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ANOMALOUS BETA DECAY IN TYPE-I SUPERNOVAE

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The maximal effects of the absence of near neighbors on the beta decay of Co^{56} were calculated. An increase in the number of low-energy positrons was found, but the effects on K-capture were infinitestimally small. The corrections were too small to explain the accelerated decay rate of the luminosity of type-I supernovae.

Key words: type-I supernovae—beta decay—supernova luminosity

I. Introduction

Two decades ago (Pankey 1962, 1963), it was suggested that during type-I supernova eruptions a resonant fusion of two Si^{28} nuclei, followed by the beta decay of Ni^{56} and Co^{56} to Fe^{56}, would explain the characteristic features of the luminosity curve (Fig. 1):

$$Si^{28}\ (Si^{28}, \gamma)\ Ni^{56} \tag{1a}$$

and

$$Ni^{56} \xrightarrow{6.4d} Co^{56} \xrightarrow{77.2d} Fe^{56}\quad . \tag{1b}$$

At the time, a Cm^{254} mechanism (Baade et al. 1956) was somewhat questionable because it predicted an overabundance of heavy elements.

More recently, a new theory, widely known as silicon burning (Bodansky, Clayton, and Fowler 1968) has been extended to type-I supernovae (Colgate and McKee 1969). It is assumed in this model that silicon burning is already occurring in the prenova star. The latter theory differs from the former in the method of formation of Ni^{56}. In silicon burning this occurs through a number of intermediate steps (mostly radiative capture of alpha particles), that are initiated through the photo disintegration of Si^{28}, and proceed to build up elements through Ni^{56} in approximately correct cosmic abundance ratios.

On the basis of available experimental evidences, it is difficult to make a definite choice between these two versions. The only known bombardment of Si^{28} with Si^{28} (Medsker et al. 1979) has been in the energy range 65-90 MeV, clearly outside the range of a possible resonance. The results, however, agree reasonably well with present models of heavy ion fusion (Glas and Mosel 1974; Sperr et al. 1976), thus favoring silicon burning.

For the present discussion, the exact nuclear pathway between Si^{28} and Ni^{56} is relatively unimportant as long as the end result is accomplished. The important point is that as far as type-I supernovae are concerned Si^{28} is now discussed as the important percusor to Fe^{56} in explosive nucleosynthesis (Chevalier 1976). Presently there is a far more important, yet related point of interest, namely that the long-term exponential decay of the luminosity of type-I supernovae, with a 55 ± 5 day half-life (Baade 1945; Van Hise 1974; Kirshner and Oke 1975) as compared to the 77.2 day half-life of Co^{56} (Burgus et al. 1954) is anomalous. Of course this difficulty can be reconciled by a selective admixture of nuclear reactants, the adjustment of mass and velocity parameters, or similar methods (Colgate and McKee 1969; Meyerott 1977). But the small deviation of the mean value suggests a more fundamental basis for the discrepancy. It is not untenable that the beta decay of Co^{56} proceeds in a supernova environment at an *accelerated rate* as compared to the terrestrial half-life. This proposition is examined critically in the following sections.

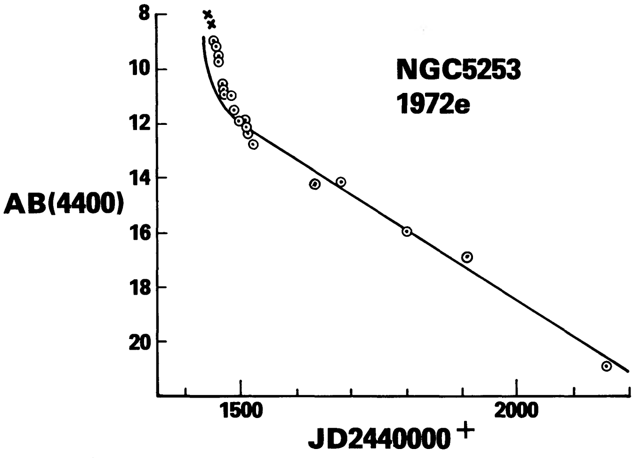

FIG. 1—The solid curve represents the parent-daughter relationship for Ni^{56} and Co^{56}

$$dn/dt = -N_0 \left[\frac{2\lambda_2\lambda_1 - \lambda_1{}^2}{\lambda_2 - \lambda_1} e^{-\lambda\, 1^{t}} - \frac{\lambda_2\, \lambda_1}{\lambda_2 - \lambda_1} e^{-\lambda 2^{t}} \right] ,$$

where the decay rates λ have been increased by a factor 1/ln2. The data points are the AB(4400) magnitudes of SN 1972e versus Julian day. AB(4400) is roughly the standard *B* magnitude. The data are accurately corrected for atmospheric extinction.

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II. Contributing Mechanisms to Accelerated Beta Decay

A type-I supernova is a very diffuse gas in the later stages, at 10^4 K to 10^5 K probably containing relatively large amounts of Co^{56} and Fe^{56} (Pankey 1962; Colgate and McKee 1969; Kirshner and Oke 1975; Chevalier 1976; Meyerott 1977). At temperatures of this magnitude, very little ionization of the inner shells would occur. But even if for some recondite reason there were *complete* ionization, the calculated screening effects would be minimal and can be neglected (Rose 1936; Reitz 1949; Longmire and Brown 1949; Brysk and Rose 1958). Similarly the recently calculated transition rates in hot *dense* matter (Takahashi, El Eid, and Hillebrandt 1978) are not applicable to tenuous supernovae. The absence of near neighbors however has not been examined, even for terrestrial experiments. For the present purposes, it is only necessary to evaluate the *maximum possible* effects, as it will be shown that these are negligible for supernova decay rates.

In examining the effects of the complete absence of near neighbors, it is important in the theory of weak interactions that the Hamiltonian in the matrix element contains the wave functions of the leptons (Fermi 1934; Eisele 1969). Among these, the neutrino and antineutrino do not interact appreciably with fields and matter exterior to the nucleus. But the wave-functions of the electrons and positrons *couple* the interaction Hamiltonian to exterior fields (Konopinski 1966). Thus relative to the forementioned physical condition, i.e., the absence of electrostatic fields from near neighbors, there would be an effect on beta decay rates. It is now important to estimate the maximum effect to be expected.

The model chosen was a Co fcc lattice with 12 near neighbors at 2.52 Å. Actually the decaying Co^{56} as measured terrestrially would be in an iron or nickel lattice, probably interstitially, but the overall effect would be essentially the same. The simplifications to be made are to neglect the shielding effects of the orbital electrons of the decaying nuclide and to furthermore assume that the coulomb potential subtended by the near neighbors is constant over the very small distance that the positron wavefunction (Co^{56} decays 20% by positron emission and 80% by K capture) extends beyond the nucleus (Konopinski 1966). In virtue of the Thomas-Fermi statistical model (Bush and Caldwell 1931) these near neighbors would modify the coulomb potential at the decaying nucleus by 14.16 eV. The maximal effects of the modification of the coulomb potential can therefore be evaluated (for positron decay) by the Fermi function, that for Z less than 40 assumes the simple form

$$F(Z,W)\,(2\pi\delta)/1-e^{-2\pi\delta} \quad , \tag{2}$$

where $\delta = (-Z/137)\,\beta = 0.18978$, $\beta = V/C$, and the appropriate Z is 26. Since the additional potential under normal circumstances would repel positrons, the net result of its *absence* would be to lower the barrier to emission, add to W, and thereby increase T ($T = W - 0.511$ MeV).

The quantity to be evaluated is $\phi^{1/2}$, where (Konopinski 1966)

$$\begin{aligned} \phi &= F_c(Z,W)/F(Z,W) \\ &\quad \cdot [(W - mc^2 + e)/(W - mc^2)]^{1/2} \end{aligned} \tag{3}$$

where $e = 14.16$ eV and $F_c(Z,W) = F(Z,W + e)$. The results of the calculation are given in Table I. For energies below 5 keV the increase in the number of emitted particles would be significant. But the decay rate is related to the integration of $F(Z,W)$ over the entire energy spectrum (Konopinski 1966);

$$\lambda \equiv 1/\tau \equiv \ln(2/t) = Cf(Z,W_0) \tag{4a}$$

$$\begin{aligned} f(Z,W_0) = &\int_{mc^2}^{W_0} dW \\ &\cdot cpW(W_0 - W)^2F(Z,W)/(mc^2)^5 \quad . \end{aligned} \tag{4b}$$

Therefore the maximum effects from the absence of near neighbors would not contribute noticeably to the positron decay of Co^{56}.

For K-capture, the mechanism is different, but the decay rate is given by (Konopinski 1966)

$$\lambda = (g^2S_0/\pi^2)\,(\alpha Z)^3\,(W_0 + W_{1\text{-}1/2})^2 \quad , \tag{5}$$

where g is the radial-wave function of a K electron, S_0 is a shape factor that includes the vector and axial vector coupling constants, α is the fine structure constant, and W_0 is the mass energy of the parent nucleus minus energy of the daughter. In this case the quantity to be evaluated is

$$\begin{aligned} (\lambda^1/\lambda)^{1/2} &= (W_0 + W_{1\text{-}1/2} \\ &\quad + 0.014\text{ keV})/(W_0 + W_{1\text{-}1/2}) \\ &= 8008.32 + 501.076 \\ &\quad + 0.014/8008.32 + 501.076 \\ &= 1.000003 \quad . \end{aligned} \tag{6}$$

TABLE I

Absence of Near Neighbors Increases Low Energy Positron Emission

T (Kev)[a]	$F_c(Z,W) \times 10^3$	$F(Z,W) \times 10^3$	$\phi^{1/2}$
1	0.00011092	0.000097918	1.068
2	0.0019022	0.0018216	1.024
5	1.6196	1.60238	1.006
10	13.582	13.530	1.0002

a. $T = W - mc^2$

In equation (6), $W_{1\text{-}1/2}$ is the ground state energy of a K electron. Again the effects of the absence of near neighbors are negligible for the supernova enigma.

III. Discussion

Thus it seems that anomalous beta decay would not contribute to the accelerated decay of the luminosity of type-I supernovae. The solution to the dilemma appears to be vested in physical parameters of the eruption, in addition to those already studied, rather than anomalous nuclear behavior. In fact, two new mechanisms were presented very recently. Colgate, Petschek, and Kriese (1980), by considering the progressive escape of positrons from expanding nebulae, have constructed models in agreement with observation. Axelrod (1980) has created a numerical model that generates self-consistent optical spectra, temperature, and ionization states for expanding Ni^{56} shells that matches the 270-day optical spectrum of SN 1972e. Other studies of this type will probably be made before a full understanding of the anomaly is assured.

A somewhat different approach seems at least worthy of mention. In one respect the enigma is very similar to the puzzling systematic redshift of the spectra of distant nebulae (Wirtz 1918; Hubble 1929) at the beginning of the century, the proper resolution of course having been basic to our present cosmological models (Weinberg 1972; Craig, Craig, and Pankey 1978). Here we are obtaining, rather accurately, data associated with a nuclear decay rate at *astronomical distances,* and seeking to compare these data with terrestrial measurements of the selfsame parameter, precisely as in the case of the cosmological redshift. Although progress has been made in understanding the resulting disparity (Colgate and McKee 1969; Meyerott 1977; Colgate et al. 1980; Axelrod 1980), the annoying possibility remains that the behavior may be partially of more fundamental origin. For example the S-operator of the universal 4-Fermion model for the nonstrange weak interactions (Feynmann and Gell-Mann 1958) may not *be* universal, in the sense that it shrouds a *local* adaptation. The theory, though very successful, was developed entirely from terrestrial evidences. If this were indeed the case, then weak interactions at astronomical distances would probably proceed at a different rate than terrestrially. This proposition is beyond the scope of the present paper. It will be examined in depth elsewhere.

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