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THE PROPERTIES OF Ni → Co → Fe DECAY

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ABSTRACT

A compilation of ^{56}Ni and ^{56}Co decay data is presented to make their use in astrophysical applications more convenient. The data are derived from a review of Huo et al. (1987) accounting for the laboratory measurements published up to 1985 December.

Subject headings: atomic data — nuclear reactions, nucleosynthesis, abundances

1. A SIMPLIFIED SCHEME OF ^{56}Ni DECAY

Radioactive ^{56}Ni transforms via electron capture decay (EC) into radioactive ^{56}Co:

$$^{56}\mathrm{Ni} \Rightarrow {}^{56}\mathrm{Co} + \gamma + \nu_e . \tag{1}$$

The half-life of ^{56}Ni is $T_{1/2} = 6.10$ days, and the lifetime $\tau_{\rm Ni} = T_{1/2}/\ln 2 = 8.80$ days.

Figure 1 shows a simplified scheme of ^{56}Ni decay adapted from Huo et al. (1987). The transition energies E_i are in MeV, i being the number of the excited level (for the ground state, $i = 0$). Spins and parities are also shown. The gamma transition intensities defined as the number of transitions per 100 ^{56}Ni decays are given in parentheses. The electron capture is followed by the emission of monoenergetic electron neutrinos, ν_e, primarily of energy 0.416 MeV because of the decay into level 9 that occurs in 98 cases out of 100.

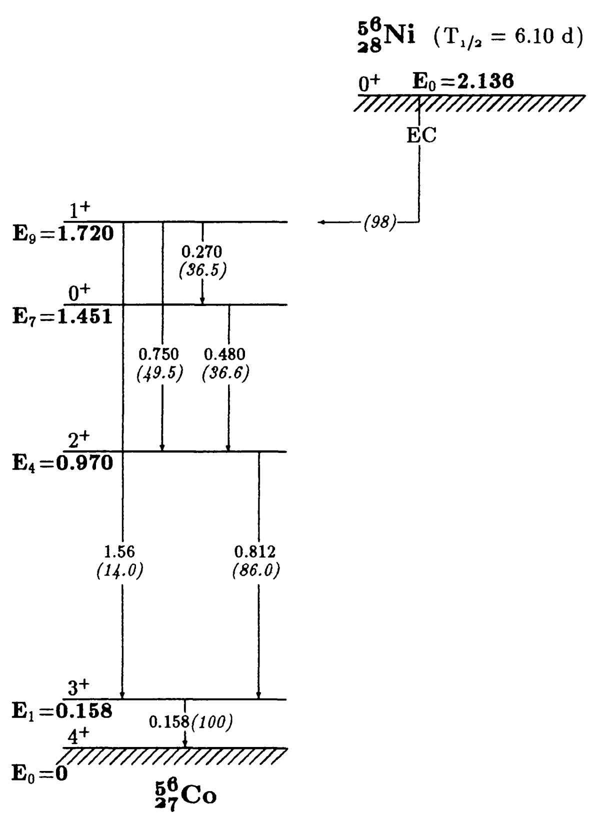

FIG. 1.—Simplified ^{56}Ni → ^{56}Co decay scheme

The total energies released per ^{56}Ni decay, as calculated from the full scheme of Huo et al. (1987), are

$$\text{Total energy emitted via gamma photons:} \quad Q_\gamma = 1.75 \text{ MeV} ,$$
$$\text{Total energy carried away by neutrinos:} \quad Q_{\nu e} = 0.41 \text{ MeV} .$$

The simplified scheme presented in Figure 1 gives Q_γ = 1.72 MeV, i.e., ~2% less than the exact value.

2. A SIMPLIFIED SCHEME OF ^{56}Co DECAY

Radioactive ^{56}Co, the product of ^{56}Ni decay, transforms into a stable isotope ^{56}Fe either by means of electron capture (EC) (81 cases out of 100) or via positron decay (β^+) (19 cases out of 100):

$$^{56}\text{Co} \Rightarrow \begin{cases} ^{56}\text{Fe} + \gamma + \nu_e & (81 \text{ cases}) , \\ ^{56}\text{Fe} + e^+ + \gamma + \nu_e & (19 \text{ cases}) . \end{cases} \tag{2}$$

The half-life and lifetime of ^{56}Co are $T_{1/2}$ = 77.12 days and $\tau_{\text{Co}} = T_{1/2}/\ln 2$ = 111.3 days, respectively.

The scheme shown in Figure 2 presents the transition energies E_i (in MeV), intensities (the number of transitions per 100 ^{56}Co decays), spins, and parities for the eight most efficient levels. Three close levels (i = 18–20) are represented by the total effective intensity and mean transition energy.

The β^+ decay is a source of positrons, e^+, of kinetic energy distributed within the interval 0–1.459 MeV, the mean value being 0.632 MeV. The positrons interact with matter and, having lost all their kinetic energy, annihilate with the electrons, producing a pair of 0.511 MeV gamma photons. In total, 38 annihilation gamma photons are produced per 100 ^{56}Co decays.

The electron capture is followed by the emission of *monoenergetic* neutrinos ν_e, with discrete energies ranging from 0.51–0.45 MeV (for decays into levels i = 18–20) to up to 2.48 MeV for decay into level i = 2. In contrast, β^+ decay produces neutrinos of energies distributed continuously between 0 and 1.459 MeV with mean energy of 0.827 MeV.

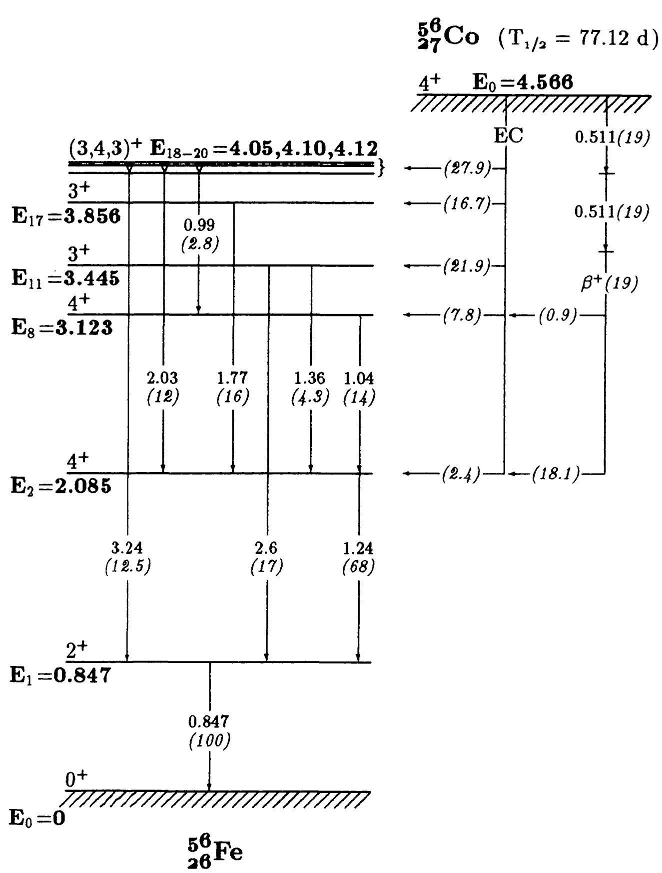

FIG. 2.—Simplified ^{56}Co → ^{56}Fe decay scheme

The full scheme of Huo et al. (1987) gives, per ^{56}Co decay:

Total energy emitted via gamma photons:	$Q_\gamma = 3.61$ MeV ,
Total kinetic energy of positrons:	$Q_{\rm kin} = 0.12$ MeV ,
Total energy carried away by neutrinos:	$Q_{\nu e} = 0.84$ MeV .

The simplified scheme results in about a 3% lower value, $Q_\gamma = 3.49$ MeV. One could also include in the simplified scheme the transitions from level $E_{21} = 4.298$ MeV (4^+) (the intensity of ^{56}Co decay into this level is equal to (3.7)) to level $i = 1$ followed by the emission of 3.45 MeV gamma photons with intensity (0.9), as well as those to level 8, 1.175 MeV (intensity 2.3). In such a case, Q_γ would be equal to 3.55 MeV, that is, only 1.5% less than the strict value.

The number of positrons, dn_+, per unit time emitted with kinetic energy w within an interval $[w, w + dw]$ can be represented as follows:

$$dn_+ = N_{\rm Co} \frac{\ln 2}{ft} \Phi(w) \frac{dw}{0.511} , \tag{3}$$

$$\Phi \equiv (\varepsilon + 1)^2 (2.8552 - \varepsilon)^2 G(w) , \tag{4}$$

where $N_{\rm Co}$ is the number of ^{56}Co atoms in the system, $\varepsilon = w/0.511$, and w is in MeV. The function $G(w)$ was tabulated by Rose et al. (1955). Figure 3 shows the positron and neutrino spectra for the β^+ transition to level $E_2 = 2.085$ MeV for which $\log ft = 8.625$. Here $t \equiv t_+ = T_{1/2}/0.181 = 3.681 \times 10^7$ s. Since the neutrino energy $w_\nu = 1.459 - w$, one can describe the neutrino spectrum by equations (3) and (4) when substituting $\Phi(1.459 - w_\nu)$ for $\Phi(w)$. For the dashed curve in Figure 3, w means the neutrino energy w_ν, while $\Phi(w)$ stands for $\Phi(1.459 - w_\nu)$.

The total number of positrons emitted per unit time, dN_+/dt, is given by

$$\frac{dN_+}{dt} = \int_0^{1.459} \frac{dn_+}{dw} dw = \frac{\ln 2}{t_+} N_{\rm Co}(t) . \tag{5}$$

The energies and gamma photon number per 100 decays are compiled in Table 1.

3. THE KINETICS OF Ni → Co → Fe DECAY

The numbers of ^{56}Ni, ^{56}Co, and ^{56}Fe nuclides are controlled by a simple set of differential equations:

$$\frac{dN_{\rm Ni}}{dt} = -\frac{N_{\rm Ni}}{\tau_{\rm Ni}} , \tag{6}$$

$$\frac{dN_{\rm Co}}{dt} = \frac{N_{\rm Ni}}{\tau_{\rm Ni}} - \frac{N_{\rm Co}}{\tau_{\rm Co}} , \tag{7}$$

$$\frac{dN_{\rm Fe}}{dt} = \frac{N_{\rm Co}}{\tau_{\rm Co}} , \tag{8}$$

with the initial conditions

$$N_{\rm Ni} = N_{\rm Ni0}, \qquad N_{\rm Co} = 0, \qquad N_{\rm Fe} = 0, \qquad \text{at} \qquad t = 0 . \tag{9}$$

Solving equations (6)–(9), one gets

$$N_{\rm Ni} = N_{\rm Ni0} e^{-(t/\tau_{\rm Ni})} , \tag{10}$$

$$N_{\rm Co} = N_{\rm Ni0} \frac{\tau_{\rm Co}}{\tau_{\rm Co} - \tau_{\rm Ni}} \left(e^{-(t/\tau_{\rm Co})} - e^{-(t/\tau_{\rm Ni})}\right) , \tag{11}$$

$$N_{\rm Fe} = N_{\rm Ni0} \left(1 + \frac{\tau_{\rm Ni}}{\tau_{\rm Co} - \tau_{\rm Ni}} e^{-(t/\tau_{\rm Ni})} - \frac{\tau_{\rm Co}}{\tau_{\rm Co} - \tau_{\rm Ni}} e^{-(t/\tau_{\rm Co})}\right) . \tag{12}$$

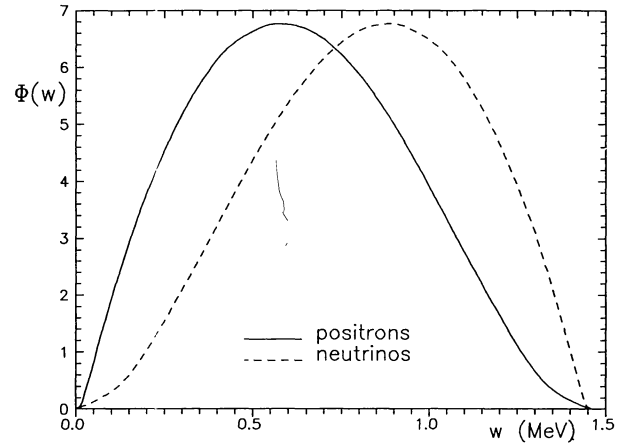

FIG. 3.—Normalized positron and neutrino spectra for the β^+ branch of ^{56}Co decay (eqs. [3] and [4])

The total initial mass of ^{56}Ni, $M_{\rm Ni0}$, is connected with $N_{\rm Ni0}$ by

$$N_{\rm Ni0} = \frac{M_\odot}{56m_u}\frac{M_{\rm Ni0}}{M_\odot} = 2.141 \times 10^{55}\frac{M_{\rm Ni0}}{M_\odot} . \quad (13)$$

$N_{\rm Ni}$ and $N_{\rm Fe}$ are monotonic functions of time (decreasing and increasing, respectively), whereas $N_{\rm Co}$ comes through a maximum at $t = t_m$:

$$t_m = \frac{\tau_{\rm Co}\tau_{\rm Ni}}{\tau_{\rm Co} - \tau_{\rm Ni}} \ln\left(\frac{\tau_{\rm Co}}{\tau_{\rm Ni}}\right) = 24.25 \text{ days} , \quad (14)$$

$$N_{\rm Co}(t_m) = N_{{\rm Co}m} = N_{\rm Ni0}\alpha^{1/(1-\alpha)} = 0.804N_{\rm Ni0} \qquad \left(\alpha \equiv \frac{\tau_{\rm Co}}{\tau_{\rm Ni}} = 12.65\right) , \quad (15)$$

$$N_{\rm Ni}(t_m) = \frac{\tau_{\rm Ni}}{\tau_{\rm Co}} N_{{\rm Co}m} = 0.0636N_{\rm Ni0} , \quad (16)$$

$$N_{\rm Fe}(t_m) = 0.132N_{\rm Ni0} . \quad (17)$$

TABLE 1

ENERGIES AND NUMBER OF GAMMA PHOTONS PER 100 DECAYS FOR ^{56}Co AND ^{56}Ni[a]

E (MeV)	I	E (MeV)	I
^{56}Co Decay		^{56}Ni Decay	
0.511	38	0.158	100
0.847	100	0.270	36.5
0.990	2.8	0.480	36.6
1.04	14	0.750	49.5
1.24	68	0.812	86.0
1.36	4.3	1.56	14.0
2.03	12		
2.60	17		
3.24	12.5		

[a] See Figs. 1 and 2.

The total rate of energy production, ϵ, is given by

$$\epsilon = \frac{M_\odot}{56 m_u} \frac{1}{\tau_{Co} - \tau_{Ni}} \left\{ \left[Q_{Ni} \left(\frac{\tau_{Co}}{\tau_{Ni}} - 1 \right) - Q_{Co} \right] e^{-(t/\tau_{Ni})} + Q_{Co} e^{-(t/\tau_{Co})} \right\} \frac{M_{Ni0}}{M_\odot} , \tag{18}$$

where

$$Q_{Ni} = (Q_\gamma)_{Ni} = 1.75 \text{ MeV} ,$$

$$Q_{Co} = (Q_\gamma + Q_{kin})_{Co} = 3.73 \text{ MeV} .$$

Finally,

$$\epsilon = (6.45 \times 10^{43} e^{-(t/8.8)} + 1.45 \times 10^{43} e^{-(t/111.3)}) \frac{M_{Ni0}}{M_\odot} \text{ ergs s}^{-1} \qquad (t \text{ in days}) , \tag{19}$$

and the time-integrated total energy production is

$$\mathscr{E} = \mathscr{E}_{Ni} + \mathscr{E}_{Co} = 1.885 \times 10^{50} \frac{M_{Ni0}}{M_\odot} \text{ ergs} ,$$

where

$$\mathscr{E}_{Ni} = 6.22 \times 10^{49} \frac{M_{Ni0}}{M_\odot} \text{ ergs} ,$$

$$\mathscr{E}_{Co} = 1.26 \times 10^{50} \frac{M_{Ni0}}{M_\odot} \text{ ergs}$$

are the total energies coming from decays of ^{56}Ni into ^{56}Co and of ^{56}Co into ^{56}Fe, respectively.

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