Neutrino Interaction Cross Sections And Branching Ratios

In this section we present tables of cross sections and particle evaporation branching ratios for charged current and neutral current inelastic neutrino scattering reactions involving intermediate mass target nuclei ($^{12}C \leq ^{A}Z \leq ^{80}Kr$). The tables are given for a select set of neutrino energies and are based on the work of Wick Haxton as discussed in Woosley, Hartmann, Hoffman, and Haxton (1990).

Given first are neutral and charged current cross sections per nucleon (in units of 10^{-42} cm^2) averaged over a normalized Fermi-Dirac distribution for three neutrino temperatures $T_\nu = 4, 6,$ and 8 Mev. Listed are the neutral current inelastic scattering cross section (σ_{neut}), and the charged current electron-neutrino (σ_{e^-}) and anti-electron-neutrino (σ_{e^+}) cross sections for target nucleus ^{A}Z. Charged current electron neutrino reactions are labeled $^{A}Z(\nu_e,e^-)^{A}(Z{+}1)$, while the antineutrino reaction is labeled by $^{A}Z(\bar{\nu}_e,e^+)^{A}(Z{-}1)$. As a special case, the neutral current neutrino scattering cross sections and branching ratios for scattering off of ^4He and ^8Be are given below:

NEUTRAL CURRENT ν−SCATTERING CROSS SECTION FOR ^4He

$T_{\nu\mu} = 4.0$	5.0	6.0	7.0	8.0	9.0	10.0
1.35(-3)	1.05(-2)	3.87(-2)	1.01(-1)	2.14(-1)	3.99(-1)	6.78(-1)
6.45(-3)	2.54(-2)	6.57(-2)	1.36(-1)	2.45(-1)	4.01(-1)	6.15(-1)

The neutron and proton branching ratios for ^4He are 0.484 and 0.516 respectively, independent of neutrino temperature.

Next come the neutral current branching ratios for two neutrino temperatures $T_{\nu\mu} = 6$ and 8 MeV. Listed are the probabilities for neutron (B_n), proton (B_p), alpha (B_α), and gamma (B_γ) particle emission following inelastic neutrino scattering off of the target nucleus ^{A}Z. The γ channel branching ratio is given by $B_\gamma = 1-(B_n+B_p+B_\alpha)$. Special neutral current de-excitation branching ratios for ^{12}C are given in Table 13.

Finally, we tabulate charged current branching ratios for $T_{\nu e} = 4$ and 6 MeV. Listed are the probabilities for neutron ($B_{n\beta^-}$), proton ($B_{p\beta^-}$), and gamma ($B_{\gamma\beta^-}$) particle emission following electron-neutrino capture on target nucleus ^{A}Z, and similar probabilities ($B_{n\beta^+}$, $B_{p\beta^+}$, and $B_{\gamma\beta^-}$), for particle emission following anti-electron-neutrino capture on target nucleus ^{A}Z. Again, the γ channel is assumed to be one minus the sum of the neutron, proton, and alpha (not listed) particle emission probabilities.

Total Cross Sections, Implementation into Reaction Networks

We now describe the implementation of the neutrino scattering cross sections and branching ratios into a nuclear reaction network that describes the time rate of change of a target nucleus (I) by all possible interactions (previously defined in the introduction) involving a single neutron, proton, α-particle, or γ-ray in either the incident (j) or exit (k) channel to create the product nucleus (L). We also include reaction linkages via the three weak interactions beta decay (β^-), positron decay (β^+), and electron capture (E.C.). Specifically, we concentrate on the nuclear cross section (as a function of incident particle energy) that describes the probability of producing nucleus L via the weak or strong and electromagnetic reactions mentioned above. The product of a charged or neutral current cross section with an appropriate branching ratio provides for enhancement of some of these "standard" reaction network linkages (as is the case with all three neutral current reactions considered), although two of the six charged current reactions have no analog to possible reaction linkages within the standard reaction network described in the introduction. Table 12 lists the neutrino scattering reactions for neutral and charged currents:

TABLE 12

NEUTRINO SCATTERING REACTIONS

Neutral Current	Analog	Charged Current	Analog
$(\nu, \nu'\mathrm{n})$	(γ,n)	(ν, e^-)	β^-
$(\nu, \nu'\mathrm{p})$	(γ,p)	(ν, e^+)	β^+ + E.C.
$(\nu, \nu'\alpha)$	(γ, α)	(ν, e^-, n)	none
		(ν, e^-, p)	(γ, n)
		(ν, e^+, n)	(γ, p)
		(ν, e^+, p)	none

Neutral Current Contributions

The product of the neutral current cross section σ_{neut} and the appropriate neutral current proton (B_p), neutron (B_n), or $\alpha-$particle (B_α) branching ratio provide for enhancement of the three reverse reactions (γ,p), (γ,n), and (γ,α), respectively. These are analogous to photodisintegration reactions in the standard reaction network described above.

As a special case, we present in Table 13 special neutral current de-excitation branching ratios for the target nucleus ^{12}C with decay proceeding through channels exit n, p, α, pn, pα, nα, ^{3}He, ^{3}He+n, and ^{3}H+p.

Charged Current Contributions

The gamma-ray channel of the charged current interaction is a modification to the beta decay or positron decay + E.C. rate. For the modification of the positron rate, one must modify the rate that flows into target nucleus I, not I itself.

The beta decay (β^-) rate *out of* target nucleus I should be modified by addition of the product $\sigma_{e^-} \times \mathrm{B}_{\gamma\beta^-}$.

The positron decay plus electron capture (β^+ + E.C.) rate flowing *into* target nucleus I should be modified by addition of the product $\sigma_{e^+} \times \mathrm{B}_{\gamma\beta^+}$.

The product of $\sigma_{e^-} \times \mathrm{B}_{n\beta^-}$ is the cross section for the target nucleus I to interact with a neutrino and eject an electron and a neutron. It is like a (p,2n) reaction (except that no proton is absorbed and only one neutron is ejected) and has no present analog in the standard reaction network.

The product of $\sigma_{e^-} \times \mathrm{B}_{p\beta^-}$ is the cross section for the target nucleus I to interact with a neutrino and eject an electron and a proton. It makes the same product nucleus as a (γ,n) reaction but ejects a proton rather than a neutron.

The product of $\sigma_{e^+} \times \mathrm{B}_{n\beta^+}$ is the cross section for the target nucleus I to interact with an antineutrino and eject a positron and a neutron. It yields the same product nucleus as a (γ,p) reaction but makes a neutron rather than a proton.

The product of $\sigma_{e^+} \times \mathrm{B}_{p\beta^+}$ is the cross section for the target nucleus I to interact with an antineutrino and eject a positron and a proton. It is like a (n,2p) reaction (except that no neutron is absorbed and only one proton is ejected) and has no present analog in the standard reaction network.

TABLE 13

SPECIAL ^{12}C DE-EXCITATION BRANCHING RATIOS

$\mathrm{T}_{\nu\mu}$ (MeV)	4.0	6.0	8.0	10.0
$^{12}\mathrm{C}(\nu,\nu'\,\mathrm{n})^{11}\mathrm{C}$	2.37(-2)	5.84(-2)	9.20(-2)	1.18(-1)
$^{12}\mathrm{C}(\nu,\nu'\,\mathrm{p})^{11}\mathrm{B}$	1.25(-1)	2.40(-1)	3.34(-1)	4.00(-1)
$^{12}\mathrm{C}(\nu,\nu'\,\alpha)3\alpha$	4.11(-2)	3.93(-2)	3.71(-2)	3.52(-2)
$^{12}\mathrm{C}(\nu,\nu'\,\mathrm{pn})^{10}\mathrm{B}$	1.11(-3)	5.80(-3)	1.28(-2)	2.00(-2)
$^{12}\mathrm{C}(\nu,\nu'\,\mathrm{p}\alpha)^{7}\mathrm{Li}$	5.40(-4)	2.48(-3)	5.26(-3)	8.05(-3)
$^{12}\mathrm{C}(\nu,\nu'\,\mathrm{n}\alpha)^{7}\mathrm{Be}$	5.80(-4)	2.61(-3)	5.45(-3)	8.22(-3)
$^{12}\mathrm{C}(\nu,\nu'\,^{3}\mathrm{He})^{9}\mathrm{Be}$	4.00(-5)	2.00(-4)	4.30(-4)	6.60(-4)
$^{12}\mathrm{C}(\nu,\nu'\,^{3}\mathrm{H}+p)3\alpha$	1.50(-4)	1.02(-3)	2.61(-3)	4.49(-3)
$^{12}\mathrm{C}(\nu,\nu'\,^{3}\mathrm{He}+n)3\alpha$	1.10(-4)	7.40(-4)	1.93(-3)	3.36(-3)