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TITLE. EXCHANGE EFFECTS IN DOUBLE BETA DECAY

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EXCHANGE EFFECTS IN DOUBLE BETA DECAY^{†‡}

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Over the past decade there has been very impressive progress in the laboratory study of double beta decay with very precise limits on 0-neutrino decay in ^{76}Ge ¹, the imminent prospect of the observation of 2-neutrino decay in ^{100}Mo ² and the first laboratory observation of 2-neutrino decay in ^{82}Se ³. For the last case, the laboratory rate is in essential agreement with geochemical results and in reasonable agreement with theoretical predictions based on a full shell model calculation⁴.

The motivation underlying the resurgence of interest in double beta decay is the hope that the observation of or limits on the 0-neutrino mode will provide information about the nature of the neutrino⁵. This clearly requires confidence in the nuclear matrix elements involved in the transition. The shell model calculations⁶ do not agree well with the geochemical values for ^{130}Te , which has led to a spate of papers offering specific fixes for the problem. In this contribution we shall not comment on any of the specific nuclear calculations, rather we make some remarks which should be relevant to any model calculation.

These remarks, elaborated below are:

- a) Due to quark interchange (viewed as tunneling, as pion exchange or as multiquark bag components) there are components of the transition depending on the short range behavior of the two neutron wave function for 2-neutrino decay as well as for 0-neutrino decay.
- b) Although the specific matrix elements differ, there is a similar dependence on the structure of the wave function for pion double charge exchange.
- c) Due to improved experimental techniques, it should be possible to measure a few double beta decay rates and couple this with more extensive pion double charge exchange measurements to constrain the nuclear matrix elements.

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Were it not for the existence of pairing in nuclear ground states, double beta decay would be prohibitively hindered by the mismatch, for neutron rich nuclei, between the last filled neutron orbitals and the first empty proton orbitals. Within a single parity shell, the relative wave function for paired nucleons peaks at 0 and 180 degrees. If both parities are active, the backward peaking is suppressed. Therefore we expect the dominant pair of nucleons in the double beta decay to be physically close, subject to the usual Brueckner anti-correlation. In this configuration the requirements of quark antisymmetry generate exchange effects which can give rise to distinct pieces of the matrix element. In addition, important effects may occur as a result of pion exchange currents⁷ and the distortion of nucleon quark wave functions in the medium (by which we also include effects induced by possible multi-quark bag components of the nuclear wave function.⁸) Using a relativistic potential model for hadrons which we have applied to ${}^4\text{He}$ ⁹ we have calculated the overlap between quark wave functions centered in different wells as a function of the separation between the well centers, which we display in Figure 1.

Taking the full space-color-isospin-spin symmetry into account, including all 9 pairs, the exchange term leads to a small enhancement of the matrix element, $19/75 \times (\text{overlap})^2 \times \text{normal matrix element}$. As Vergados noted⁷ in the context of pion exchange, such short ranged terms can be dominant for 0-neutrino decay. It thus becomes important to find a method for sorting out the contributions to the normal, 2-neutrino decay from correlated and uncorrelated components in the nuclear wave function.

This leads us to consider pion charge exchange. Many people have suggested for some time that the nuclear matrix for forward double charge exchange should be the same as for double beta decay. Given the very different momentum dependencies involved, especially in the intermediate state, this claim seems to be overly optimistic. However, the discrete operations are the same and recent theoretical studies at Los Alamos, which we shall now summarize, indicate that the same aspects of the nuclear wave functions come into play.

Auerbach, Gibbs and Piasetzky¹⁰ have shown that, for isotopes with only active neutrons in a single j-shell (the Calcium isotopes), the pion double charge exchange (non-analog) cross-section can be parameterized as

$$\sigma(\theta) = \frac{n(n-1)}{2} \left| \alpha + \frac{\beta}{(n-1)} \right|^2 \quad (1)$$

where the first term refers to sequential scattering from uncorrelated neutrons and the second term to (short-ranged) scattering from correlated neutrons. These formulas have been extended¹¹, using generalized seniority wave functions, to allow both neutrons and protons in the active space and including more than one j-shell. The basic structure of the amplitude remains the same. This allows one to study the relative importance of the short-range correlations systematically, using both isotopes and isotones.

Note that such a program does not directly lead to double beta decay matrix elements, but does give a strong handle on the relevant description of the nuclear wave functions. To have a serious impact on double beta decay, eventually allowing one to convert 0-neutrino limits into statements about neutrino properties, it will be necessary to have measurements of 2-neutrino rates for a (small) number of nuclei in the same region of the periodic table. In Table 1, which is a partial reproduction of Table 1A in Haxton and Stephenson⁵, we note some candidates with large energy release that cluster near 82Se , 100Mo , or 130Te .

Given the existing efforts in 82Se and 76Ge , as well as the relative success of shell model calculations there, this may well be the most fruitful region to study, provided that it is possible to carry out the necessary systematic pion double charge exchange measurements throughout the region.

Some caveats are in order. First, the seniority scheme is presented as an approximation to the full interacting shell model. Therefore the proper blend of short range correlation and "uncorrelated" nucleons should be present, awaiting a proper treatment of exchange effects. The approach suggested here will not replace complete calculations, but may allow one to focus on the dominant features of the wave function and study their systematics over several cases.

Second, the quark exchange described above is, in some sense, already present in nuclear wavefunctions, albeit masquerading as effective operators. For example, using a quenched value of G_A and enumerating quark exchanges may double count. This requires careful study. Third, while the double beta decay and pion double charge exchange transitions may probe the same pieces of the initial and final wave functions, the range of intermediate states may be different. Nevertheless, the possibility of including a few distinct double beta decays with systematic pion studies should provide a handle on the difference.

To summarize, the very great strides in experimental techniques now open the possibility of a systematic study of double beta decay, coupled with pion double charge exchange, in a limited region of the periodic table to minimize the uncertainties due to models for nuclear structure. The elucidation of the effect of short range correlations will permit us to extract reliable information about neutrino properties from the results on the 0-neutrino mode.

Table 1. Selected possible $\beta^-\beta^-$ decay parent isotopes and the corresponding energy release.

Transition	Energy Release (keV)
$76\text{Ge} \rightarrow 76\text{Se}$	2045
$82\text{Se} \rightarrow 82\text{Kr}$	3005
$86\text{Kr} \rightarrow 86\text{Sr}$	1249
$94\text{Zr} \rightarrow 94\text{Mo}$	1148
$96\text{Zr} \rightarrow 96\text{Mo}$	3350
$100\text{Mo} \rightarrow 100\text{Ru}$	3033
$104\text{Ru} \rightarrow 104\text{Pd}$	1301
$110\text{Pd} \rightarrow 110\text{Cd}$	2014
$124\text{Sn} \rightarrow 124\text{Te}$	2278
$130\text{Te} \rightarrow 130\text{Xe}$	2533
$136\text{Xe} \rightarrow 136\text{Ba}$	2481

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Fig. 1. Overlap integral as a function of well separation⁹.