CHAPTER VI

BETA DECAY RATES OF A > 60 FP SHELL NUCLEI FOR PRESUPERNOVA STARS

6.1 MOTIVATION

The role of beta decay of some neutron-rich A>60 nuclei in the silicon-burning stage of presupernova evolution is receiving a fair amount of attention recently[1),2),3)]. In earlier stellar evolution calculations these were not considered on the surmise of negligibly small abundances of the nuclei involved. But recently Aufderheide et al[2)] argue that at typical temperatures ($2-5 \times 10^9$ ^{0}K) and densities ($10^8 - 10^9$ g/cc) during the advanced stages of pre-SN evolution the abundances of some Cu and Co isotopes (in particular ^{63}Co) are not very small. With the approximate abundances of Aufderheide et al at a typical temperature of T = 4×10^9 K and $\rho = 10^8$ g/cc and the electron fraction $Y_e = 0.44$, the beta decay of ^{63}Co will lead to an increase of Y_e at the rate[1)] of 1.3×10^{-6} s^{-1} . As the contraction phase lasts for 4×10^4 s, this could increase Y_e appreciably. But on the other hand these beta decays will result in cooling through the loss of the neutrinos produced and this results in the reduction of electron pressure and consequently in the reduction of the size of core that can support itself. One should also keep in mind that lower temperatures cut off the abundances of the odd-odd and odd-A nuclei fast as demonstrated by Aufderheide et al[2)]. So the only way one can get an answer to the question of the importance of the beta decays in the Si-burning stages is by studying this process self-consistently by incorporating the beta decay rates of the relevant nuclei into the stellar evolution code. Fuller, Fowler and Newman (FFN) made a detailed study[4)] of the beta decay and electron capture rates using simple shell model arguments supplemented by experimental information for nuclei with A $\leq$ 60 and this is immensely useful for the evolution calculations. Detailed shell model calculations can give the most reliable estimates of these decay rates but unfortunately because of the large dimensionality of the spaces involved for the fp shell nuclei, Hamiltonian diagonalisation and calculation of β decay strengths is a formidable job. Bloom and Fuller[5)] performed shell model calculations for some A < 60 nuclei using truncated basis space and their results are the most detailed theoretical study of the strength distribution for the fp shell nuclei. On the other hand the results of Gamow-Teller giant resonance studies through (p,n) reactions experimentally give information about the same strength function and one of the key features of this is the observation that the total strength in the low energy region of the resonance is quenched compared to its sum rule value. This suggests that any theoretical evaluation of strength should be multiplied by an appropriate quenching factor before comparison with experiments. For nuclei with A > 60 no shell model results are available yet. Aufderheide et al[2)] used experimental logft values along with detailed balance arguments to generate the decay rates of some Co, Cu isotopes. But the contribution of the excited states to these rates could not be probed this way.

In this chapter we develop a simple model for the average beta strength distribution of the quenched sum rule strength and calculate rates using a continuous approximation for the final states. This can easily incorporate the effects of the excited states of the mother nucleus. On the other hand evaluation of beta decay halflives in agreement with experimental observations has always been a challenging problem for nuclear theorists. Among the microscopic theories best results are obtained by performing complete shell model diagonalisation calculation[6] for $A \leq 40$ nuclei and doing quasiparticle RPA (QRPA) for heavier nuclei[7),8)]. The QRPA methods for the ground state are quite successful all over the periodic table. Their extension to non-zero temperature situation for the rates has not been done yet. On the other hand, the gross theory of Takahashi and Yamada[9] uses a statistically averaged allowed and forbidden strength function and makes global best fits of its parameters to experimental halflives of a large number of nuclei. In our model we first calculate the allowed beta decay sum rule strength using the form developed in chapter IV [equation (4.2-8a)] , with occupancies evaluated by spectral distribution theory[10] and then assuming a Gaussian form for the strength distribution, estimate its width by a best fit to halflives of a number of $A > 60$ nuclei. The comparison of the predicted halflives with the experimental ones gives one an idea about the accuracy of the predicted decay rates

6.2 THE MODEL

The ft value of an allowed beta decay from the state $|i\rangle$ of the mother to the state $|f\rangle$ of the daughter is given as

$$ft = \frac{6250 \text{ sec}}{\left[B(F) + \left(g_A/g_V\right)^2 B(GT) \right]} \qquad (6.2-1)$$

where g_V , g_A are the vector and axial-vector coupling constants and the Fermi (F) and Gamow-Teller (GT) transition probabilities B(F) and B(GT) are defined as

$$B(F) = \frac{1}{(2J_i+1)} \left| \langle J_f || \; O_F \; || J_i \rangle \right|^2$$

$$B(GT) = \frac{1}{(2J_i+1)} \left| \langle J_f || \; O_{GT} \; || J_i \rangle \right|^2$$

(6.2-2)

In equation (6.2-2) J_f , J_i are the final and initial J values and O_F and O_{GT} are the Fermi and GT operators $\left(O_F = \sum_i t_{\pm}(i) \text{ for } \beta^{\pm} \text{ decay, where } \vec{t}(i) \right.$ stands for the isospin vector of the ith nucleon$\left. \right)$. To calculate the ground state beta decay halflife one should consider all final states $|f\rangle$ (with energy E_f) which are allowed by the Q-value. Thus one has

$$\tau_{1/2} = \frac{6250 \text{ sec}}{\sum_f \left\{ B_F(E_f) + (g_A/g_V)^2 \, B_{GT}(E_f) \right\} f(Q-E_f)} \tag{6.2-3}$$

We assume that the final level density is large enough to replace the summation over f by an integration over the Q-value. This gives

$$\tau_{1/2} = \frac{6250 \text{ sec}}{\int_0^Q \left\{ |M_F(E')|^2 + (g_A/g_V)^2 \, | M_{GT}(E')|^2 \right\} f(Q-E')dE'} \tag{6.2-4}$$

In equation(6.2-4) $| M_{F(GT)}(E') |^2 = B_{F(GT)}(E') \, \rho(E')$, the level density $\rho(E')$ coming because $\sum_{E'} \longrightarrow \int \rho(E')dE'$ in the continuous approximation. In our model we replace the actual microscopic strengths by a statistically averaged smoothed strength function. In the pre-SN situation with non-zero temperature (T) not only the ground state but the excited states also make contributions to the decay rate and so we sum the strengths over initial excited states as well with the weight factor $\exp(-E_i/kT)$ times $(2J_i+1)$ and divide it by the nuclear partition function G. E_i and J_i are the energies and spins of the initial states and are taken from the experimental spectrum wherever known and $G = \sum_i (2J_i+1) \exp(-E_i/kT)$. Then the decay rate is expressed as

$$\lambda = \ln 2 \, \frac{(6250 \text{ sec})^{-1}}{G} \sum_i (2J_i+1) \exp(-E_i/kT) \times$$

$$\int_0^{Q_i} \left(|M_F^i(E')|^2 + (g_A/g_V)^2 \, | M_{GT}^i(E')|^2 \right) f(Q_i-E')dE' \qquad (6.2-5)$$

The Q-value for the excited states are $Q_i = Q+E_i$. The Fermi strength is concentrated in a very narrow resonance centred around the Isobaric Analog State (IAS) for the ground as well as the excited states and the total Fermi strength for beta decay is given by (N−Z) where N(Z) is the neutron (proton) number. For nuclei with N > Z, the Fermi transition for β^+ decay or electron capture is ruled out by isospin selection rule. For the position of the IAS, the coulomb displacement energy Δ_c is taken as Δ_c = 1.44 Z $A^{-1/3}$ MeV[11) . It is the coulomb interaction that makes the Fermi strength spread and for the width of the resonance we use the expression σ_c = 0.157 Z $A^{-1/3}$ MeV. This leads to vanishingly small contribution to β^- −decay halflives and transition rates as the narrow Fermi resonance lies high up in energy. For the Gamow−Teller strength function, we assume the statistically averaged smoothed form is a Gaussian in energy E'. This is a reasonable assumption to make for the global behaviour of the strength distribution as according to the spectral distribution theory the strength density[12) (i.e. the average strength times the density of states) has an asymptotic bivariate Gaussian form in the initial and final energies in large spaces. This was discussed in chapter II and V. But one notes here that the actual experimental or shell model strength for specific states may deviate from this global smoothed asymptotic form showing microscopic structure. To minimise this deviation we use the width of the Gaussian strength as a parameter and fit the experimental halflives with the predictions of the model for a number of nuclei. More accurately the width of the resonance σ_s has two parts, $\sigma_s^2 = \sigma_c^2 + \sigma_N^2$, the first part coming from the spreading due to coulomb force, and the dominant second part coming from the spreading due to the nucleon–nucleon interactions. We vary σ_N for the best fit of a number nuclei's calculated halflives to their experimentally determined values. Two more quantities are needed to fix the GT strength; firstly the sum rule strength that gives the area below the Gaussian and the second one is the centroid of the distribution. We note that the physically accessible region through the Q–value of the ground state (the excited states) covers only the tail of the Gaussian strength distribution. For the Gamow–Teller β^- sum rule strength from the initial state $|i\rangle$ we use the expression (4.2–8a) of chapter IV which is seen to be a fair approximation in fp shell

$$S_{\beta^-}^{GT} = \langle i|\ O_{GT}^{+}(\beta^-) O_{GT}(\beta^-)\ |i\rangle$$

$$= 3\ Z_n \sum_{nljj'} \left| C_{nl}^{jj'} \right|^2 \left(1 - \langle n_{nlj'}^{\pi} \rangle\right) \langle n_{nlj}^{\nu} \rangle \qquad (6.2\text{–}6)$$

where $C_{nl}^{jj'} = (-1)^{j-j'} \left[2(2j+1)(2j'+1)\right]^{1/2} W(l1/2jl:j'1/2)$, $\langle n_{nlj'}^{\pi} \rangle$ and $\langle n_{nlj}^{\nu} \rangle$ are the fractional occupancies of the proton orbit (nlj') and the neutron orbit (nlj) in the state $|i\rangle$. Z_n is an empirical quenching factor for a realistic description of the decay. Following Aufderheide et al[2] we use the value of 0.6 for Z_n. The expectation value of the fractional neutron number operator n^{ν}_{nlj} in the state of energy E is given in the framework of SDM by

$$\langle n^{\nu}_{nlj} \rangle^{m_p, m_n, E} = \sum_{\tilde{m}_p, \tilde{m}_n} \frac{I^{\sim}_{\tilde{m}_p, \tilde{m}_n}(E)}{I_{m_p, m_n}(E)} \frac{m^{\nu}_{nlj}(\tilde{m}_p, \tilde{m}_n)}{N^{\nu}_{nlj}} \tag{6.2-7}$$

These are the expressions we use to evaluate the GT sum rule strength in eq.(6.2-6). Finally for the centroid of the GT strength distribution we use the relation developed by Nakayama et al[13] which gives a best fit to the centroid observed through (p,n) reactions. The expression is

$$\epsilon_{GT} = \epsilon_{IAS} + 26\ A^{-1/3} - 18.5\ (N-Z)/A \tag{6.2-8}$$

where ϵ_{GT} is the centroid energy and ϵ_{IAS} is the energy of the IAS. Eq.(6.2-8) is valid for the strength distribution from the ground state. For the excited state decays we just extend the isobaric analog argument and add the excitation energy of the initial state to fix the centroid of the GT distribution. The phase space factor appearing in eq.(6.2-4) is given by

$$f(T;\mu,E_{\alpha}) = \int_{1}^{\epsilon_0} \frac{F(Z,\epsilon)\epsilon(\epsilon^2-1)^{1/2}(\epsilon_0-\epsilon)^2}{1+\exp[(\mu-\epsilon)/kT]}\, d\epsilon \tag{6.2-9}$$

where we use a Fermi-Dirac distribution for the electron gas outside the nuclei with the chemical potential μ within the stellar environment at temperature T. In the RHS of eq.(6.2-9) the maximum energy ϵ_0 is expressed in terms of the electron rest mass energy ($\epsilon_0 = E_0/m_0c^2$, where m_0 is the rest mass of the electron). $F(Z,\epsilon)$ is the coulomb correction factor and we use the Schenter and Vogel approximation[14)] for it (as used by Aufderheide et al).

To determine the chemical potential we note that at the density and temperature under consideration, the pressure is dominated by relativistic electrons and the net density of electron-positron pairs ($m_e \approx 0$) is given by[15)]

$$n_e = \rho Y_e = 2 \int \frac{d^3k}{(2\pi)^3} \left(f_{e^-} - f_{e^+} \right) \tag{6.2-10}$$

where $f_{e^\pm} = f\left\{(k \mp \mu_e)/kT\right\} = \left(1 + \exp\left[(k \mp \mu_e)/kT \right]\right)^{-1}$, the factor 2 being for spin and $\mu_e = \mu_{e^-} = \mu_{e^+}$ is the electron chemical potential. For this discussion we take $\hbar = c = 1$ and as the distributions are isotropic one gets from eq.(6.2-10)

$$n_e = \frac{T^3}{\pi^3} \left(F_2(\eta_e) - F_2(-\eta_e) \right) \tag{6.2-11}$$

where $\eta_e = \mu_e/kT$ and the Fermi integral $F_n(\eta) \equiv \int_0^\infty dx\, x^n\, f(x-\eta)$.

The quantity $G_n(\eta) \equiv F_n(\eta) - (-1)^n F_n(-\eta)$ is evaluated by recursive integral and one finds[16)] $G_2(\eta) = \eta^3/3 + \pi^2\, \eta/3$. We find the root of the 3rd order equation for η,

$$\frac{3\pi^3}{T^3}\, \rho\, Y_e = \eta^3 + \pi^2\, \eta \tag{6.2-12}$$

and use that μ_e for given ρ, T and Y_e.

6.3 RESULTS AND DISCUSSIONS

To test the predictions of the model and to fix the parameter σ_N, we calculate the halflives of a number of nuclei in the fp shell with A > 60. The free decay is the $\rho \longrightarrow 0$, $T \longrightarrow 0$ limit of our calculations. We minimise the quantity $\sum_i \left[\log_{10}\left(\tau^{exp}_{1/2}(i) \;/\; \tau^{calc}_{1/2}(i) \right) \right]^2$ as a function of σ_N , where $\tau^{calc}_{1/2}(i)$ and $\tau^{exp}_{1/2}(i)$ stand for the calculated and experimental halflife respectively for the ith nucleus. For the 13 nuclei considered i.e. ^{69}Cu, ^{68}Cu, ^{67}Ni, ^{66}Cu, ^{65}Ni, ^{65}Co, ^{64}Co, ^{63}Co, ^{63}Fe, ^{62}Co, ^{62}Fe, ^{62}Mn, ^{61}Fe the best fit is obtained with σ_N = 6.3 MeV. In table 6.3-T1 we compare the halflives thus calculated with experimental values. The table also gives the predictions wherever available of Klapdor et al[7) by the microscopic quasiparticle random phase approximation (QRPA) calculations[7),8) as well as by the gross theory[9). We find from the table 6.3-T1 that our predictions for the nuclei ^{65}Ni, ^{64}Co, and ^{61}Fe are off by an order of magnitude and clearly the use of a Gaussian with a global effective width for the strength distribution is not the correct approach for these nuclei. We see that the use of a negative skewness of γ_1 = −0.3 for the ^{64}Co strength distribution and use of the Edgeworth expansion with this skewness brings the calculated halflife to a value as low as 0.69 sec. On the other hand increasing the width to 7 MeV brings it down only to 1.76 sec.

The rates for all the nuclei can now be calculated as functions of density and temperatures using σ_N = 6.3 MeV. In table 6.3-T2 we give the examples of the rates for four of the nuclei, ^{69}Cu, ^{67}Ni, ^{63}Co, and ^{62}Co for the ranges of temperature and density typical of the pre-SN burning stage. The grid points for temperature and density used are T = 2 × 10^9, 3 × 10^9, 4 × 10^9 , 5 × 10^9 and 6 × 10^9 ^{0}K and $\log_{10} \rho_{10}$ = −0.5, −1.0, −1.5,

-2.5 and -3.0 respectively. ρ_{10} is the density in 10^{10} g/cc. The rates given in table 6.3-T2 are for $Y_e = 0.50$. Changing Y_e gives rise to different chemical potentials and this allows a finer gridding of the parameter ρ. The rates for all the nuclei show the general feature that the rates decrease with increasing density. This is easy to understand — increasing the density increases the chemical potential of electrons outside the nuclei impeding the decay process. The Fermi function, f is very strongly dependent on the Q-value — actually for free decays one sees that in the absence of F(Z,E), it goes as the fifth power of the Q-value. As the excitation energy in the daughter nucleus increases, the Q-value decreases and so the Fermi function goes down. But on the other hand the GT strength rises because one goes higher up from the tail region. Thus there is a competition between two opposing effects. Through the continuous approximation of the level density of the daughter nucleus we take into account all these features in an averaged manner to give rise to realistic decay rates.

The decay rates as given by Aufderheide et al[2] for ^{63}Co and ^{62}Co with $\rho = 10^8$ g/cc are 1.53×10^{-2} s^{-1}, 1.14×10^{-1} s^{-1} for $T = 3 \times 10^9$ ^{0}K and 1.69×10^{-2} s^{-1}, and 2.55×10^{-1} s^{-1} for $T = 5 \times 10^{9}$ ^{0}K. The corresponding ground state decay rates from our calculation are 6.38×10^{-3} s^{-1}, 3.15×10^{-2} s^{-1} for $T = 3 \times 10^{9}$ ^{0}K and 7.53×10^{-3} s^{-1} and 3.35×10^{-2} s^{-1} for $T = 5 \times 10^{9}$ ^{0}K. We see from table 6.3-T2 that the contributions from excited states can make the rates increase by a factor as high as 12.1 (as seen for ^{69}Cu with log $\rho_{10} = -0.5$ and $T = 5 \times 10^9$ ^{0}K). These contributions increase with higher densities as well as usually with higher temperatures (due to $e^{-E_i/kT}$ factor) except for some cases of high ρ where the increase in the ground state rate relative to the excited states coming from the T dependence in the f-factor more than cancels this increase. One should try to include excited states in calculations wherever they are known experimentally. The work of Aufderheide et at[2] does not have this feature. In the shell model, extensive and time consuming calculations are needed to estimate how the rates get affected by excited states but in our statistical approach this is estimated quite easily.

The global width of the Gamow-Teller giant resonance is somewhat on the high side compared to the widths observed in (p,n) experiments which is about 4-6 MeV. But the nuclei we consider are the neutron rich ones in the upper half of the fp shell. The closest cases studied experimentally are $^{54,56}Fe$ and $^{58,60}Ni$ [17]. In the gross theory [9] a Gaussian strength distribution for the Gamow-Teller excitation gives a width of 6 MeV after fitting the beta decay halflives globally over the whole periodic table. But this method among other things differs from ours in the calculation of the sum rule strength. Thus we feel that a careful evaluation of the Gamow-Teller resonance width for neutron-rich nuclei with $A > 60$ both theoretically and experimentally will be very useful for this problem.

Table 6.3-T1

Comparisons of calculated and experimental halflives

Nucleus	Halflife $\tau_{1/2}$(sec)			
	Experimental	Calculated		
		Ours	Gross theory	QRPA
^{69}Cu	180	251.4		
^{68}Cu	31	22.0		
^{66}Cu	306	312.1		
^{67}Ni	21	47.0	94	23
^{65}Ni	9072	728.3		
^{62}Co	90	15.1		
^{63}Co	27.4	52.1		
^{64}Co	0.3	3.53		10.0
^{65}Co	1.25	5.66	8	8.59
^{61}Fe	360	34.5		
^{62}Fe	68	183.4		
^{63}Fe	4.9	3.49	10	14.8
^{62}Mn	0.88	1.05	2	0.773

Table 6.3-T2

β^- decay rates for the nuclei ^{69}Cu, ^{67}Ni, ^{63}Co and ^{62}Co. The number of excited states known experimentally for ^{69}Cu, ^{63}Co and ^{62}Co are 7, 12 and 25 respectively, whereas for ^{67}Ni, no excited state is available. The numbers within paranthesis are the rates from the ground state only. Y_e=0.50.

Nucleus	Temp T (in ^{0}K)	log 10					
		-0.5	-1.0	-1.5	-2.0	-2.5	-3.0
	$2x10^9$	$1.82x10^{-12}$ $(1.65x10^{-13})$	$8.76x10^{-8}$ $(1.09x10^{-8})$	$2.32x10^{-5}$ $(1.76x10^{-5})$	$4.79x10^{-4}$ $(4.59x10^{-4})$	$1.57x10^{-3}$ $(1.54x10^{-3})$	$2.35x10^{-3}$ $(2.31x10^{-3})$
	$3x10^9$	$2.62x10^{-9}$ $(2.21x10^{-10})$	$3.44x10^{-6}$ $(3.61x10^{-7})$	$1.26x10^{-4}$ $(4.79x10^{-5})$	$9.34x10^{-4}$ $(6.69x10^{-4})$	$2.08x10^{-3}$ $(1.68x10^{-3})$	$2.81x10^{-3}$ $(2.36x10^{-3})$
^{69}Cu	$4x10^9$	$1.18x10^{-7}$ $(9.75x10^{-9})$	$2.53x10^{-5}$ $(2.50x10^{-6})$	$4.96x10^{-4}$ $(1.30x10^{-4})$	$1.81x10^{-3}$ $(8.55x10^{-4})$	$3.18x10^{-3}$ $(1.83x10^{-3})$	$3.92x10^{-3}$ $(2.40x10^{-3})$
	$5x10^9$	$1.23x10^{-6}$ $(1.03x10^{-7})$	$1.15x10^{-4}$ $(1.17x10^{-5})$	$1.10x10^{-3}$ $(2.29x10^{-4})$	$3.06x10^{-3}$ $(1.05x10^{-3})$	$4.67x10^{-3}$ $(1.95x10^{-3})$	$5.39x10^{-3}$ $(2.40x10^{-3})$
	$6x10^9$	$5.88x10^{-6}$ $(5.15x10^{-7})$	$2.82x10^{-4}$ $(2.98x10^{-5})$	$1.89x10^{-3}$ $(3.51x10^{-4})$	$4.42x10^{-3}$ $(1.23x10^{-3})$	$6.17x10^{-3}$ $(2.04x10^{-3})$	$6.83x10^{-3}$ $(2.37x10^{-3})$

contd.

	$2x10^{9}$	$1.37x10^{-10}$	$8.61x10^{-6}$	$1.34x10^{-3}$	$5.94x10^{-3}$	$1.09x10^{-2}$	$1.34x10^{-2}$
	$3x10^{9}$	$2.49x10^{-8}$	$3.80x10^{-5}$	$1.60x10^{-3}$	$6.81x10^{-3}$	$1.13x10^{-2}$	$1.35x10^{-2}$
^{67}Ni	$4x10^{9}$	$4.23x10^{-7}$	$1.01x10^{-4}$	$2.36x10^{-3}$	$7.46x10^{-3}$	$1.16x10^{-2}$	$1.36x10^{-2}$
	$5x10^{9}$	$2.62x10^{-6}$	$2.71x10^{-4}$	$3.00x10^{-3}$	$8.14x10^{-3}$	$1.20x10^{-2}$	$1.36x10^{-2}$
	$6x10^{9}$	$9.34x10^{-6}$	$4.88x10^{-4}$	$3.70x10^{-3}$	$8.80x10^{-3}$	$1.22x10^{-2}$	$1.34x10^{-2}$
	$2x10^{9}$	$4.66x10^{-10}$ ($2.14x10^{-10}$)	$1.33x10^{-5}$ ($1.28x10^{-5}$)	$1.40x10^{-3}$ ($1.40x10^{-3}$)	$5.64x10^{-3}$ ($5.63x10^{-3}$)	$9.99x10^{-3}$ ($9.98x10^{-3}$)	$1.22x10^{-2}$ ($1.22x10^{-2}$)
	$3x10^{9}$	$7.10x10^{-8}$ ($3.13x10^{-8}$)	$5.55x10^{-5}$ ($4.63x10^{-5}$)	$1.68x10^{-3}$ ($1.63x10^{-3}$)	$6.48x10^{-3}$ ($6.38x10^{-3}$)	$1.04x10^{-3}$ ($1.03x10^{-2}$)	$1.24x10^{-2}$ ($1.22x10^{-2}$)
^{63}Co	$4x10^{9}$	$1.13x10^{-6}$ ($4.80x10^{-7}$)	$1.57x10^{-4}$ ($1.12x10^{-4}$)	$2.55x10^{-3}$ ($2.33x10^{-3}$)	$7.32x10^{-3}$ ($6.94x10^{-3}$)	$1.11x10^{-2}$ ($1.06x10^{-2}$)	$1.28x10^{-2}$ ($1.23x10^{-2}$)
	$5x10^{9}$	$6.73x10^{-6}$ ($2.80x10^{-6}$)	$4.36x10^{-4}$ ($2.82x10^{-4}$)	$3.46x10^{-3}$ ($2.90x10^{-3}$)	$8.44x10^{-3}$ ($7.53x10^{-3}$)	$1.19x10^{-2}$ ($1.09x10^{-2}$)	$1.34x10^{-2}$ ($1.22x10^{-2}$)
	$6x10^{9}$	$2.36x10^{-5}$ ($9.64x10^{-6}$)	$8.26x10^{-4}$ ($4.91x10^{-4}$)	$4.59x10^{-3}$ ($3.52x10^{-3}$)	$9.74x10^{-3}$ ($8.09x10^{-3}$)	$1.30x10^{-2}$ ($1.10x10^{-2}$)	$1.41x10^{-2}$ ($1.21x10^{-2}$)

	$2x10^{9}$	$3.15x10^{-6}$ ($2.51x10^{-6}$)	$2.87x10^{-3}$ ($2.77x10^{-3}$)	$1.60x10^{-2}$ ($1.57x10^{-2}$)	$3.04x10^{-2}$ ($3.00x10^{-2}$)	$4.03x10^{-2}$ ($3.98x10^{-2}$)	$4.44x10^{-2}$ ($4.40x10^{-2}$)
	$3x10^{9}$	$1.98x10^{-5}$ ($1.59x10^{-5}$)	$3.36x10^{-3}$ ($3.16x10^{-3}$)	$1.66x10^{-2}$ ($1.61x10^{-2}$)	$3.23x10^{-2}$ ($3.15x10^{-2}$)	$4.11x10^{-2}$ ($4.02x10^{-2}$)	$4.50x10^{-2}$ ($4.42x10^{-2}$)
^{62}Co	$4x10^{9}$	$6.48x10^{-5}$ ($5.31x10^{-5}$)	$3.98x10^{-3}$ ($3.67x10^{-3}$)	$1.91x10^{-2}$ ($1.82x10^{-2}$)	$3.36x10^{-2}$ ($3.25x10^{-2}$)	$4.20x10^{-2}$ ($4.07x10^{-2}$)	$4.54x10^{-2}$ ($4.40x10^{-2}$)
	$5x10^{9}$	$1.53x10^{-4}$ ($1.27x10^{-4}$)	$5.56x10^{-3}$ ($5.09x10^{-3}$)	$2.08x10^{-2}$ ($1.96x10^{-2}$)	$3.50x10^{-2}$ ($3.35x10^{-2}$)	$4.28x10^{-2}$ ($4.11x10^{-2}$)	$4.56x10^{-2}$ ($4.39x10^{-2}$)
	$6x10^{9}$	$2.94x10^{-4}$ ($2.49x10^{-4}$)	$6.84x10^{-3}$ ($6.23x10^{-3}$)	$2.25x10^{-2}$ ($2.12x10^{-2}$)	$3.63x10^{-2}$ ($3.45x10^{-2}$)	$4.33x10^{-2}$ ($4.31x10^{-2}$)	$4.56x10^{-2}$ ($4.36x10^{-2}$)

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