

NUCLEAR DOUBLE BETA DECAY
AND THE EVIDENCE FOR
LEPTON NUMBER NON-CONSERVATION
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ABSTRACT

The reported ratio of double beta decay of the isotopic ^{128}Te and ^{130}Te measured by geochemical techniques, coupled with an assumed equality of the nuclear matrix elements, would indicate the existence of a neutrinoless branch indicative of lepton number violation. We have performed a large scale shell model calculation of the nuclear matrix elements and find them to be approximately equal. However, the absolute rates calculated for the normal, two neutrino branch alone are 49 times faster than experiment for ^{128}Te and 156 times faster than experiment for ^{130}Te . In a similar vein, we calculate a rate that is 18 times faster than the geochemical result for the transition $^{82}\text{Se} \rightarrow ^{82}\text{Kr}$; however that calculation is in essential agreement with a recent counting experiment. We argue that, until these large discrepancies are resolved, we cannot say anything definitive about lepton number violation, although the possibility that the ratio of rates is indicating a positive signal remains. We also note that, for the case of $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$, a pure Majorana mass of 35 eV is ruled out by Fiorini's limit on neutrinoless double beta decay.

Professor Wu¹ has given a magnificent introduction to an historical review of the subject and Professor Rosen² has laid out the general theoretical framework for the problem. I will therefore discuss some results of calculations performed with Wick Haxton of LASL and Purdue, Dan Strottman of LASL, and for ^{76}Ge , with extensive discussion with Frank Avignone of the University of South Carolina. Our interest in calculating the nuclear matrix elements for double beta decay was triggered by an excellent review by Bryman and Picciotto³ which appeared in 1978.

In that article, Bryman and Picciotto review the data on double beta decay then extant and focus particularly on the half-lives of ^{128}Te and ^{130}Te . Many years ago Primakoff and Rosen⁴ pointed out the fact that the very different phase space factors occurring for normal double beta decay with two electrons and two neutrinos in the final state and for neutrinoless double beta decay with only two final leptons lead to very different dependences of the lifetimes of the total energy released. Furthermore, they argued that, since the nuclides involved are very close in A and identical in Z, all other factors in the total rates would factor out of that ratio. In particular, this would include the nuclear matrix element. Also uncertainties in the exact age of an ore sample, which directly affect the absolute lifetime, would cancel in the experimental ratio. Since $R(2\nu) = 10^{3.8}$ under these assumptions, $R(0\nu) = 10^{2.4}$ and $R(\text{exp}) = 10^{3.2}$ with a very small error^{5,6} Bryman and Picciotto conclude that there exists evidence that the no-neutrino mode does exist.

It is not obvious, however, that the two neutrino matrix elements are really immune to isotopic effects, especially when the required variation is just a factor of 2. To investigate first the actual value of the ratio of matrix elements and second the stability of that ratio to allowed variations of the nuclear Hamiltonian, we have undertaken a large scale calculation of these and other matrix elements relevant to double beta decay, first for the two-neutrino mode and then for the no-neutrino mode under various assumptions about the form of the no-neutrino interaction. The Los Alamos version of the Glasgow shell model code has made possible the requisite large basis structure calculations in realistic model spaces. Effective interactions have been employed which are appropriate in these spaces and which successfully reproduce the nuclear spectroscopy of the relevant portion of the

periodic table. In this contribution we summarize the input to the calculations, which will be described in detail elsewhere, and compare the results for the two neutrino mode to existing data. We conclude that any inference that lepton number must be violated is, at best, premature.

Calculations were performed for 5 transitions: $^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$, $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$, $^{82}\text{Se} \rightarrow ^{82}\text{Kr}$, $^{128}\text{Te} \rightarrow ^{128}\text{Xe}$ and $^{130}\text{Te} \rightarrow ^{130}\text{Xe}$. For ^{48}Ca the entire calculation was performed with protons and neutrons in the full f-p shell, an effective interaction due to Kuo,⁷ and complete diagonalization with the shell model code. For the other cases, neutron states and proton states were separately generated with the shell model code and combined in a weak coupling approximation to form states of definite angular momentum. For ^{76}Ge and ^{82}Se , the active space consists of $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ and $g_{9/2}$ and the interaction is due to Kuo;⁷ for ^{128}Te and ^{130}Te for the interaction is taken from Baldrige and Vary⁸. The active space consists of $g_{7/2}$, $d_{5/2}$, $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ (though some restrictions were placed on allowed configurations in the cases of the 6- and 8-neutron hole calculations). Since closure is employed in summing over the virtual states of the intermediate odd-odd nuclei, an estimate of the mean excitation energy is needed. These estimates and the calculated lifetimes are presented in Table I. In all cases except ^{48}Ca , there is very little cancellation so that the results are expected to be stable with respect to perturbations of the nuclear input. The rates are larger than some early estimates³ because of the strong matrix elements of the double Gamow-Teller amplitude and because of our improved treatment of Coulomb distortions.⁹ The data shown in the table for ^{48}Ca were obtained by Bardin et al.,¹⁰ and the geochemical results for ^{82}Se and ^{130}Te are from Kirsten et al.⁵ The geochemical ^{128}Te lifetime (or more properly the ratio τ_{128}/τ_{130}) is from Srinivasan et al.,⁸ while the counter experiment result on ^{82}Se is from M. Moe.¹¹

TABLE I

Parent	<E>	τ_{calc} (yrs)	τ_{exp} (yrs)	Method
^{48}Ca	6 MeV	3.3×10^{19}	$>3.6 \times 10^{19}$	counter ⁸⁾
^{76}Ge	6 MeV	2.4×10^{20}		
^{82}Se	6 MeV	1.5×10	$(1 \pm .4) \times 10^{19}$	counter ⁹⁾
^{82}Se	8 MeV	2.35×10^{19}	2.63×10^{20}	geochemical ⁵⁾
^{128}Te	11 MeV	7.1×10^{22}	3.47×10^{24}	geochemical ⁶⁾
	full truncation	1.07×10^{23}		
^{130}Te	11 MeV	1.4×10^{19}	2.19×10^{21}	geochemical ⁵⁾
	full truncation	3.24×10^{19}		

Calculated and measured lifetimes discussed in the text.

There are several possible corrections to the nuclear structure calculation which we are currently evaluating. First, there is the truncation in the neutron space of Tellurium. For four holes (^{130}Te) the full space is open, for six holes (^{128}Te and ^{130}Xe) the $d_{5/2}$ is closed and for 8 holes (^{128}Xe) the $g_{7/2}$ is also closed. Perturbation calculations were performed allowing two holes in these shells and those results are quoted as our best results. Second, our choices of Te active spaces omit the spin-orbit partners of certain subshells. For single beta decay, the resulting core polarization correction can be quite important for suppressed Gamow-Teller transitions. However, in the present case we expect these effects to be small since our summations over complete sets of intermediate nuclear states have yielded strong two-body transition amplitudes. Third, the weak-coupling asymmetry between proton and neutron spaces can lead to a spurious isospin mixing. To assure that this does not result in an unrealistic determination of the small isospin-violating double Fermi strength, this amplitude has been approximated perturbatively. Fourth, the estimates of the mean excitation energy of the intermediate odd-odd nuclei have been taken from earlier work¹² which used less realistic active spaces. A consistent evaluation of this quantity using a doorway

state approximation is underway. All of the corrections are expected to be reasonably small and, while they may have some effect on the Tellurium ratio, the discrepancy with the geochemical rates is not expected to disappear.

In Table II we repeat the values of the Tellurium ratios and, in Table III we present the ratios of calculated and geochemically determined lifetimes. In view of the latter, it appears that we have three possible interpretations:

a) the geochemical results are wrong. In this case we clearly make no statement about lepton number conservation.

b) the geochemical results are completely right. In this case there is a major cancellation that we are missing in the matrix element, large enough to reduce the Tellurium matrix elements by an order of magnitude. In this event we cannot conclude that the ratio of matrix elements is known to a factor of two and we can make no statement about lepton number conservation.

c) for some reason the absolute rates are wrong but the measured ratio will stand. Thus, that ratio coupled with our calculation would indeed be evidence for neutrinoless double beta decay and against lepton number conservation.

A clear choice amongst these alternatives awaits a resolution of the discrepancy between existing measurements made by different techniques.

TABLE II

Method	τ_{128}/τ_{130}
Exp ^(5,6)	$10^{3.2}$
0 ν , constant matrix element	$10^{2.4}$
2 ν , constant matrix element	$10^{3.8}$
2 ν , our calculation	$10^{3.71}$

Ratios of Tellurium Lifetimes

TABLE III

Isotope	τ Geochemical/ τ calculated
$^{82}\text{Se}^5$	18
$^{128}\text{Te}^6$	49
$^{130}\text{Te}^5$	156

Ratio of lifetimes from geochemical means to values obtained in this work.

Of course, a direct measurement of two electrons with the total energy release, a direct observation of the no neutrino mode, would be the most convincing evidence. Many versions of Grand Unified Theories do suggest light, yet massive, Majorana neutrinos which couple to the various weak current eigenstates with various amplitudes. Should that be the case, the amplitude for neutrinoless double beta decay is proportional to the mass times the coupling amplitude, or more properly, the sum of such terms.

In this workshop we have also heard evidence that the "electron" neutrino is mixed into an object with mass around 35eV. If we assume a unit mixing amplitude, i.e. a pure massive Majorana electron neutrino, then a mass of 35eV implies a no-neutrino lifetime for ^{76}Ge of 10^{21} years. Fiorini¹³ has obtained a limit on this mode of $\tau > 10^{21.73}$ years. a lifetime that would match a pure Majorana mass of 15eV. Even modest improvements in such limits will be very constraining on Grand Unified Theories, especially if the current mass values prove out.

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REFERENCES

1. C. S. Wu, these proceedings, page _____ (1980)
2. S. P. Rosen, these proceedings, page _____ (1980)
3. Douglas Bryman and Charles Picciotto, Rev. Mod. Phys. 50, 11 (1978).
4. H. Primakoff and S. P. Rosen, Rep. Prog. Phys. 22, 121 (1959); Phys. Rev. 184, 1925 (1969); Phys. Rev. D5 1784 (1972).
5. T. Kirsten, O. A. Schaeffer, E. Norton and R. W. Stoner, Phys. Rev. Lett. 20, 1300 (1968); T. Kirsten, W. Gentner and O. A. Schaeffer, Z. Phys. 202, 273 (1967).
6. B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, Economic Geology 67, 592 (1972); B. Srinivasan, E. C. Alexander, Jr., R. D. Beaty, D. Sinclair, and O. K. Manuel, Economic Geology, 68, 252 (1973); E. W. Hermecke, O. K. Manuel and D. D. Sabu, Phys. Rev. C11, 1378 (1975).
7. T. T. S. Kuo and G. E. Brown, Nucl. Phys. A114, 241 (1968).
8. W. T. Baldrige and J. P. Vary, Phys. Rev. C14 2246 (1976).
9. H. Behrens and J. Jänecke, "Numerical Tables for Beta-Decay and Electron Capture," Springer-Verlag, Berlin (1969).
10. R. K. Bardin, P. J. Gollon, J. D. Ullman and C. S. Wu, Nucl. Phys. A158, 337 (1970).
11. M. Moe, U. C. Irvine reprint (1980); Phys. Rev. C22, to be published.
12. J. D. Vergados, Phys. Rev. C13, 865 (1976).
13. E. Fiorini, et al., Phys. Lett. 25B, 602 (1967).

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ABSTRACT

Possible forms of the neutrino mass matrix that might appear in grand unified theories are discussed at the SU(2) × U(1) level. Two models are discussed, one based on a heavy Majorana singlet derived from SO(10) and one due to Zee based on a charged heavy scalar boson singlet inspired by SU(5). The patterns of neutrino masses and mixings are very different in the two cases.

It has been noted in many papers that it is quite natural for neutrinos to acquire a small mass in grand unified theories (GUT).¹ By fairly general arguments² this mass has the order of magnitude

$$m_\nu \sim (\text{light mass})^2/M \quad (1)$$

where the "light mass" is of the order of charged lepton or quark masses and M is a very heavy mass. Because of the small magnitude of m_ν , the best hope for observing this mass may be in the phenomenon of neutrino oscillations. For oscillations to occur, however, not only must there be a non-zero neutrino mass but the mass eigenstates must involve significant mixing among the neutrino flavors. In this talk the major emphasis is on the mixing that might occur in grand unified theories.

Our approach is to look at the neutrino mass matrix at the SU(2) × U(1) level. We assume that the only light particles (masses $\leq M_w$) are those that are in the standard model. In particular, we assume that there are no light neutral lepton singlets so that the neutrino mass matrix necessarily has a Majorana form (connecting ν_L and $\bar{\nu}_R$) with $\Delta L=2$ and $\Delta I_3=1$. If SU(2) is broken only by the vacuum expectation values of Higgs doublets, the lowest dimensionality interaction that can lead to the neutrino mass matrix is given by the form²

$$f_{\alpha\beta\gamma} \psi_{\alpha L}^i C \psi_{\beta L}^j \phi_{\gamma}^k \phi_{\beta}^l \epsilon_{ik} \epsilon_{jl} + \text{h.c.} \quad (2)$$

where α, β are lepton family indices; α, β distinguish different Higgs doublets; i, j are SU(2) indices which are summed over; and C is the Dirac charge conjugation matrix. The neutrino mass matrix is obtained by replacing each ϕ by its vacuum expectation value

$$\sum_{\alpha\beta} f_{\alpha\beta\gamma} \psi_{\alpha L}^i C \psi_{\beta L}^j \langle \phi_{\alpha}^o \rangle \langle \phi_{\beta}^o \rangle \quad (3)$$

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