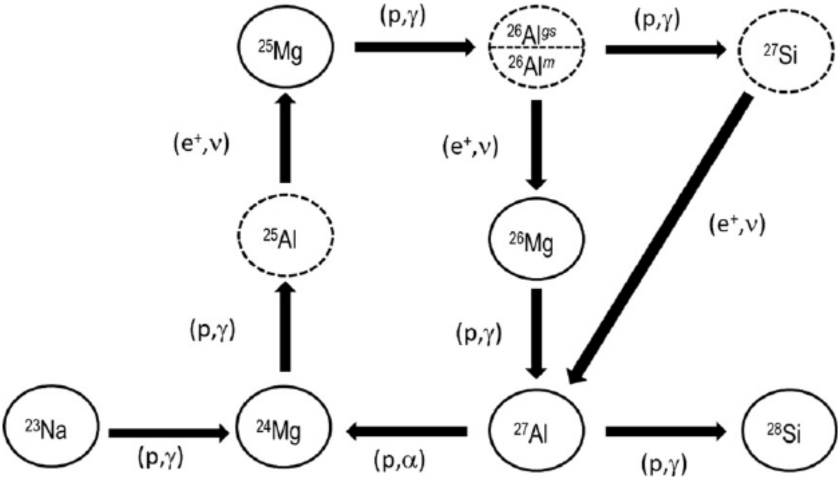

Figure 3.4: Manganese-Aluminium cycle.