LA-UR- 96-1754

CONF-9510369--1

Title: Model-Space Approach to Parity Violation in Heavy Nuclei

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Submitted to: *International Workshop on Parity and Time Reversal Violation in Compound Nuclear States and Related Topics*
Trento, Italy
October 16–27, 1995

Los Alamos
NATIONAL LABORATORY

MODEL-SPACE APPROACH TO PARITY VIOLATION IN HEAVY NUCLEI

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The model-space approach is the basis of both shell model and statistical spectroscopy analyses of nuclear phenomena. The goal of this session is to bring out the main theoretical issues involved in its application to parity violation in the compound nucleus. Section 1 of the current paper sets the stage for the session, and Sect. 2 introduces and explores the model-space formulation as it underlies quantitative connections that are being made between the mean-square matrix element M^2 measured in polarized neutron scattering from compound nuclei and the underlying parity violating interaction. This is followed in the paper by Tomsovic by a description of how statistical spectroscopy is applied to this problem, and in the paper by Hayes by a discussion of shell-model aspects of parity violation in the compound nucleus.

1 Introduction to Session

The use of polarized neutron scattering from compound nuclei for empirical studies of parity violation has well-known advantages. The large parity violating signal was first obtained in Ref.[1] in measurements of the longitudinal spin asymmetry P_ν,

$$P_\nu = \frac{\sigma_\nu(\rightarrow) - \sigma_\nu(\leftarrow)}{\sigma_\nu(\rightarrow) + \sigma_\nu(\leftarrow)}, \tag{1}$$

where $\sigma_\nu(\rightarrow)$ is the total cross section for neutrons polarized parallel to their momenta to scatter from a p-wave compound nuclear (CN) resonances $|\nu>$ at $E = E_\nu$. It has been understood for a long time how a magnification of a factor of about 10^6 can arise from the the chaotic behavior of compound-nuclear resonances when the measurements are performed on low-lying p-wave resonances [2,3].

Recently, there have been important developments on the experimental side to exploit the large magnification in such reactions. The TRIPLE collaboration [4,5] used the intense neutron beam at the LAMPF/LANSCE facility to measure P_ν on ensembles of p-wave resonances in the same nucleus, making it possible to extract the mean value M^2,

$$M^2 = \overline{<\mu|V^{PV}|\nu>^2}, \tag{2}$$

where V^{PV} is the parity violating interaction in the nucleus, using statistical averaging and known properties of the CN resonances. The average in Eq. (2)

occurs over a number of CN states in a narrow energy window. Taking advantage of the large flux of epithermal neutrons available at this facility, TRIPLE measured five CN resonances in ^{239}U [4] in 1990 and 7 in ^{233}Th [5] in 1991. Since then, improvements in the methods have enabled TRIPLE to measure ensembles in the mass 100 region and to greatly increase the statistical accuracy of the earlier measurements in the region of mass $A \sim 230$. Other measurements are planned for the future, including the interesting case of ^{117}Sn, which has only active neutrons suggesting the possibility of separately determining the parity-violating interaction among neutrons in this nucleus.

Theoretically, the primary objective is to determine empirically the underlying free-space parity-violating interaction from the measurements of M^2 in nuclei. It is advantageous that the CN states $|\nu>$ on which the measurement of P_ν is made are situated a chaotic regime of the nucleus, i.e., that the amplitudes of the principle independent-particle model configurations $|\nu>$ are described by Gaussian-distributed random variables. This suggests that M^2 is proportional to the average of $(V^{PV})^2$ over a large number N of independent-particle model configurations [6],

$$M^2 \sim \frac{Tr[(V^{PV})^2]}{N}. \qquad (3)$$

This makes the unfolding of the nuclear structure and the V^{PV} in Eq. (2) a qualitatively different procedure from that familiar in shell-model analyses of matrix elements between specific nuclear states, where one is expected to be much more sensitive to phases and specific admixture components of the nuclear eigenstates. One expects that the extraction of V^{PV} from data to be a more robust procedure for M^2, since one is only interested in an overall scale that is determined by the average squared matrix element of the parity-violating interaction.

Two theoretical questions that need to be answered in order to accomplish the primary theoretical objective are (1) how does one determine the (effective) PV interaction V^{PV} in nuclei if one is given the free-space PV interaction and (2) how does one determine M^2 from V^{PV}? Various answers to these questions have been given, and a major goal of this session is to assess theoretically the status of the answers. The former issue is considered in the talk by Johnson and the latter in the talk by Tomsovic. Of course, the experimental data on the N, Z, and A dependence of M^2 mentioned above will supply information for a complementary empirical assessment.

Tomsovic will discuss statistical spectroscopy [7]; he, along with French and collaborators, applied this method to the problem of time reversal symmetry. The same method was later applied to parity-violation in the compound

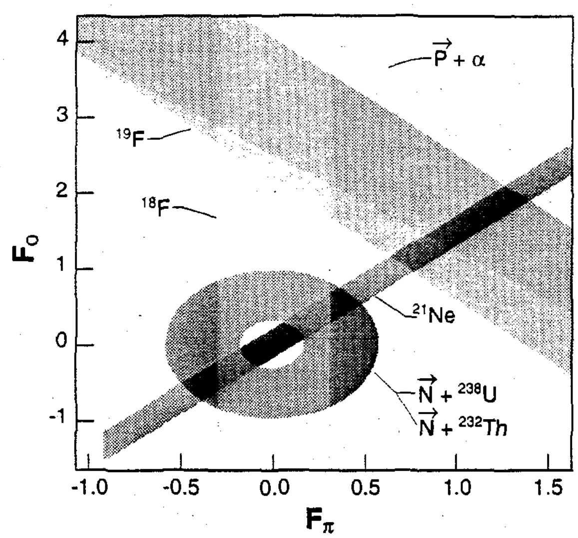

Figure 1: Constraints on F_π and F_0 imposed by experiments in light nuclei and neutron-resonance scattering (ellipse).

nucleus by Johnson, Bowman, and Yoo[6] under the assumption that the CN states are statistical admixtures of plane-wave states characteristic of nuclear matter. The result of this very straightforward calculation is shown in Fig. 1 and indicates that the constraints on the main coupling constants F_π and F_0 of V^{PV} obtained from the analysis of the CN resonances (ellipse) agrees to within a factor of two or so with those obtained earlier from the analysis of various data in light nuclei.

Let me briefly mention an alternative method to statistical spectroscopy; namely, that of Flambaum and Vorov[8]. They average $(V^{PV})^2$ over principle components of many-body wave functions within a spreading width to get M^2. The differences between the approaches is the following. French and Tomsovic use the central limit theorem to establish a bivariate Gaussian/partitioned form for strength functions. They determine the properties of the bivariate Gaussians from moments of the Hamiltonian and V^{PV}. On the other hand, Vorov and Flambaum introduce two main parameters in their averaging procedure, the number of principle components making up the CN wave function N and the spreading width Γ, which they take directly from experiment.

An attractive point about the French and Tomsovic approach is that it is formulated in a 0-$\hbar\omega$ model space of very large dimension, making it possible to develop at least a formal connection to the nuclear shell model. Note however, in contrast to the usual situation to which the shell model is applied, that *the corresponding model spaces for the CN are too large to permit an exact* diagonalization of the strong interaction Hamiltonian. Statistical spectroscopy provides, effectively, an alternative to the step of diagonalizing a Hamiltonian matrix in such spaces.

Because of the underlying conceptual connection between the shell model and the statistical formulations, a fruitful dialog between the respective communities should be possible, and Hayes in her talk will open up such a discussion from the shell-modelists perspective that will hopefully lead to a deeper understanding of the underlying issues and a more general confidence in the statistical methods that will be needed to improve the constraints on V^{PV} from measurements of M^2.

2 The Model-Space Approach

In the model-space approach, one begins by choosing a finite set of single-particle orbitals to span the model space in which the valence nucleons move. The valence nucleons are those that lie outside a conveniently chosen "core". For Uranium and Thorium, ^{208}Pb forms a natural core; although the nucleons in the core are completely passive from the point of view of the nuclear model-space wave function, they do play an important role in the dynamics. Effective interaction theory developed 20 years ago (see for example Ref.[9]) is a procedure for calculating the strong-interaction Hamiltonian and effective operators appropriate to the model space from their underlying free-space counterparts. The methods of effective interaction theory provide a book keeping scheme for writing down terms that contribute and for making calculations. One may think of V^{PV} as one of the effective operators, in which case V^{PV} has a one-body part, which expresses the PV influence of the core nucleons on a valence nucleon, and a two-body part, which expresses the PV influence of one valence nucleon on another valence nucleon. Each of these has a definite relationship to the V^{PV} in free space, given by the theory of Ref.[9], for example.

One may wonder why, in view of the introductory comments, such sophisticated techniques might be needed for the problem of relating M^2 and V^{PV}? It is necessary to mention a bit of history to answer this. In the original calculation of Johnson, Bowman, and Yoo[6] (Fig. 1), we see that the values of the parameters are about the same as those needed to explain PV in light nuclei. Johnson, Bowman, and Yoo found in their nuclear matter approach that the result arises mainly from the one-body part of the parity violating interaction.

For the nuclear matter approach to be valid, it is necessary for there to be a large amount of intershell (1-$\hbar\omega$) mixing, since the one-body part of V^{PV}, which dominates the final result, connects states of the same total angular momentum and opposite parity. A large intershell mixing may be induced by collective behavior such as vibrations and deformation. Such a large mixing was obtained in calculations of Auerbach [10] within the doorway model and in the approach of Flambaum and Vorov [8] when they mixed shells perturbatively.

Motivated by an interest in improving the prediction of Fig. 1, Bowman and I [11] went back to examine the Flambaum-Vorov and the Auerbach works within the framework of effective interaction theory of Ref. [9]. To do this, we had to abandon the nuclear matter approach and work within a 0-$\hbar\omega$ shell-model space. We came to the conclusion that the calculations of Auerbach/Flambaum-Vorov overestimated the intershell PV mixing.

In the absence of other mechanisms to accomplish the mixing (deformation may actually supply one), the entire M^2 would have to come from the free two-body piece of V^{PV}. This means that the calculation now becomes more complicated, and the ellipse in Fig. 1 is sure to grow [6]. But, will it grow too much? This remains to be seen in detailed calculations, which will have to accomodate nuclear models and which are now in progress [12].

To summarize, I would say that there is now reason to open more broadly the debate of how much intershell 1-$\hbar\omega$ mixing occurs in the compound-nuclear eigenstates. In the next two subsections I discuss two important aspects of the discussion. The first (Sect. 2.1) will be an attempt to express the issue of intershell mixing in a toy problem, to which shell model and statistical spectroscopy methods may both be applied and thus perhaps lead to common understanding. The second (Sect 2.2) will revisit the Auerbach/Flambaum-Vorov models of mixing, explaining how it was cast into the language of the model-space approach and how this led to the conclusion of reduced intershell mixing with these mechanisms.

2.1 Shell-Model Tests of Intershell Mixing

The possibility exists of using the effective interaction theory to test the effectiveness of statistical spectroscopy using an appropriately chosen toy problem. The point is that one would like to gain experience applying statistical spectroscopy to cases where intershell mixing is of crucial importance, as it is for parity violation. I will discuss two tests.

Imagine a model space consisting of a shell composed of nearly degenerate single-particle states of odd parity, say. To make the situation analogous to a heavy nucleus, we embed an intruder state of positive parity and angular momentum j_a, $|j_a(+)>$, among these. In the first toy problem, this 0-$\hbar\omega$ space is imagined to be the full Hilbert space, so that no renormalizations from the effective interaction theory are needed to get the effective strong interaction and the effective PV interaction. If the PV interaction, which we take for this toy problem to be purely two-body in nature, has some nonvanishing matrix elements in is space, then V^{PV} will make a nonvanishing contribution to M^2. This is the type of situation for which statistical spectroscopy was invented, and thus the shell model and statistical spectroscopy should both independently lead to the same value for M^2, so that the theory would thus pass the test provided by this first toy problem.

Let us now consider a second toy problem, one of perhaps greater interest. We will add two elements: a second shell, and take the underlying PV interaction to have both a one- and a two-body piece. We shall keep the first shell the same as it was in the first toy problem, but suppose that none of the odd parity states in the first shell has the same angular momentum as the intruder state $|j_a(+)>$, so that when the Hamiltonian is diagonalized in the model space and M^2 calculated according to Eq.(2), the one-body piece of the PV interaction would not contribute.

Suppose the second shell consists of positive parity states separated by ΔE from the first; these two shells constitute the full space for this toy problem. Let us further suppose that the second shell contains a state $|j_b(+)>$, where total angular momentum j_b happens to be the same as that of one of the negative parity states in the lower shell, such that the one-body part of V^{PV} has a non-vanishing intershell matrix element $< j_b(+)|V^{PV}|j_b(-)>$.

The task for the shell model is to diagonalize the strong interaction numerically in the combined space of the two shells and calculate M^2 according to Eq. (2) (it is important to remember that the averaging is done over a *few* exact eigenstates in the low-lying region of the spectrum). Now, from the way we have set up the spaces, M^2 will have a non-vanishing piece coming from the one-body as well as the two-body pieces of V^{PV}.

How do we calculate M^2 using statistical spectroscopy? Statistical spectroscopy applies, by assumpion, only in the lower (0-$\hbar\omega$) shell. We will have use effective interaction theory to calculate both the renormalized strong and PV interactions in this shell, as they arise from the influence of the shell separated by ΔE. We may then apply statistical spectroscopy in the 0-$\hbar\omega$ shell with the renormalized interactions to evaluate a value for M^2. The behavior of the matrix element of the one-body part is of particular interest, since it contributes only by virtue of intershell mixing.

What are our expectations? If ΔE is sufficiently large, a perturbative calculation of the renormalization (Flambaum and Vorov calculated one of the perturbative terms), which is entirely feasible following Ref. [9], should be sufficient to achieve agreement between the shell-model calculation and the approach through statistical spectroscopy. Another expectation is that when ΔE goes to zero, so that the shells lie on top of each other, statistical spectroscopy and the shell model will completely agree (this is essentially the first toy problem). The difficult case is the intermediate values of ΔE, where in practice one may have to resort to dynamical models (the Doorway model of Auerbach [10], for example). As long as a model can be cast into the language of effective interaction theory, it can be tested in this simple toy problem (or a straightforward extension of it) and criteria can be developed for what ranges of ΔE it would be applicable.

Finally, let me mention a technical issue that causes a lot of problem in the shell-model: the issue of spurious center of mass motion. In the problem that I have proposed, the spurious center of mass motion is present equally in both cases and would not necessarily invalidate the test. However, one would like to do realistic calculations without contamination by spurious center of mass motion, and hopefully one can devise effective ways to project out or minimize the intershell mixing due to spurious motion in a toy problem.

2.2 The Doorway Mechanism

Now, let me discuss why our calculation [11] of the Auerbach/Flambaum-Vorov mechanisms gave much smaller results than originally found by the authors of this work. Bowman and I first wrote down, using the book keeping language of Ref. [9] (the language of folded diagrams), the renormalization of the two-body part of the effective V^{PV} that corresponded to the 0^- spin dipole doorway state contribution of Auerbach [10] and the perturbative term of Flambaum and Vorov [8]. These two pieces were seen to be, in fact, quite closely related using the many-body language: in the doorway approach, the doorway state couples the one-body piece of the PV interaction, through particle-hole excitations coupled to 0^-, into the two-body piece of the effective PV interaction. The perturbative term [8] represents the leading term of the sequence; see Ref. [11] for details. When we put these terms together and evaluated them consistently, the net contribution got very small!

We [11] represented the 0^- vibrations (an isovector and an isoscalar) in the Tam-Dancoff approximation (TDA), fixing the energy of these states empirically. We coupled this TDA phonon into the valence space with a two-body residual effective interaction of the Landau-Migdal type; the TDA phonon starts out as a vibration of the core induced by the one-body PV interaction. Important to obtaining our small result was the implication of experimental data [13] that the energy of the isovector 0^- resonance is pushed up to nearly 3-$\hbar\omega$. (The location of the 1^- component of the spin dipole resonance is known experimentally, and the location of the 0^- is inferred from this using knowledge of the effective strong interaction.)

An important issue is the influence of the the tensor force on the splitting between the 0^- and 1^- isovector spin dipole states: Can pull the isovector 0^- spin dipole resonance down significantly from 3-$\hbar\omega$ that is obtained from the calculations [14]. All the arguments are presented in Ref. [11]. I find it convenient to just restate a few of the salient considerations here:

(1) The relevant doorway in the renormalized two-body interaction is the isovector 0^- (which renormalizes the pion exchange components of V^{PV}). This is because of the presence of an anticommutator [8] of the one-body PV interaction with the residual strong interaction, which greatly suppresses the coupling to the isoscalar 0^- spin dipole resonance and which was not considered in Ref. [10].

(2) The isovector 0^- resonance is the mode that would become unstable in pion condensation.

(3) Many empirical searches and theoretical studies have been undertaken for pion condensation precursor effects. All have been negative, suggesting that attraction (from tensor forces) cannot compete against the central interaction that gives a large repulsion [14].

(4) As an example of (3), the latest experiments at Los Alamos [15], namely (p,n) measurements on ^{40}Ca (at q $\sim$ 2 fm^{-1}, small ω), of the ratio of the spin-longitudinal/spin-transverse response function, found little evidence for an attraction in the spin-longitudinal channels.

The net effect of the above considerations is that the renormalization from the Auerbach/Flambaum-Vorov mechanisms is much suppressed, so that the large intershell mixing needed to give the results in Fig. 1 is missing from the theory at present.

The close connection between the 0^- resonances and the effective PV interaction depends quite closely on our using the TDA phonons and the assumption that these couple back into the model space with the Landau-Migdal interaction. Subtle dynamical considerations arise when one tries to justify this assumption, so it is probably useful emphasize out that the A-dependence of the new TRIPLE data could give an empirical means to distinguish alternative models, given that the A-dependence of the theory can be quite strong [8].

2.3 *Conclusions*

The points made in this talk are the following: (1) The effective interaction theory provides a book-keeping procedure by which specific models of parity violation can be built up microscopically and evaluated based on conventional many-body ideas used in other areas of nuclear physics. A specific example of this was given, namely the doorway model of Auerbach. In the doorway model, 0^- giant (doorway) resonances lead to a parity violating spreading width by mediating the mixing eigenstates of one parity into those of the opposite parity through the (one-body) PV interaction. It was shown that when this is done, relying on experience with pion condensation and studies of the longitudinal and transverse response functions in (n,p) reactions, the doorway mechanism is suppressed. (2) Combining effective interaction theory and statistical spectroscopy in a large but sufficiently restricted model space (so that shell-model diagonalizations are possible) permitts toy-problem tests of statistical averaging schemes. Such tests of the model-space approach as a toy problem should enable one to investigate intershell mixing, which appears to be the key to understanding the extent of parity violation in M^2.

Tests along the lines of (2) above have not yet been made, and doing so would be instructive as a means to test and confirm assertions and expectations about the merits and applicability of methods of the shell model and statistical theory, to the problem of parity violation in light and heavy nuclei.

Acknowledgments

The author gratefully acknowledges support from Los Alamos National Laboratory and the European Center for Theoretical Nuclear Physics, Trento and thanks N. Auerbach and J. D. Bowman for the invitation to participate in this workshop.

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