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PARITY NONCONSERVATION IN NUCLEI

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I review the status of parity nonconservation in nuclei with emphasis on the observed effects in light nuclei and in ^{93}Tc. The results are compared to those from nucleon-nucleon scattering nucleon-alpha scattering. The special problems associated with parity nonconservation in the compound nucleus are discussed.

1 Introduction

Following the suggestion in 1956 of Lee and Yang,' parity nonconservation (PNC) in the weak interaction was discovered in 1957 by Wu et al. in the β decay of polarized ^{60}Co. [2] This led quickly to the $V-A$ model for weak interactions[3] and eventually in 1967 to the Wienberg-Salam "standard" model' in which the electroweak interaction is mediated by the exchange of charged bosons, W^- and W^+, the photon, γ, as well as the neutral boson, Z^0. The electroweak currents induce purely leptonic interactions (such as muon beta decay), semi-leptonic interactions (such as nuclear beta decay), and purely nonleptonic interactions (such as Λ^0 decay). Nonleptonic strangeness changing ($\Delta S=1$) processes (such as $\Lambda^o \to p\pi^-$) are well known. PNC in nuclear states, which is the topic of this talk, is due to the nonleptonic strangeness nonchanging ($\Delta S=0$) sector of the electroweak interaction. This is the most difficult part of the weak interaction to study since its effect must be observed as a small interference with the strong interaction. Thus its size is usually experimentally very small, and the strong interaction must be taken into account in the interpretation. The first suggestions and experiments [5,6] for the investigation of PNC in nuclei came immediately after the discovery of PNC in beta decay.

Just after its introduction, there were of course many unanswered questions about the standard model - one of these was where to look for evidence of neutral currents. Since the nuclear PNC does not change the charge, neutral currents are allowed and will influence the results, and hence this was one of the early motivations for its investigation. [7] However, neutral currents in the leptonic and semileptonic sectors are by now well established, first

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in 1973-74 by its indication in muonless neutrino-induced interactions,[8] and then its PNC nature was confirmed from the scattering of polarized electrons from deuterium[9] and from PNC in atomic levels.[10,11] (The suggestion to use atomic PNC experiments to look for neutral currents was made by Zel'dovich[12] in already 1959.) Since then the W and Z bosons have been directly observed.[13] All of these studies are beautifully consistent with the Weinberg-Salam standard model predictions. Thus, although the nonleptonic $\Delta S=0$ part of the weak interaction is relatively poorly measured up to now, there is little doubt that the standard electroweak model (charged and neutral currents) is applicable to the weak interaction between quarks. The continuing motivation for studying PNC in nuclei is the more complex one of understanding the influence of the strong interaction (ultimately at the QCD level) on the electroweak observables.

The first indication of nuclear PNC came in 1967 from the Lobashov experiment on radiative neutron capture on ^{181}Ta.[14] Since then many of the experiments in nuclei have used the interference between ML and EL gamma decay multipolarities as a signature of nuclear PNC.[15] In addition, the experiments have focussed on the results for those cases in which two nuclear levels with opposite parities lie very close to each other – parity mixed doublets (PMD) – because the small energy denominator enhances the mixing due to the weak interaction, and because the two members of the doublet are the only ones important for the PNC mixing. The closeness of the levels is an accidental result of the nuclear strong interaction. One the most spectacular examples[16] of a PMD is the $17/2^{\pm}$ doublet in ^{93}Tc where the levels are separated by only 300 eV. I will discuss the results and calculations for this case in detail below. The close spacing of the PMD in conjunction with the situation where the allowed γ decay multipolarity is hindered with respect the PNC γ decay multipolarity, often leads to relatively large effects which can be accurately measured. One of the most accurately measured is the $8^{\pm}$ doublet in ^{180}Hf in which the levels are separated by 57 keV.[17] However, the resulting PNC matrix element connecting the two levels is only 1.0 ± 0.1 μeV. It is hindered by a factor of 10^6 over the usual global estimate (1 eV) for the nuclear PNC matrix element. The E1 transition between the two levels is also very hindered. The nuclear structure models which describe this hindrance are not accurate enough to use for a quantitative interpretation of this experiment. There are many other cases where the interpretation of PNC observables are complicated by the lack of accurate nuclear wave functions. Recently, large PNC effects in low-energy neutron scattering have been observed, and this is the main topic of this workshop. The interpretation of the results for these compound nucleus states remains rather qualitative,[18] but hopefully more quantitative interpretations will be forthcoming.

In this talk I will focus on the interpretation of PNC matrix elements in light nuclei where the nuclear wave functions are rather well understood, and on the case in ^{93}Tc which has recently been measured by Hass et al.[19] and whose levels are described in zeroth order by relatively simple wave functions.

The interpretation of nuclear PNC can be factorized into two strong interaction problems. One of these is the nucleon-nucleon (NN) PNC interaction which is usually interpreted in terms of meson exchange models, where one meson-nucleon vertex is from the weak interaction and the other meson-nucleon vertex is from the strong interaction. One must relate the elementary weak interaction between quarks to the weak meson-nucleon coupling constants. Theoretical values for the nominal "best value" strengths of NN PNC interactions were established by Desplanques, Donoghue and Holstein (DDH) [20] and their hadronic model dependence has been investigated. [20,21] The DDH "best value" (DDHB) results may turn out to be wrong, however, they serve as a good reference for comparison much like the Wiesskopf unit for electromagnetic transitions. The second strong interaction problem is that for the nuclear wave functions themselves, and this is the main focus of my talk.

In order to experimentally establish the strengths of the isoscalar (ΔT=0), isovector (ΔT=1) and isotensor (ΔT=2) components of the NN PNC interaction, it is important to compare results from NN scattering with those from nuclear bound states. In the DDHB prediction, ΔT=0 is dominated by ρ meson exchange, and ΔT=1 is dominated by one-pion exchange (OPE). In light nuclei there are cases in which the isospin of the initial and final states restricts the allowed isospin components. For example, the mixing between the 0^+ T=1 and 0^- T=0 states in ^{18}F filters out the ΔT=1 PNC interaction.

2 Results for Light Nuclei

The first microscopic calculations for PNC in light nuclei were reported in 1980. [22,23] The most important cases of interest at that time were the 0^+,T=1 – 0^-,T=0 PMD in ^{18}F and the $1/2^+$,T=1/2 – $1/2^-$,T=1/2 PMD in ^{19}F. It was soon realized [24] that the ΔT=1 PNC matrix element needed for these cases could be calibrated by using the analogue first-forbidden (FF) β decays: ^{18}Ne 0^+,T=1 $\rightarrow$ ^{18}F 0^-,T=0 and ^{19}Ne $1/2^+$,T=1/2 $\rightarrow$ ^{19}F $1/2^-$,T=1/2. FF β decay has an impulse term (A) plus a two-body exchange correction term (B). In the one-pion exchange (OPE) approximation, the operator for the exchange correction is proportional to the OPE contribution to the ΔT=1 DDH operator. One often expresses the sum of these two terms in the form $(A+B) = A\epsilon$, where $\epsilon = (A+B)/A$ is the mesonic exchange enhancement factor. The value of ϵ calculated with the OPE model for B does not strongly depend on the nuclear wave functions. [15,24,25] Thus if ϵ can be accurately calculated from OPE, the OPE DDH matrix element can be directly related to the β decay matrix element, and the uncertainties in the nuclear structure matrix element can be greatly reduced. This β decay calibration showed that the results obtained in the first microscopic calculations [22,23] were too large by a factor of about three. It also showed that the experimental upper limit [26,27] of <0.09 eV for the PNC matrix element in ^{18}F was about a factor of four smaller than the DDHB prediction. The DDHB result for the purely ΔT=1 transition in ^{18}F is dominated by the OPE term.

For ^{19}F the experimental value[28,29] for the PNC matrix element is (0.40±0.10 eV). With DDHB this PNC matrix element is a coherent addition of the ΔT=0 and ΔT=1 contributions. Assuming that the ΔT=1 part is suppressed relative to DDHB as in ^{18}F, then ^{19}F should be dominated by the ΔT=0 part and is, in fact, in reasonable agreement with the ΔT=0 part of DDHB.[30] A. Hayes presented a nice comparison at this workshop which showed how the PNC mixing was dominated by mixing between the two levels of the PMD, in spite of the fact that the strongest E1 matrix elements go to levels at high excitation energy.

More recently, several developments have taken place for light nuclei. Due to improved computational methods and facilities, more complete wave functions are now available.[30,31,32,33] The effective interactions have been improved.[32] And the FF β decays have been studied more completely.[25] First I discuss the β decay. There are four relatively simple FF β decays in this region of light nuclei which can serve as a test of the OPE correction models as well as for tests of the interactions and model spaces assumed. The simplest of these is the ^{16}N 0^-,T=1 $\rightarrow$ ^{16}O 0^+,T=0 (ground state) transition.[25] The simplest model for this is a pure one-particle ($1s_{1/2}$) one-hole ($0p_{1/2}$) transition which would give a FF matrix element of 81 (I am not concerned about the units here since I only want to show how the results changes when the wave functions are changed.) The $0d_{3/2}$ – $0p_{3/2}$ matrix element is however much larger than $1s_{1/2}$ – $0p_{1/2}$ and thus a very small admixture of this component in the 0^- state (about 0.3%) causes the FF matrix element to be reduced to 61. Furthermore, the many $\hbar\omega$ admixtures are very large, typically one finds[25] $| 0^+ > = 0.66 \mid 0\hbar\omega > +0.66 \mid 2\hbar\omega > +0.37 \mid 4\hbar\omega >$ and $| 0^- > = 0.84 \mid 1\hbar\omega > +0.54 \mid 3\hbar\omega >$. The FF matrix element has the form 34 ($1\hbar\omega \rightarrow 0\hbar\omega$) -7 ($1\hbar\omega \rightarrow 2\hbar\omega$) $+18$ ($3\hbar\omega \rightarrow 2\hbar\omega$) -3 ($3\hbar\omega \rightarrow 4\hbar\omega$) = 42. Thus the total matrix element is reduced by about a factor of two over the simplest estimate. The reduction factors for other FF β decays, which do not have such simple zeroth-order wave functions, are even larger. What one finds from this study[25] is that the enhancement factor is ϵ=1.61±0.03. This value is in excellent agreement with the "soft-pion" approximation[34] to the mesonic exchange current, and is close to that assumed in the ^{18}F PNC analysis discussed above. These calculations for the FF β demonstrate the importance of the many-$\hbar\omega$ correlations in the nuclear wave functions to the reduction of the PNC and FF β matrix elements.

Another interesting case in light nuclei is that for the $1/2^+$,T=1/2 – $1/2^-$,T=1/2 PMD in ^{21}Ne. The upper limit[35] on the PNC matrix element of <0.029 eV is small compared to the ^{18}F and ^{19}F values discussed above. This result has been compared[26] with a calculation[23] in a (0+2)$\hbar\omega$ model space for $1/2^+$ and $1\hbar\omega$ model space for $1/2^-$ which gives a DDHB result with both the ΔT=0 and ΔT=1 parts being relatively large, but they are out of phase, so that the total DDHB value becomes small. However, when the ΔT=1 part is suppressed as observed in ^{18}F, this cancellation no longer can occur and the remaining ΔT=0 DDHB contribution is larger than the experimental limit. Thus, with these wave functions, the experimental results for ^{18}F, ^{19}F and ^{21}Ne are not consistent with each other.

However, it was pointed out in the first calculations[22] that the multi-$\hbar\omega$ admixtures, as estimated within the ZBM[36] model-space truncation ($0p_{1/2}$, $0d_{5/2}$, $1s_{1/2}$), gave a result which was unstable and potentially very small. Even though we are still not able to carry out the full many-$\hbar\omega$ calculation for ^{21}Ne, recent analyses[30,37] confirms the likelyhood that the ^{21}Ne matrix element is small, not due to a cancellation between ΔT=1 and ΔT=0, but because the ΔT=0 part is small due to nuclear structure. Thus, the ^{21}Ne matrix element is dominated by ΔT=1 and, like the purely ΔT=1 transition in ^{18}F, the small experimental limit indicates that the DDHB ΔT=1 strength is too large. A figure which shows the compatibility of the ^{18}F, ^{19}F and ^{21}Ne results is shown in Ref 30. The experimental boundaries are consistent with the ΔT=0 DDHB prediction but are a factor of four smaller than the ΔT=1 DDHB prediction. A nice test of the various calculations for ^{21}Ne would be to measure the PNC matrix element in the mirror levels of ^{21}Na, where the PNC matrix element comes will enter in the form [ΔT=0 + ΔT=1] as compared to [ΔT=0 − ΔT=1] in ^{21}Ne.

Another case of recent interest is the 0^+,T=1 - 0^-,T=1 doublet in ^{14}N. It has recently been measured in a $\vec{p} +^{13} C$ experiment[38] with a result of +0.38±0.28 eV for the PNC matrix element. The first relative simple shell-model calculation for this matrix element[39] gave −1.4 eV. The PNC matrix element is dominated by the ΔT=0 term with the isotensor term (ΔT=2) entering at the level of about 7%.[30] (The ΔT=1 term does not enter because of the vanishing Clebsch-Gordan coefficient $<1,0,1,0|1,0>=0$.) More recent calculations[30] have taken into account shell-model excitations of up to $4\hbar\omega$ as well as the effect of the finite potential well on the radial wave functions. The range of calculated values of 0.22 to 0.54 eV for the PNC matrix element is in agreement with the experimental magnitude but differs in sign from experiment. The difference in sign is common to all calculations.[30,38] We note that the ^{19}F PNC matrix element, which is also presumably dominated by the ΔT=0 PNC interaction, has a experimental sign which is in agreement with calculations. However, in this case the sign depend upon a theoretical sign for the E1 matrix element (relative to the sign for the M1 matrix element). The E1 matrix element is hindered, but the experimental sign appears to be stable with respect to reasonable variations in the shell-model wave functions. Also the sign of the asymmetry in $\vec{p}$+p and $\vec{p}=\alpha$ scattering is in agreement with DDHB (see below). The sign for the ^{14}N experiment relies on the reaction theory calculations, and it may be possible that there is an inconsistency somewhere in the formalism.

The shell-model wave functions for light nuclei will continue to be improved. Recent advances in the area of effective interactions[40] as well as computational techniques are important,[41] together with the continued improvement of the empirical shell-model interactions. The removal of spurious states demands that the wave functions be expanded in terms of increasing $\hbar\omega$, so that a large number of orbitals are required. In contrast, many of the important low-lying states appear to be partly described by excitation of many particles across a few orbitals near the fermi surface – as modeled in the ZBM wave functions. The continued improvement of the wave functions which are important for PNC in light nuclei will be a challenge.

3 Comparison to Nucleon-Nucleon Scattering

The results obtained for light nuclei can be compared to those from low-energy nucleon-nucleon and nucleon-alpha scattering. One of the most important and accurate of these is the $\vec{p}+p$ scattering at 45 MeV which gives a longitudinal analyzing power,[42] $A_z = -(1.57 \pm 0.23) \times 10^{-7}$, in excellent agreement in both magnitude and sign with the DDHB value[43] of -1.45×10^{-7}. The DDHB value is dominated by $\Delta T=0$ with about 20% $\Delta T=2$ (and no $\Delta T=1$).

$\vec{p}+\alpha$ scattering at 46 MeV gives $A_z = -(3.34 \pm 0.93) \times 10^{-7}$. The calculated value[44] based upon DDHB is -3.3×10^{-7}. Its dependence upon the isospin channels is nearly the same as for the ^{19}F PMD, with about equal and in phase contributions from $\Delta T=0$ and $\Delta T=1$ in DDHB. The calculated result depends upon the choice of short-range correlation and was obtained from the Miller-Spencer correlation factor.[45] Other types of short-range correlations explored in Ref 44 gave an A_z value about twice as large as experiment. As noted in Ref 44 the Miller-Spencer correlation factor was also used in the light nucleus calculations.[22,23,30,33] For $p+\alpha$ and for nuclear structure, the choice of short-range correlations functions is important for all components of the NN PNC interaction except the OPE contribution to $\Delta T=1$. If the OPE $\Delta T=1$ term were eliminated, the remaining DDHB terms would give about $A_z = -1.7 \times 10^{-7}$, which is small but not inconsistent compared to experiment given the uncertainties in the short-range correlations.

These and other scattering experiments are summarized in Ref 46. The experimental errors and limits for other experiments are significantly larger than the two discussed above. In particular, there is no good determination of the $\Delta T=1$ component. The most sensitive experiment appears to be the forward-backward asymmetry $A_\gamma = (-0.15 \pm 0.47) \times 10^{-7}$ obtained[47] for the γ's observed in $\vec{n}+p \to d+\gamma$. Comparison to the DDHB value[46] of -0.5×10^{-7}, shows that this experiment is consistent with but has a much larger error than the limits inferred from the ^{18}F results discussed above.

4 Interpretation of the Results for $\Delta T=1$

The upper limit for the empirical strength of the $\Delta T=1$ component found from light nuclei[30] is a factor of four smaller than the DDHB (DDH "best value"). There is not much doubt that nonleptonic neutral currents exist, and the deviation from DDHB is interpreted as a lack of understanding of the hadronic wave functions. Indeed, DDH showed that this was sensitive to the assumptions of the quark models and that the allowed "range of values" actually goes down to zero.[20]

More recently, Henley et al.[48] have used QCD sum-rules to calculate the ΔT=1 PNC OPE interaction. The results is an order of magnitude smaller than DDHB. The neutral current contribution is smaller than the DDHB value due to a cancellation between perturbative and nonperturbative QCD processes not found in quark models, but explicit in the QCD sum rule method.[48] This result agrees with the small value obtained in the chiral soliton model of Kaiser and Miessner..[49] Comparison to other models is discussed in Ref 48.

5 Results for ^{93}Tc

The case of ^{93}Tc presents a unique situation. The structure of the nuclei with 50 neutrons near ^{93}Tc are well described by shell-model wave functions,[50,51] and thus reasonable nuclear-structure calculations can be carried. It is different from the cases studied in light nuclei because it is a high-spin doublet and because there is (in the simplest model) no "one-body" component – it is entirely two-body. In addition, as I will show below, the ^{93}Tc PNC is particularly sensitive to the isotensor ΔT=2 component of the NN PNC potential.

The $\frac{17}{2}^-$ isomeric level of ^{93}Tc has a $\frac{17}{2}^+$ partner at a separation of only 300 eV.[16] The isomer decays to a $\frac{13}{2}^+$state through a mixed M2/E3 transition. Any contribution of the opposite parity $\frac{17}{2}^+$ state would lead to an E2 admixture to the transition whose intrinsic transition matrix element is larger by a factor of $\sim$ 1000 than M2 and E3. The asymmetry on the γ decay from a polarized initial state has recently been measured by Hass et al.[19] and has been used to deduce a parity nonconserving matrix element of 0.59$\pm$19$\pm$25 meV, where the first error indicates the statistical error and the second error is associated with the nuclear physics parameters and polarization of the intial state. The experimental results were discussed by M. Hass at this workshop.

The calculations discussed here are based upon DDHB (the DDH "best value" PNC interaction). The method of calculation including the description of the Miller-Spencer short-range correlations is the same as used in Ref 30 and Ref 22. Harmonic-oscillator radial wave functions with $\hbar\omega$=8.7 MeV are used.

When there is a closed shell of nucleons, the exact two-body PNC matrix element can be written as a sum of a one-body contribution and a residual two-body contribution.[22] The one-body contribution represents the two-body interaction between the valence and core nucleons summed over all of the core nucleons. This division is analogous to the division of the strong interaction into one-body (single-particle energy) and two-body (the residual two-body interaction) parts. The one-body PNC term is usually large compared the two-body term – expecially for heavy nuclei. The one-body PNC term has the form $< \ell, j \mid V_{PNC} \mid \ell-1, j >$ so that it only connects valence orbits which has the same j but different ℓ.

We start with Model A which is the simple $1p_{1/2} - 0g_{9/2}$ model space used by Morrison and McKellar.[52] The one-body term is zero because the there are only two orbitals and they do not differ in spin by zero. The PNC effects in this model space come entirely from the residual two-body PNC interaction. For the nuclear interaction we use the "seniority-conserving" interaction of Glockner and Serduke.[50] Morrison and McKellar used the PNC interaction of Desplanques and Missimer (DM) which predates DDHB. But the DM and DDHB PNC interactions are similar and the results given in Table 1 (with a total 5.5 meV) are close to those obtained by Morrison and McKellar – both are nearly an order of magnitude larger than the present experiment. We note that the $\Delta T=1$ terms are small in Model A since the dominant pion-exchange contribution has an isospin structure which vanishes for T=1 two-body configurations. In this regard, the structure of the matrix element in ^{93}Tc is very similar to that for $\vec{p} + p$ scattering, except in this case the two protons are bound in the nucleus.

The isotensor contribution ($\Delta T=2$) is usually small compared to the $\Delta T=0$ and $\Delta T=1$ terms since it does not contribute the the one-body PNC matrix element. In addition, the $\Delta T=2$ contribution does not contribute to ^{18}F and ^{19}F because of isospin selection rules and in the case if ^{14}N it turns out to be small[33,39] The case of ^{93}Tc is thus the first which we are aware of where the experimental PNC matrix element is comparable to the size of the expected $\Delta T=2$ contribution.

Next we consider Model B where the model space is enlarged to include $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$ and $0g_{9/2}$. We have calculated the PNC matrix elements in the full Model B space with the nuclear interaction of Ji and Wildenthal.[51] The results for the ^{93}Tc PNC matrix element given in Table 1 are not very different from the Model A results and are still much larger than experiment.

Finally, we examine the effects beyond the space of Model B. The most important excitations to consider are: (a) $1s_{1/2} \to 1p_{1/2}$, (b) $1p_{1/2} \to 2s_{1/2}$ and (c) $0g_{9/2} \to 0h_{9/2}$. These are important because even though the amplitude may be small, in each case the PNC matrix element picks up a coherent contribution from all of the core nucleons. Consider, for example, process (b) in terms of the zeroth-order two-body matrix element $< 0g_{9/2}^2, 4^+ \mid H_{pnc} \mid 0g_{9/2}, 1p_{1/2}, 4^- >$ (which has a DDHB value of 22 eV). The first-order correction is $< 0g_{9/2}^2, 4^+ \mid H_s \mid 0g_{9/2}, 2s_{1/2}, 4^+ > \times < 0g_{9/2}, 2s_{1/2}, 4^+ \mid H_{pnc} \mid 0g_{9/2}, 1p_{1/2}, 4^- > /\Delta E$. The strong interaction (H_s) matrix element calculated with the interaction used in[53] is 0.12 MeV and the energy denominator is about 9 MeV. The coherent sum over the core nucleons for $< 0g_{9/2}, 2s_{1/2}, 4^+ \mid H_{pnc} \mid 0g_{9/2}, 1p_{1/2}, 4^- >$ gives a PNC matrix element of the order of one eV and thus leads to a correction with magnitude (0.12MeV) $\times$ (1eV)/(9MeV) = 13 meV which is similar in magnitude to the zeroth order two-body term.

We have made an explicit calculation of contribution (b) by enlarging the Model A to include the $2s_{1/2}$ orbital and then allowing one nucleon to be excited into this orbital (Model C). Following again the formalism of Ref 22 and Ref 30, all of the terms discussed above including the summation over the core nucleons are explicitly taken into account. The model space and interaction are described in Ref 53. In Table 1 we give the results obtained from this calculation. We indeed find a large change in the two PNC matrix elements which contribute to the coherent core summation. The additional contribution to ΔT=0 cancels with the zeroth order two-body term. The change in ΔT=1 brings in a new ΔT=1 OPE contribution. The other PNC operators, in particular the isotensor operator, do not contribute to the core summation and thus are not much effected by the $2s_{1/2}$ admixtures. We are not able to calculate the effects of contributions (a) and (c), however, they should be less important. Contribution (a) should be smaller than (b) because the $1p_{1/2}$ is most filled and the $1s_{1/2} \rightarrow 1p_{1/2}$ excitations are thus blocked. Contribution (c) should be smaller than (b) because the $0g_{9/2}$ proton orbital is not completely filled and because the $0g_{9/2} - 0h_{9/2}$ energy denominator is larger due to the spin-orbit splitting.

Model B and Model C are two independent enlargements of the simplest Model A. Since the enlargements are both relatively small in amplitude, in the spirit of perturbation theory, we should add the changes obtained from both together. Thus we arrive at the final results labeled Model D in Table 1 which are obtained by $M_D = M_A + [M_B - M_A] + [M_C - M_A]$, where M are the PNC matrix elements.

The total Model D value of (ΔT=0)+(ΔT=1)+(ΔT=2) = (0.0-4.3+1.0) = −3.3 meV changes sign from Model A but is still larger in magnitude than experiment. However, as discussed above, the experimental result in ^{18}F indicates that the ΔT=1 term is strongly suppressed from the DDHB. Also as discussed above, recent quark sum-rule calculations give a result for OPE part of ΔT=1 which is an order of magnitude smaller than DDHB. In the limit when the ΔT=1 part is zero, the Model D result becomes (ΔT=0)+(ΔT=2) = (0.0+1.0) = 1.0 meV, which is in reasonable agreement with experiment. Thus, it appears that the PNC matrix element may be dominated by the isotensor (ΔT=2) term. The main theoretical uncertainty is in the size of the ΔT=0 term, and it should be calculated more accurately. In particular, second-order effects, such as the excitation of two neutrons across the N=50 closed shell, should be examined.

In summary, we find that the PNC calculation for ^{93}Tc leads to rather complicated but potentially interesting conclusions when compared with the small experimental value. The PNC matrix element obtained in the simplest $1p_{1/2} - 0g_{9/2}$ model space is in itself very stable and much larger than the experimental value. Small admixtures of other orbitals strongly change the result for the ΔT=0 and ΔT=1 contributions. The nuclear structure part of the isotensor ΔT=2 contribution can be reliably calculated and, compared to other PNC observables, gives a large contribution compared with the experimental value. Agreement with experiment is improved if the ΔT=1 DDHB strength is reduced as observed for light nuclei.

The DDH "range of values" is smallest for ΔT=2. It is dominated by ρ exchange and the neutral currents lead to about a factor of two reduction over the value obtained with only charged currents.[20] ΔT=2 thus provides important complementary information to the ΔT=0 and ΔT=1 components.

6 PNC in the Compound Nucleus

Finally I will briefly discuss the problem of PNC in the compound states. Other speakers have gone into more detail on this. One needs to make a quantitative connection with the microscopic nuclear structure calculations which have been used in the discussion of light nuclei and ^{93}Tc above. A start in this direction was made in the model calculations of highly excited states in the A=9 system[54] and discussed by N. Auerbach at this workshop. In this calculation we used the effective one-body operator and emphasized the role of the "giant" PNC resonance. The mixing was shown to be dominated by nearby states, and the role of "dynamical" enhancement is important. It is however not easy to extrapolate these results to the cases in heavy nuclei which are studied in thermal neutron capture.[18] It is interesting to note that the valence shell-model space for these heavy nuclei contains orbitals which cannot be mixed via the one-body PNC interaction. For example, for ^{233}Th the active space for neutrons is $0j_{15/2}$, $0i_{11/2}$, $1g_{9/2}$, $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$ and $3s_{1/2}$ and the active space for protons is $0i_{13/2}$, $1h_{9/2}$, $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$ and $2p_{1/2}$. So the situation is rather similar to the ^{93}Tc case in this regard.

The PNC effects could arise from mixing with the PNC "door-way" states (e.g. $J^\pi=0^-$) which lie at a higher energy and which are formed by particle-hole excitations not contained it the valence shell-model space. This is the model which has been used thus far.[18] When interpreted in this way the fluctuating part of the observed effects are qualitatively consistent with expectations, but the surprisingly large average value found for the special case of ^{233}Th requires a unusually large value of about 100 eV for the one-body matrix element. The calculated values obtained[55] for one-body matrix elements in heavy nuclear with the DDHB interaction are on the order of 1 eV. Also A. Hayes presented a talk at this workshop which discussed the details behind the calculation of the exact one-body operator and its relationship to the $\vec{\sigma}\cdot\vec{p}$ approximation.[56] The discrepancy between 100 eV and 1 eV has motivated experiments in heavy nuclei to look for cases of PNC among relatively simple shell-model configurations such as the one in ^{207}Pb discussed by J. Szymanski at this workshop.[55] Previous experiments on the nuclear anapole moment of ^{207}Pb already place constraints[57] of <14 eV for a PNC matrix element in ^{207}Pb. Thus the average value observed for ^{233}Th cannot be understood, except perhaps by the octupole deformation mechanism discussed by V. Flambaum[58] and V. Spevak[59] at this workshop.

However, PNC in the compound states could also arise from the residual two-body PNC interaction within the valence model space. If the situation turns out to be similar to that of ^{93}Tc it could turn out that the matrix elements are dominated by the isotensor

$\Delta T=2$ component. This remains to be explored. With the computational techniques recently available, it might be possible to carry out this calculation in an analogous medium-mass model space such as $0f_{7/2}$, $0d_{5/2}$, $0d_{3/2}$ and $1s_{1/2}$ for protons and $0g_{9/2}$, $0f_{5/2}$, $1p_{3/2}$ and $1p_{1/2}$ for neutrons. It is important to note that there are no problems with spurious center-of-mass motion in this model space as well as the one discussed above for ^{233}Th. Thus all configurations can be included, in contrast to the situation for the light nucleus calculations in which only those configurations up to a given $\hbar\omega$ can be included.

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Table 1: PNC matrix elements for ^{93}Tc (in units of meV)

ΔT	term		Model A	Model B	Model C	Model D
0	1	$-g_\rho h_\rho^{(0)}(1+\chi_v)$	3.05	2.39	0.17	
	2	$-g_\rho h_\rho^{(0)}$	0.40	0.35	0.42	
	3	$-g_\omega h_\omega^{(0)}(1+\chi_s)$	0.28	0.22	0.20	
	4	$-g_\omega h_\omega^{(0)}$	0.20	0.18	0.01	
	Σ		3.93	3.14	0.80	0.01
1	1	$f_\pi g_{\pi NN}$	0	0	−4.36	
	2	$-g_\rho h_\rho^{(1)} - g_\omega h_\omega^{(1)}$	0.13	0.11	0.07	
	3	$-g_\rho h_\rho^{(1)}(1+\chi_v) - g_\omega\ h_\omega^{(1)}(1+\chi_s)$	0.22	0.17	0.15	
	4	$g_\rho h_\rho^{(1)} - g_\omega h_\omega^{(1)}$	0	0	−0.06	
	5	$-g_\rho h_\rho^{\prime 1}$	0	0	−0.07	
	Σ		0.35	0.28	−4.26	−4.33
2	1	$-g_\rho h_\rho^{(2)}$	0.13	0.12	0.14	
	2	$-g_\rho h_\rho^{(2)}(1+\chi_v)$	1.05	0.82	1.10	
	Σ		1.18	0.94	1.26	1.02
Σ			5.46	4.36	−2.20	−3.30

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