Parity violation in the compound nucleus

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Parity violation in the compound nucleus is reviewed as an example of a wider class of phenomena: The breaking of a discrete symmetry by a weak interaction in a stochastic or chaotic quantum system. Generically, enhancement factors amplify the signal for symmetry breaking, and the stochastic properties allow the strength of the symmetry-breaking interaction to be inferred from that signal without the need to know the wave functions of individual states. We describe recent experiments on parity violation that have been undertaken in this spirit. The scattering of spin-polarized neutrons by medium-weight and heavy nuclei provides signals for parity violation at the percent level. The statistical analysis of the data yields values for the spreading width around 10^{-6} eV, in keeping with theoretical expectations. We discuss open problems and possible future directions. [S0034-6861(99)00201-9]

CONTENTS

I. INTRODUCTION

Two developments have spurred the study of the weak interaction in nuclei in recent years: The discovery of large enhancement factors for parity violation in the scattering of low-energy neutrons, and the realization that the stochastic properties of the compound nucleus simplify the analysis. In this paper, we review the considerable effort, both experimental and theoretical, which has been devoted to the subject.

In the last half century, the study of the weak interaction has contributed very importantly to our understanding of the elementary constituents of matter and their interactions. This continued success must be ascribed at least partly to the very weakness of the interaction, and to the clear signals available for weak-interaction effects. These facts combine to make the weak interaction both an object of fundamental research and a tool for investigating strongly interacting systems.

Work on the weak interaction in nuclei reflects this dual role. Understanding the ''effective'' weak interaction in nuclei, i.e., the modification of the weak interaction in the nuclear medium, poses a fundamental problem of many-body theory. But the weak interaction can also be used to investigate strongly interacting hadronic systems. For example, leptons emitted in a collision between relativistic heavy ions may yield information not otherwise available on a hypothetical new state of matter, the quark-gluon plasma.

The dual role of the weak interaction as both an object of study, and a tool for studying strongly interacting systems, has also shaped the work on parity violation in the compound nucleus reviewed in the present paper. On the one hand, the helicity dependence of the scattering amplitude of slow neutrons on unpolarized nuclei offered a novel way of investigating the effective weak interaction in nuclei. Earlier, the circular polarization of gamma rays emitted from unpolarized nuclei had been the main tool for such work. The neutron work was made possible by two enhancement factors that cause the signal for parity violation to attain values in the percent region. The stochastic properties of the compound nucleus added another dimension to the work. The compound nucleus possesses spectral fluctuation properties that are well described by random matrix theory and that are related to those of quantum chaotic systems. This fact has profound implications. The signal for parity violation becomes a random variable, and a statistical analysis of the data is called for.

There is convincing evidence that the stochastic properties of the compound nucleus are shared by other strongly interacting or chaotic quantum systems. The two central features of parity violation in the compound nucleus—large enhancement factors and stochasticity—are, therefore, expected to occur quite generally. Thus, parity violation in the compound nucleus attains generic features: It is a case study in the breaking of a discrete symmetry in a stochastic quantum system.

The enhancement factors, and the general layout of experiments on parity violation with slow neutrons, are introduced in Sec. II. The impact of the stochastic properties of the compound nucleus on the analysis of the data is described in Sec. III. By far the most complete set of data has been obtained in the experiments by the TRIPLE (time reversal invariance and parity at low energies) Collaboration. The experimental setup is described in Sec. IV and the statistical analysis of the data in Sec. V. This is followed by sections giving a summary of the results, their interpretation, and a brief commentary on the status of the field.

II. AN AMAZING PREDICTION AND ITS EXPERIMENTAL VERIFICATION

Ever since its discovery, the topic of parity violation has played an important role in nuclear physics. For a long time, experimental and theoretical efforts were mainly directed towards transitions between isolated and well-resolved levels at low excitation energies. It was hoped that the precise measurement of an observable indicating parity violation (the circular polarization of gamma rays is an example), combined with a thorough theoretical analysis, would cast light on the nature of the effective parity-violating interaction in nuclei.

In spite of beautiful experimental results, this program has been only partially successful. The difficulties reside in the theoretical analysis. The determination of the effective parity-violating interaction in nuclei requires the wave functions of the states involved to be known with a precision that is beyond the reach of present-day nuclear many-body theory (Adelberger and Haxton, 1985; Desplanques, 1998).

This situation changed dramatically after Sushkov and Flambaum (1980) predicted the existence of two enhancement factors which combined may yield large signals for parity violation near neutron threshold. This prediction was confirmed experimentally at Dubna (Alfimenkov, 1982, 1983). A signal of several percent was observed. Taken by itself, the experimental verification of the prediction by Sushkov and Flambaum might not have improved the status of the field. Indeed, the wave functions of the nuclear levels at neutron threshold are, if anything, much more complex than those of the low-lying states. What helped, and what eventually led to the successful experimental effort described in this paper, was the application of statistical ideas to the analysis of the data. Such analysis is restricted to levels of sufficient complexity.

In this section, we introduce the enhancement factors and describe the Dubna results. The statistical concepts are the subject of the following section.

To test parity violation in nuclei, ideally one measures the transmission of polarized slow neutrons through an isotopically pure target. (In the actual experiment neutrons with energies between 1 and 1000 eV and natural targets are used, see Sec. IV.A.) We denote the transmitted intensities for the two helicities (spin parallel or antiparallel to the momentum of the neutron) by I_+ and I_-, respectively. The observable is

$$\epsilon=\frac{I_+-I_-}{I_++I_-}. \tag{1}$$

(For simplicity, we assume that the incident neutrons are 100% polarized.) A nonzero value of ϵ is an unambiguous signal for parity violation.

A detectable signal for ϵ can be expected only at bombarding energies that coincide with the energy of one of the long-lived resonances of the compound nucleus. Only in this case can the weak parity-violating interaction act sufficiently long to produce a significant mixing of parities. The mixing will involve the state (resonance) at hand and one or more close-lying states (resonances) of the same spin but opposite parity.

Long-lived compound-nucleus resonances occur in the scattering of slow neutrons on heavy target nuclei. Figure 1 shows the total neutron cross section versus neutron bombarding energy for the target nucleus ^{238}U. The cross section displays a sequence of narrow resonances. At the low neutron bombarding energies shown in the figure, all visible resonances correspond to s-wave neutrons. The mean spacing D of the resonances is about 10–20 eV. The typical width $\Gamma \sim 1$ eV corresponds to a lifetime $\tau = h/\Gamma \sim 10^{-15}$ s, which is much longer than the average time of passage $t \sim 10^{-20}$ s of a one-eV neutron through a nucleus with a radius of about 5×10^{-13} cm. We note that D is much larger than Γ. This is the regime of isolated resonances.

The resonances shown in Fig. 1 occur at excitation energies in the compound nucleus of 5 to 10 MeV, depending on the neutron binding energy. Figure 2 shows schematically the ground state of the compound nucleus [a nucleus with mass number $(A+1)$], some of the low-lying excited states of this nucleus, and much higher up with a view through the magnifying glass as a dashed line the energy defined by the ground state of the nucleus with mass number A plus a neutron at rest at large separation. The resonances formed in the compound nucleus with mass number $(A+1)$ are also shown schematically.

The two enhancement factors identified by Sushkov and Flambaum are referred to as dynamical and kinematical enhancement, respectively. Dynamical enhancement is a consequence of the strong decrease of the mean spacing D of levels of the same spin and parity with excitation energy. As in any self-bound fermionic many-body system (Bethe, 1937), D decreases almost exponentially with excitation energy. In the nuclear ground-state domain $D\sim100$ keV, while near neutron threshold $D\sim10$ eV. The mean spacing between levels with the same spin but different parities obviously shrinks with excitation energy in the same fashion. For two such levels labeled $|1\rangle$ and $|2\rangle$ with energies E_1 and E_2, respectively, the mixing amplitude A due to the weak interaction V is given to first order by

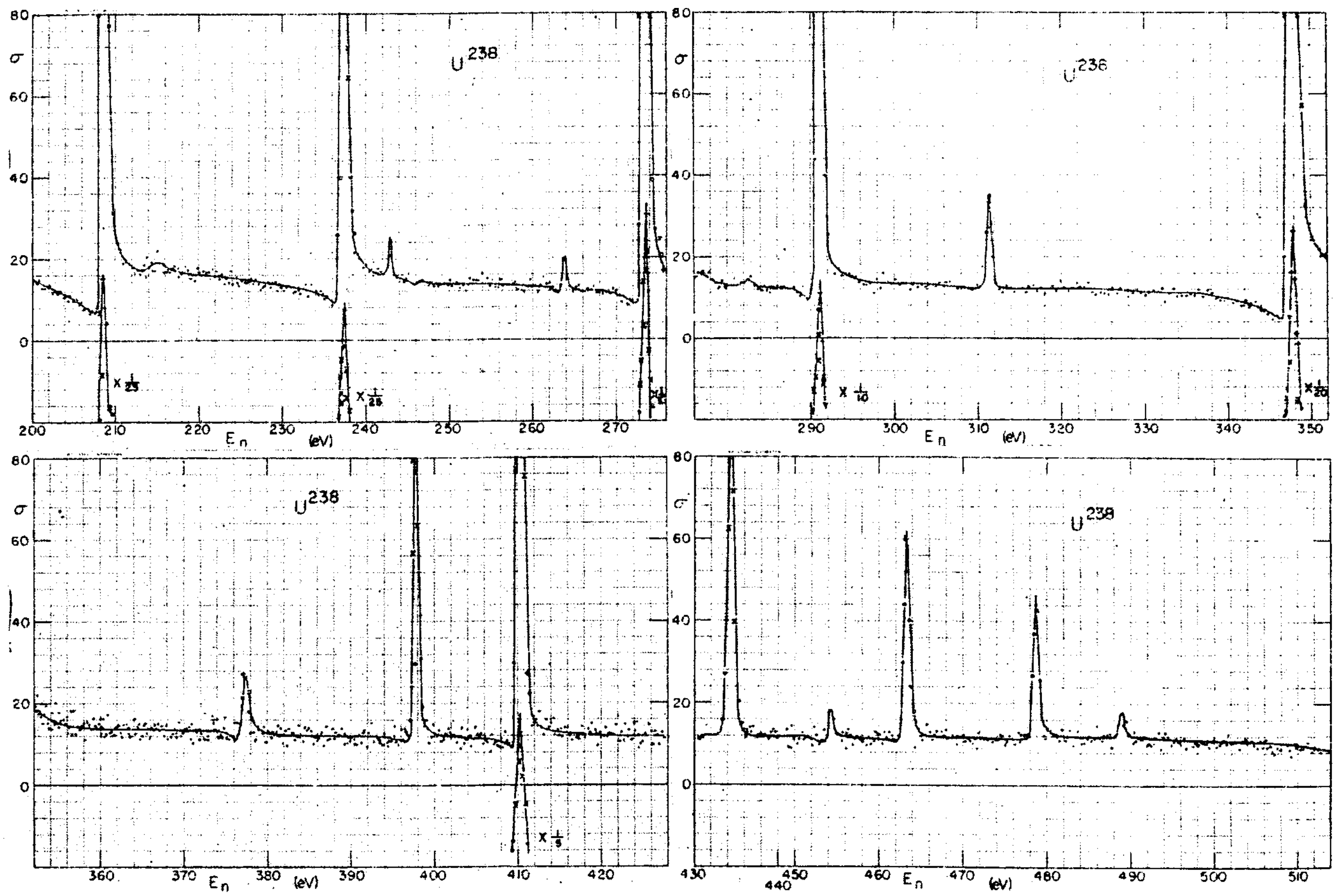

FIG. 1. Total neutron cross section on ^{238}U versus neutron energy. From Garg (1964).

$$A=\frac{\langle 1|V|2\rangle}{E_1-E_2}. \tag{2}$$

Because of the strong decrease of $|E_1 - E_2|$ with excitation energy, one might expect A to increase by a factor 10^4 as the energy changes from the ground-state domain to neutron threshold. This naive expectation is not correct because the wave functions of the nuclear states grow in complexity with increasing excitation energy, thereby reducing the overlap in the matrix element $\langle 1|V|2\rangle$. The relevant factor is $D^{-1/2}$ (French, 1988a, 1988b). The resulting dynamical enhancement factor for A is $D^{1/2}\sim 10^2$ rather than 10^4. This factor does not change dramatically with energy. From the point of view of dynamical enhancement, an experiment at neutron threshold, and another experiment 100 keV or one MeV above neutron threshold, would be equally good candidates for a test of parity violation.

This is not the case for the second enhancement factor. Kinematical enhancement favors the experiment with very small neutron energy, for the following reason. Near neutron threshold, only scattering states with orbital angular momenta 0 or 1 contribute significantly to neutron scattering, populating s-wave and p-wave resonances, respectively. In Fig. 1, we see only the s-wave resonances. Because of the angular momentum barrier, the p-wave resonances have a much smaller cross section. Nevertheless, it is these resonances on which parity violation is tested successfully. A p-wave resonance formed by neutron bombardment and mixed by V with a close-lying s-wave resonance may decay either by parity-allowed p-wave or by parity-forbidden s-wave neutron emission. The p-wave decay is strongly suppressed by the angular momentum barrier, while the s-wave decay is not likewise impeded. This fact enhances the signal for parity violation by the ratio of the two barrier penetrabilities, i.e., roughly by the factor $(kR)^{-1}$ where R is the nuclear radius, and k is the neutron wave number. Typical values for kR are 10^{-3}. With increasing neutron energy, the resulting kinematical enhancement factor quickly approaches unity.

Sizable parity violation can therefore be expected to occur only at p-wave resonances close to neutron threshold. It is customary to present the data in terms of the quantity

$$P=\frac{\sigma_+^p-\sigma_-^p}{\sigma_+^p+\sigma_-^p}, \tag{3}$$

where $\sigma_\pm^p$ is the total p-wave cross section for neutrons with helicities $\pm$. P is often referred to as the asymmetry, and we follow this convention.

Combining the two enhancement factors yields an overall enhancement of $\sim 10^5$. With V typically about 10^6 to 10^7 times weaker than the strong interaction, parity violation should be detectable as a percent effect in

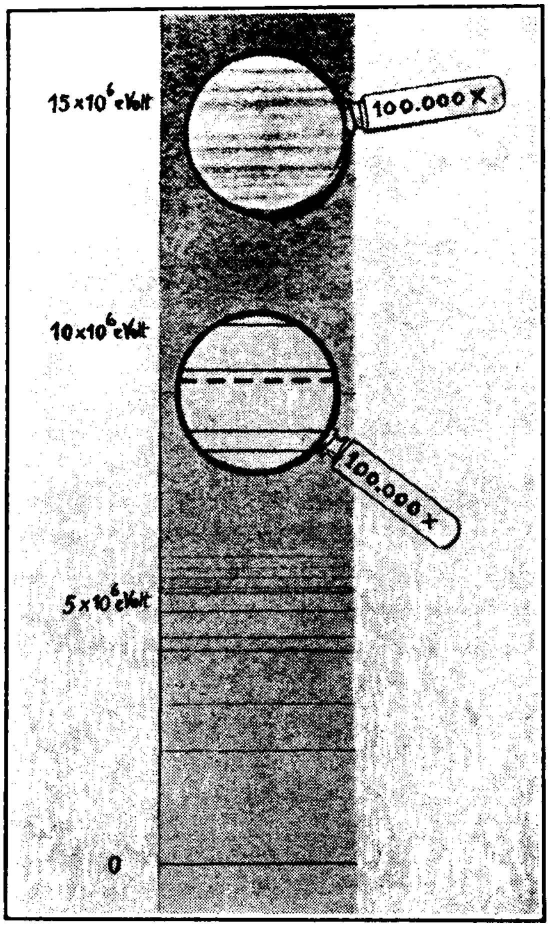

FIG. 2. Spectrum of the compound nucleus (schematic). From Nature (London) (1936).

the asymmetry P. In neutron-induced nuclear fission, the kinematical enhancement factor is missing, and we can only count on the dynamical enhancement. Thus, parity violation in fission should be an effect of order 10^{-4} or 10^{-5}.

The experiment at Dubna used polarized neutrons and a time-of-flight spectrometer. We do not give any details here since the basically similar but technically more advanced experiment performed at Los Alamos is described below. The Dubna experiment focused on selected p-wave resonances in several nuclei. A p-wave resonance at 0.74-eV neutron bombarding energy in ^{139}La was found to yield a value $P=7.3\pm0.5\%$. This very sizable value confirms the existence of the dynamical and kinematical enhancement factors.

This was an interesting result. Nevertheless, at the time the Dubna data were of little consequence for the theoretical understanding of parity violation in nuclei. This is because there was no hope of determining the resonance wave functions of the s- and p-wave states involved, and in this way to obtain information on the strength of the parity-violating effective interaction in nuclei.

Parity violation in neutron-induced fission was discovered by Danilyan *et al.* (1977) and described theoretically by Flambaum and Sushkov (1980). There are some interesting recent experimental results in this area (Gönnenwein, 1994; Graf, 1995). These experiments were performed at very low fixed energies. Only the dynamic enhancement is expected to contribute and not the kinematic enhancement factor. The observed PNC asymmetries are a few times 10^{-4}, consistent with this picture. Parity violation in fission has been mainly investigated with the aim of a better understanding of the fission process. Thus these measurements also provide an example of the use of the weak interaction as a tool for investigation of strongly interacting systems.

III. STATISTICAL CONCEPTS

The study of parity violation in compound-nucleus reactions received a boost through the application of statistical ideas (Bowman, 1990a; Weidenmüller, 1990). The main disadvantage of the neutron scattering data—the high degree of complexity of the nuclear resonance wave functions—can be turned into an advantage. It had been known for many years that the distribution of energy spacings and partial widths of neutron resonances agrees with predictions of random matrix theory (Porter, 1965; Brody *et al.*, 1981). In the spirit of this approach, a set of matrix elements $\langle 1|V|2\rangle$ obtained from neutron scattering data would determine the mean-square matrix element $\overline{v^2}$ and, from it, the spreading width introduced below. The latter quantity provides a direct measure of the strength of the effective parity-violating interaction in nuclei. Thus, the statistical approach yields physical information *without the need to make any statements about the wave functions of individual resonances*. For this reason, the statistical analysis is superior to that of individual transitions at lower energies although only *average* properties of the interaction can be determined. There is a price, however: In each nucleus, parity violation must be measured on a number of p-wave resonances. The larger this number, the smaller the statistical error attached to $\overline{v^2}$.

Statistical concepts enter the analysis of the data on parity violation in compound-nucleus scattering in three distinct but interrelated ways. First, there is, as always, the problem of signal-to-noise ratio. This is discussed in detail in Secs. IV and V and will not be considered here. Second, statistical concepts based on random matrix theory are used to determine $\overline{v^2}$ from the data. Third, statistical concepts are used to relate $\overline{v^2}$ with the strength of the effective parity-violating interaction in nuclei. In the present section, we address point two of this list. We summarize the statistical concepts that apply to compound-nucleus resonances near neutron threshold, and we describe the implications for parity violation in neutron scattering. We address point three only briefly and return to this problem in Sec. VII(ii). Details on the statistical model may be found in the reviews (Brody, 1981; Bohigas and Weidenmüller, 1988; Guhr, 1998).

In the spirit of Eq. (2), we consider the compound-nucleus resonances as quasibound states of fixed spin and parity. These states are eigenstates of the nuclear Hamiltonian. Random matrix theory replaces the Hamiltonian of a specific system by an *ensemble* of Hamiltonians. Averaging over the ensemble yields the statistical laws for eigenvalues and eigenfunctions that apply to (almost all) members of the ensemble. Data on a given nucleus, or on a number of nuclei, are compared with these laws.

The ensemble applicable to nuclei is the Gaussian orthogonal ensemble of random matrices (GOE). Because of time-reversal symmetry, the Hamiltonian matrix $H_{\mu\nu}$ for levels of fixed spin and parity can be chosen real and symmetric. The dimension N of this matrix is considered finite, but eventually the limit $N\rightarrow\infty$ is taken. The GOE is defined by the assumption that the matrix elements $H_{\mu\nu}$ with $\mu\geqslant\nu$ are uncorrelated Gaussian random variables with mean value zero. The second moments, indicated by a bar, are given by $\overline{H_{\mu\nu}H_{\mu'\nu'}}=(\lambda^2/N)(\delta_{\mu\mu'}\delta_{\nu\nu'}+\delta_{\mu\nu'}\delta_{\nu\mu'})$. The measure in matrix space is given by the product of the differentials of the independent matrix elements. The parameter λ has the dimension of energy and determines the local mean level spacing. The fluctuations about the mean are predicted in a parameter-free fashion. This ensemble is invariant under orthogonal transformations of the basis of states $|\mu\rangle$, $\mu=1,\ldots,N$, hence its name.

Several statistical measures for the distribution of spacings of eigenvalues of fixed spin and parity derived from the GOE had been found to agree with s-wave neutron resonance data. The GOE prediction for the distribution of eigenfunctions implies that the reduced partial neutron widths have a χ-square distribution with $\nu=1$. This prediction also agrees with the data. On this basis, predictions for the distribution of the parity-violating matrix elements connecting s-wave and p-wave resonances can be made under two assumptions: (i) The statistical laws established for s-wave states apply likewise to p-wave states (where a test has not been possible yet because of a lack of data). (ii) s-wave and p-wave states are statistically independent. Then, the matrix elements $\langle s|V|p\rangle$ that connect an s-wave resonance with a p-wave resonance, must have a Gaussian distribution with mean value zero both when the state $|s\rangle$ is varied for fixed $|p\rangle$, and vice versa. A sufficient number of p-wave resonances with parity violation in a given nucleus should yield $\overline{v^2}$. This is the essence of the procedure.

The measure for the strength of the parity-violating effective interaction in nuclei should depend as little as possible on excitation energy and mass number. The mean square matrix element $\overline{v^2}$ is not a good candidate. Indeed, $\overline{v^2}$ is proportional to the mean level spacing D (Bohr and Mottelson, 1969; Brody, 1981) and thus depends almost exponentially on excitation energy. This is a reflection of the fact referred to above that the complexity of the eigenstates of the nuclear Hamiltonian increases strongly with increasing energy. It is natural to introduce the spreading width

$$\Gamma^{\downarrow}=2\pi\overline{v^2}/D. \tag{4}$$

This quantity may still have a polynomial dependence on energy and/or mass number, but the exponential dependence should be removed. When one uses Eq. (4) in the case of parity violation, it is customary to take D as the mean spacing of the s-wave resonances. Experimental data and theoretical arguments suggest that the spreading width for the *strong* interaction is of the order of several MeV. Scaling this value with the square r of the ratio of the strengths of the weak and the strong interaction, and choosing $r\sim10^{-13}$, we are led to expect $\Gamma^{\downarrow}\sim10^{-6}$ eV.

It remains to relate the value of $\Gamma^{\downarrow}$ obtained from data on parity violation with the effective parity-violating nucleon-nucleon interaction of the shell model. Although very important, this problem does not yet have a complete solution. It transcends the use of Gaussian random-matrix theory and relates to the broader subject of interacting fermion systems. In nuclear physics, French and collaborators (French, 1988a, 1988b) have addressed the problem as one of information propagation into huge shell-model spaces. In atomic physics, Flambaum and collaborators (Flambaum *et al.*, 1998) have treated it using thermodynamic arguments. A novel development occurred in disordered mesoscopic physics (Sivan, 1994; Altshuler, 1997; Mirlin, 1997) where it was shown that under certain conditions on the relative strength of disorder and two-body interaction, the mixing of Slater determinants may be incomplete, leading to localization in Hilbert space. To the best of our knowledge, the implications of these last results for self-bound Fermionic many-body systems have not been investigated yet. We return to some of these problems in Sec. VII(ii).

IV. EXPERIMENT

A. Experimental apparatus and procedure

The experiment consists of a measurement of the helicity dependence of the neutron total cross section with a search for a nonzero term of the form ϵ as in Eq. (1). The TRIPLE Collaboration uses the intense neutron beam at the Manuel Lujan Neutron Scattering Center (MLNSC) at the Los Alamos Neutron Science Center (LANSCE). The 800-MeV H^- beam from the LANSCE linac is deflected and transported to the proton storage ring (PSR). The negative beam is neutralized and then injected into the PSR and converted to protons by stripping in a thin foil. The injected beam is stacked onto itself until protons from the entire linac macropulse are stored. As a result, the proton pulse width is reduced from about 800 μs to about 250 ns. Since the pulse rate is 20 Hz, the system is suitable for time-of-flight measurements. The extracted proton beam strikes a tungsten target, producing about 17 neutrons per incident proton. With proton beam currents of 50-100 μA, the resulting intense neutron flux (instantaneous value about 10^{16} per second) makes possible these measurements of parity violation. The neutrons are moderated by water and then collimated.

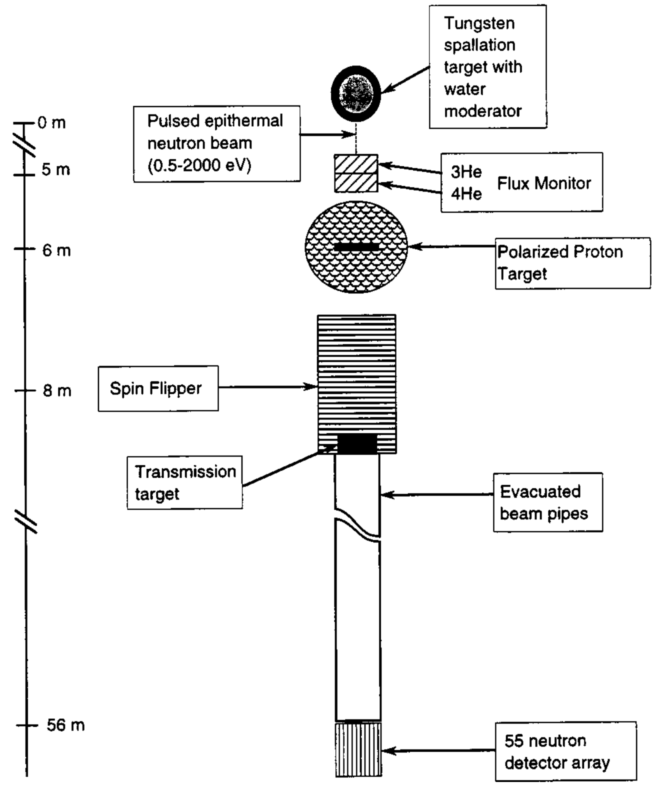

FIG. 3. TRIPLE experimental system.

Initially, the TRIPLE Collaboration measured a number of p-wave resonances in ^{238}U (Bowman, 1990b; Zhu, 1992) and ^{232}Th (Frankle, 1991, 1992a). Parity violation was observed in both of these nuclei. However, an unexpected result was found in ^{232}Th: all statistically significant nonzero values of P had the same sign, in contrast to expectations based on the statistical model. This result generated a large amount of interest and theoretical speculation. It was therefore considered very important to repeat the measurements.

The experimental system that the TRIPLE Collaboration used for detecting parity violation is shown in Fig. 3. A detailed description of the original experimental apparatus and data acquisition system was given by Roberson (1993). Although most of the system has been changed, leading to greatly improved performance, the *spirit* of the original experimental approach has been maintained. Therefore, this early paper still provides an informative overview. The detailed characteristics of the new pieces of apparatus are described in recent papers cited below.

The neutron flux is monitored by an ion chamber system (Szymanski, 1994). Next, the neutrons are polarized by selective attenuation in a cell of longitudinally polarized protons (Penttila, 1994, 1995). This method takes advantage of the large difference between the singlet and triplet neutron-proton cross sections. The apparatus produced neutron polarization of about 70%. Fast reversal of the neutron spin is accomplished in a system of magnetic fields (Bowman, Penttila, and Tippens, 1996). The spins were reversed every 10 s.

The targets for the transmission measurements had high chemical purity and thickness $n\sigma \sim 2$, where n is the density and σ the total neutron cross section. The targets were cooled to liquid nitrogen temperature to reduce Doppler broadening. The neutrons were detected by a liquid scintillator (CH) loaded with ^{10}B (Yen, 1994) and observed by 55 photomultiplier tubes. This segmented system permitted a very high count rate and had a high efficiency over the neutron energy range of interest.

To minimize several classes of errors (Roberson, 1993), an eight-step sequence $(0++0-00-)$ of spin flips was adopted. Here 0 indicates that the transverse magnetic field is turned off, and $\pm$ that it is turned on (up or down) in the transverse direction. Each step lasted 10 s or 200 neutron bursts. Data from 20 eight-step sequences were combined into a data unit (called a run) for subsequent analysis. The net result was a set of many data units, during each of which the experimental conditions could reasonably be expected to remain constant. The polarization was monitored and determined for each run. Detailed considerations on the determination of the neutron polarization are given by Yuan (1991).

B. Data

Most of the TRIPLE data consist of measurements of the helicity dependence of the neutron total cross section using the transmission method and the neutron detector array. A few parity violation measurements were performed with a capture γ-ray detector array (Frankle *et al.*, 1994; Crawford *et al.*, 1997). A number of measurements in transmission and in capture were performed with an unpolarized neutron beam in order to obtain spectroscopic information, and to provide isotopic identification of previously unobserved resonances. As noted earlier, following preliminary measurements on ^{238}U and ^{232}Th, the experimental apparatus was completely redesigned. We focus on the results obtained with this improved experimental system.

First, parity violation in ^{238}U and ^{232}Th was remeasured via the transmission method. Then, natural targets of In, Ag, Sb, Pd, Xe, Br, Nb, I, and Cs were measured (over a period of several years) with the same method. In order to aid in the isotopic identification of previously unobserved resonances, separated isotopes of In, Ag, Pd, and Sb also were studied. In addition, parity violation measurements using the capture detector were performed on ^{103}Rh, ^{113}Cd, ^{117}Sn, and ^{106,108}Pd. Due to resolution limitations, the upper energy limit for the parity violation measurements was about 500 eV.

The neutron resonance parameters were determined with a computer program written especially for these experiments by the TRIPLE Collaboration (Matsuda, 1997). The code FITXS includes the multilevel cross sections, target properties, and broadening from (a) the time structure of the neutron beam, (b) relative motion between the neutrons and the target nuclei, and (c) the time response of the detector system. Initial Monte

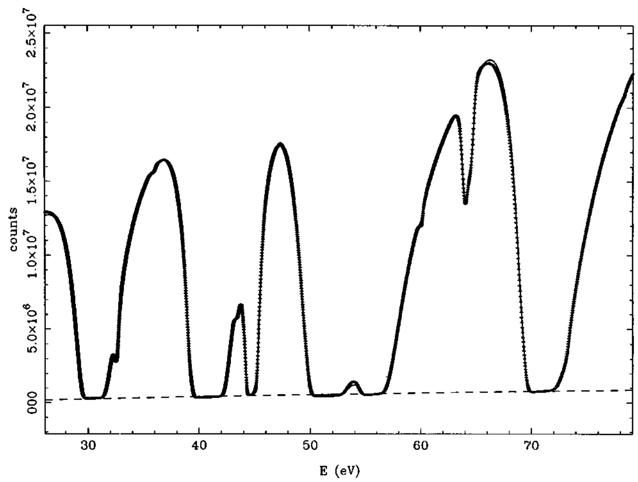

FIG. 4. Multilevel fit to a sample region of the Ag transmission spectrum.

Carlo studies of the MLNSC beam time response function were performed by Yen *et al.* (1996). More detailed information on the beam resolution function was obtained by fitting capture resonances at energies above 400 eV where the beam resolution dominates strongly over other resolution contributions (Crawford, 1997).

Data for both helicity states obtained under similar conditions were summed in order to provide very good statistics. The neutron resonance parameters were then determined from these data, including the cross section $\sigma^p_{\rm res}$ for the p-wave resonance in question. A sample fit is shown in Fig. 4 for neutron resonances in a natural Ag target. (For example, the resonance near 33 eV is a p-wave resonance in ^{109}Ag and the very weak resonance near 36 eV is a p-wave resonance in ^{107}Ag. Both resonances show large parity violation.)

With the resonance parameters held fixed, including $\sigma^p_{\rm res}$, values for the parameters P were determined from Eq. (3). The mean value of P was determined by averaging over a number N of runs. The uncertainty ΔP was obtained from the width of the distribution of P values, divided by $N^{1/2}$. This should be a conservative estimate for ΔP. In essentially all cases the histograms of the P values were approximately Gaussian, suggesting no significant systematic errors.

In addition, a search was undertaken for parity-violation effects at a number of contaminant s-wave resonances caused by trace contaminants in the target. These resonances are not expected to display any effect. No parity violations were observed. These contaminant resonances provide a useful check since they have approximately the same size as the p-wave resonances of interest. In addition, no parity-violation effect was found in the off-resonance cross section in ^{232}Th at the 10^{-5} level (Bowman, 1993).

The results for the 63.5-eV resonance in ^{238}U are shown in Fig. 5 (Crawford, 1998). The uncorrected transmission data for the two helicities show a significant difference at the dip in transmission that corresponds to the resonance, thus demonstrating the existence of parity violation by inspection.

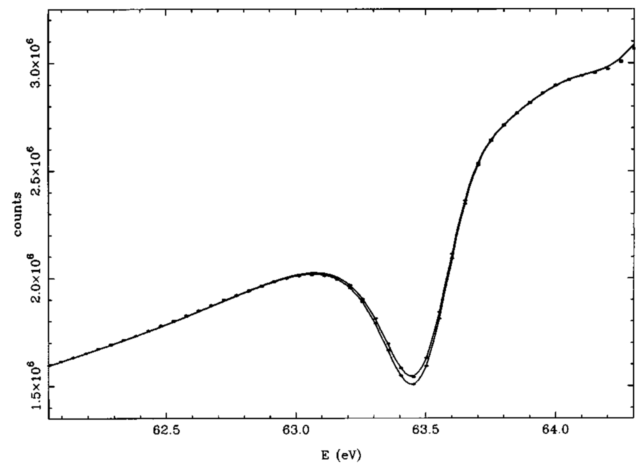

FIG. 5. Transmission spectra for the two helicity states near the 63-eV resonance in ^{238}U. The resonance appears as a dip in the transmission curve. Since the transmission at the resonance is significantly different for the two helicity states, the parity violation is apparent by inspection.

V. STATISTICAL ANALYSIS

We focus on target nuclei with spin zero and parity $\pi=+1$. This case illustrates most of the principles involved. The s-wave resonances have spin and parity $1/2^+$ and the p-wave resonances $1/2^-$ or $3/2^-$. Only the $1/2^-$ resonances are mixed with the $1/2^+$ resonances by the parity-violating interaction.

The observable P defined in Eq. (3) is related to the amplitude A defined in Eq. (2) as follows. We label the p-wave (s-wave) resonances consecutively by an index μ (ν), respectively. Then,

$$P_\mu=2\sum_\nu \frac{\langle \nu|V|\mu\rangle}{E_\nu-E_\mu}\frac{g_\nu g_\mu}{\Gamma^n_\mu}, \tag{5}$$

where g_μ and g_ν are the neutron decay amplitudes of levels μ and ν, with $g^2_\mu=\Gamma^n_\mu$ and $g^2_\nu=\Gamma^n_\nu$ the partial widths for neutron decay. Equation (5) is obtained (Sushkov and Flambaum, 1980; Bunakov and Gudkov, 1981) from standard resonance expressions for the total p-wave cross section by taking the bombarding energy E in the center of the p-wave resonance, $E=E_\mu$, by neglecting the background p-wave cross section compared to the resonance contribution, and by neglecting the total widths of the p-wave and the s-wave resonances in the denominators. This last step is legitimate since in all cases investigated so far, the spacings $|E_\nu-E_\mu|$ are large compared to the total widths. The ratio $g_\nu g_\mu/\Gamma^n_\mu=g_\nu/g_\mu$ on the right-hand side of Eq. (5) contains the kinematical enhancement factor.

For spin zero target nuclei, the resonance parameters $E_\mu, E_\nu, \Gamma^n_\mu, \Gamma^n_\nu$ are usually known. For the s-wave resonances, the information is available from previous work on s-wave neutron scattering. For the p-wave resonances, it is obtained in the framework of the TRIPLE experiments, except for the spin assignment. Here, measurements by the neutron group at the Institute for Reference Materials and Measurements at Geel have been helpful (Gunsing, 1997). Moreover, in almost every case where the spin of a p-wave resonance is known to be 1/2, parity violation is observed. This suggests that one may assign the spin value 1/2 (3/2) to a p-wave resonance by the presence (absence) of parity violation, respectively. Nevertheless, one cannot determine the individual matrix elements $\langle \nu|V|\mu\rangle$ since there are too few equations and too many unknowns. However, according to the statistical model, the matrix elements $\langle \nu|V|\mu\rangle$ have a Gaussian distribution with mean value zero and a second moment given by $\overline{v^2}$. We write Eq. (5) in the form $P_\mu = \Sigma_\nu A_{\mu\nu}\langle \nu|V|\mu\rangle$, with coefficients $A_{\mu\nu} = (2/(E_\nu - E_\mu))(g_\nu/g_\mu)$. Then, P_μ is a linear combination of equally distributed Gaussian random variables and, therefore, is itself a Gaussian random variable with mean value zero. The variance of P_μ with respect to both μ and the ensemble is given by $A^2\overline{v^2}$, where $A^2 = (1/N)\Sigma_\mu(A_\mu^2)$ and $A_\mu^2 = \Sigma_\nu A_{\nu\mu}^2$. It follows that

$$\overline{v^2} = \frac{\mathrm{var}(P_\mu)}{A^2}. \tag{6}$$

Equation (6) is the central result of the statistical analysis. It yields $\overline{v^2}$ in spite of the fact that the signs of the partial width amplitudes in Eq. (5) are usually not known. The analysis for target nuclei with nonzero spin values is more difficult and is not described here.

Since there is only a limited number of data points for each nuclide, a maximum likelihood approach to the analysis was used. The probability density function $\mathcal{P}$ of P_μ is a Gaussian G with mean zero and variance $\overline{v^2}A^2$. Including the experimental error σ yields

$$\mathcal{P}(p|vA,\sigma) = G(p,\overline{v^2}A^2 + \sigma^2). \tag{7}$$

Here, p denotes a random variable. The value of P_μ is a realization of this random variable. If all spectroscopic information is known, the likelihood function for a given p-wave resonance is

$$L(v) = G(q,\overline{v^2}A^2 + \sigma^2)\mathcal{P}^0(v), \tag{8}$$

where $\mathcal{P}^0$ is the *a priori* probability density and q is the experimental value of the asymmetry. For a number of independent resonances the likelihood function is the product of the functions for the individual resonances. One inserts the values of the experimental asymmetries q and their errors σ, determines the spectroscopic term A from the known resonance parameters, and calculates the likelihood function. The location of the maximum gives the most likely value v_L of the root mean square (rms) matrix element $v = \sqrt{\overline{v^2}}$. The confidence interval is obtained by solving the equation

$$\ln\left[\frac{L(v_\pm)}{L(v_L)}\right] = \frac{1}{2}, \tag{9}$$

where $v_\pm$ are the corresponding upper and lower values at which this equation is satisfied.

If the spins of the p-wave resonances are not known, then one considers the likelihood function as the sum of two terms, one as before and one that contains only the experimental error and is independent of the rms matrix element v,

$$L(v) = [a\,G(q,\overline{v^2}A^2 + \sigma^2) + b\,G(q,\sigma^2)]\mathcal{P}^0(v), \tag{10}$$

where a and b are the probabilities that $J = 1/2$ or 3/2, respectively. These probabilities are determined experimentally. The *a priori* probability $\mathcal{P}^0$ is common to both terms. Note that since the second term in square brackets is independent of v, the function $L(v)$ is not normalizable unless the bracket is multiplied by $\mathcal{P}^0$. In practice we assume that $\mathcal{P}^0$ is constant below $v_{\max}$ and zero above. The results are insensitive to the choice of $v_{\max}$.

This approach treats the lack of knowledge of the spin values in a straightforward fashion. The one case where all spin values are known (^{238}U) provides a test. One finds little difference between the result for $\overline{v^2}$ obtained when only the p-wave resonances with spin 1/2 are analyzed, and the one obtained when the spins of all resonances are treated as unknown, and the purely statistical approach is used. The physical reason is that resonances that show no statistically significant parity violation (whether they are $p_{3/2}$ states that cannot display parity violation or $p_{1/2}$ states that accidentally have only a small parity violation) have very little effect on the final value of $\overline{v^2}$. A maximum likelihood plot for ^{238}U is shown in Fig. 6. The likelihood function $L(v)$ in Eq. (9) was evaluated for a range of values of the rms matrix element v and has a well-defined maximum. In this case v is rather well determined.

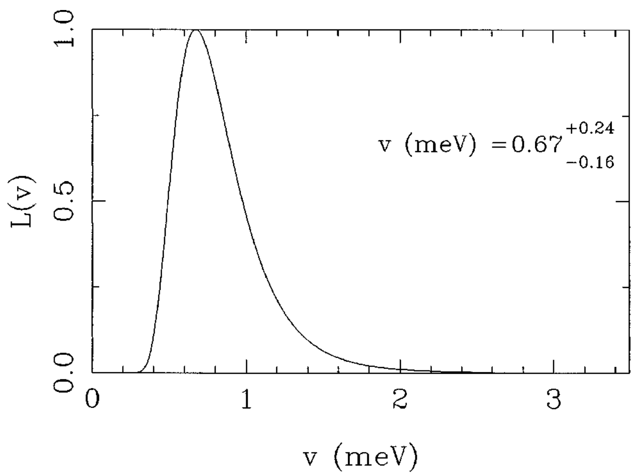

FIG. 6. Maximum likelihood plot for ^{238}U. $L(v)$ is the likelihood function in Eq. (8) (for this case the spins of all of the p-wave resonances are known) evaluated for various values of the rms parity violating matrix element v. Note that the maximum is well defined and that v is well determined.

In general, some but rarely all of the relevant spectroscopic information is available, and the analysis has to be modified. An approach suitable for targets with nonzero spin (Bowman *et al.*, 1996) permits inclusion of such partial information. Using the statistical model, the missing information is replaced by a statistical average. The price of averaging is an increase of the uncertainty in the value of $\overline{v^2}$. In practice, unknown values of the

TABLE I. Relative signs of parity violations observed by the TRIPLE Collaboration. N is the number of parity-violating asymmetries observed in each nuclide; only asymmetries with statistical significance greater than three standard deviations are included. The columns labeled $P+$ and $P-$ are the number of asymmetries with + or − sign relative to the sign of the effect at 0.74 eV in ^{139}La.

Target	N	$P+$	$P-$
^{81}Br[a]	1	1	0
^{93}Nb[b]	0	0	0
^{103}Rh[c]	4	3	1
^{107}Ag[d]	8	4	4
^{109}Ag[d]	4	2	2
^{104}Pd[c]	1	1	0
^{105}Pd[c]	7	4	3
^{106}Pd[e]	1	0	1
^{108}Pd[e]	1	1	0
^{113}Cd[f]	3	2	1
^{115}In[d]	6	3	3
^{117}Sn[c]	6	3	3
^{121}Sb[g]	5	3	2
^{123}Sb[g]	1	0	1
^{127}I[g]	7	5	2
^{131}Xe[h]	1	0	1
^{133}Cs[g]	1	1	0
^{139}La[i]	1	1	0
^{232}Th[j]	10	10	0
^{238}U[k]	5	3	2
Total	73	48	25
Total excluding Th	63	38	25

[a]Frankle *et al.* (1992b).
[b]Sharapov *et al.* (1998).
[c]Smith *et al.* (1998).
[d]Lowie (1996).
[e]Crawford (1997).
[f]Seestrom *et al.* (1998).
[g]Matsuda (1998).
[h]Szymanski *et al.* (1996).
[i]Yuan *et al.* (1991).
[j]Stephenson *et al.* (1998).
[k]Crawford *et al.* (1998).

spins of both the s-wave and p-wave resonances contribute significantly to this uncertainty. When the analysis was applied to ^{232}Th, the mean value of $\langle \nu|V|\mu\rangle$ differed from zero, and a Gaussian with nonzero mean value was required to fit the data. Therefore the procedure had to be modified. We return to this point in Sec. VI.

VI. RESULTS

A. Direct inferences from the data

A grand total of 20 nuclides was investigated. Parity violation was observed in all but one of them. The nuclides studied are listed in Table I. The number of parity violations observed (at the 3σ statistical significance level) is listed along with the number of effects with positive and negative signs (relative to the sign of the parity violation of the 0.74-eV resonance in ^{139}La). Many of these results are preliminary.

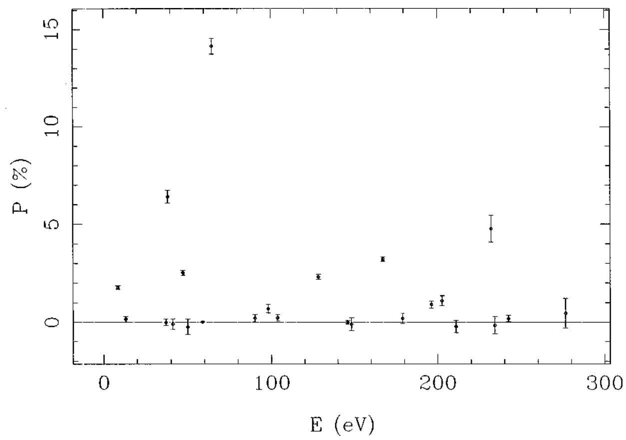

FIG. 7. Parity-violating asymmetries P versus neutron energy E for ^{232}Th.

The results on ^{232}Th are shown in Fig. 7. As compared with the earlier measurements (Frankle, 1992a), the quality of the present data (Stephenson, 1998) is much improved. Most of the p-wave resonances have spin 3/2 and cannot show parity violation, and in fact for most of the resonances, the measurements are consistent with zero asymmetry. However, the most striking result is that there are ten consecutive (statistically significant) effects with positive asymmetry.

Inspection of the experimental data allows us to draw a number of conclusions. In most nuclei, several parity violations are observed. The data are consistent with every p-wave resonance with the proper spin showing parity violation at some level. (Asymmetries consistent with zero merely indicate a limited precision.) The two-state approximation of Eq. (2) explains much of the data—large asymmetries usually are connected with a p-wave resonance near a large s-wave resonance. Asymmetries with large uncertainties usually arise when many s-wave resonances contribute, or when the p-wave resonance is located at higher energies where beam resolution is the limiting factor.

The size of the asymmetry decreases on average with energy as $E^{-1/2}$, reflecting a weakening of kinematic enhancement with increasing neutron energy. Except for ^{232}Th, the data for all cases studied are consistent with the signs of the asymmetries being random. All of these qualitative results (except for the thorium anomaly) are consistent with the statistical model for parity violation.

B. Characteristics of the root mean square matrix element v

The ^{238}U data allow for the best determination of $v = \sqrt{\overline{v^2}}$. The data are very good, the target has spin 0, the spins of all of the resonances are experimentally determined, and there are no apparent anomalies in the data. The likelihood plot for this nucleus is shown in Fig. 6.

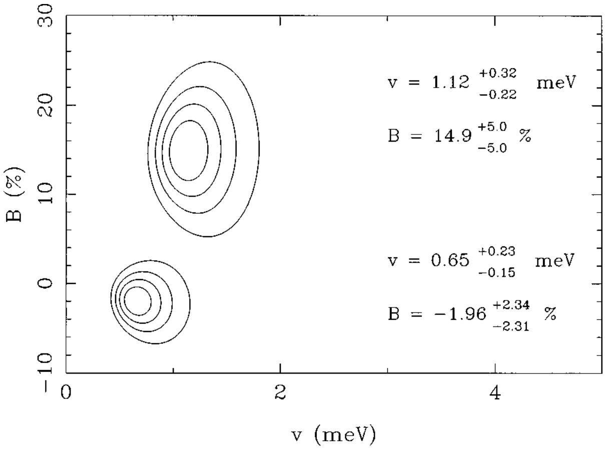

FIG. 8. Two-parameter maximum likelihood contour plots for ^{238}U (lower left) and ^{232}Th (upper left). The contours of constant likelihood are successively 80%, 60%, 40%, and 20% of the maximum value of L. The parameter v is the rms parity violating matrix element and B is the constant offset.

The value of v is $0.67^{+0.24}_{-0.16}$ meV and the corresponding spreading width is $\Gamma^{\downarrow}=(1.35^{+0.97}_{-0.64})\times 10^{-7}$ eV.

As mentioned above, the ^{232}Th data show a surprising anomaly. Ten consecutive statistically significant longitudinal asymmetries have the same sign. This is apparent by inspection of Fig. 7. Ten positive signs in a row should occur by accident only about once in a thousand times $[2^{-10}=(1024)^{-1}]$. Hence, the anomaly must be considered significant. The obvious question, whether this result invalidates the entire statistical ansatz, became the topic of much discussion (see Sec. VII).

Empirically the ^{232}Th data can be represented by introducing an additional parameter. Following Bowman *et al.* (1990b), we can express the asymmetry P_μ as the sum of two terms: a fluctuating term [Eq. (5)] plus an additional constant term,

$$P_\mu = 2\Sigma_\nu \frac{\langle \nu|V|\mu\rangle}{E_\nu - E_\mu}\frac{g_\nu g_\mu}{\Gamma^n_\mu} + B[(1\ \mathrm{eV})/E]^{1/2}, \tag{11}$$

where E is in eV. The quantities $\langle \nu|V|\mu\rangle$, E_ν, and E_μ are independent random variables, and by definition, the first term has average value zero. The energy dependence of the ratio of partial width amplitudes is $E^{-1/2}$, reflecting kinematical enhancement. This behavior is likewise stipulated for the "constant" (i.e., resonance-independent) term B. Scaling B with $E^{-1/2}$ gives the convenient result that the ratio of the fluctuating and constant terms does not depend on energy. Two-parameter maximum likelihood plots for ^{232}Th and ^{238}U are shown in Fig. 8. These plots have several significant implications. First, concerning the nonstatistical anomaly B: there is a clear offset for ^{232}Th, but not for ^{238}U. This distinct difference is also apparent in the values extracted for B for the two cases. Second, the addition of the free parameter B in fitting the likelihood function makes little difference in the value of v extracted for ^{238}U: $v=0.63$ eV versus 0.67 eV. Even for the ^{232}Th data, with a huge offset the free-parameter value of $v=1.12^{+0.32}_{-0.22}$ meV differs only by about 30% from the value of $v=1.58^{+0.38}_{-0.28}$ eV obtained for ^{232}Th when the offset is ignored. The value of the weak spreading width is $\Gamma^{\downarrow}=4.7^{+2.7}_{-1.8}\times 10^{-7}$ eV.

To test the mass dependence of the spreading width, ideally one would like to study the entire range of nuclear mass values. However, this is impossible for several reasons. For light- and medium-weight nuclei, the level spacing is so large that the enhancement factors discussed in Sec. II are lost. Moreover, a comparable neutron experiment would have to cover an energy range of MeV, not the keV range used in the TRIPLE experiment. Another limitation derives from the p-wave neutron strength function. This quantity is a measure of the visibility of p-wave resonances. It is defined as $\overline{\Gamma^n_\mu}/D_p$ (with D_p the average level spacing for p-wave resonances). This strength function shows broad maxima and minima as a function of mass number. In some regions of the periodic table (at the p-wave strength function minima) no p-wave resonances are observed. This is why most of the nuclides studied thus far are near the $3p$ and $4p$ strength function maxima at mass numbers 110 and 230, respectively.

The average level spacing for spin-zero target nuclei near the $3p$ maximum is larger than in the heavier ones, and the asymmetries are correspondingly smaller. In order to obtain level densities comparable to those in the region of the $4p$ maximum, odd-mass targets were studied. This works very well, in the sense that significant asymmetries are observed in almost all of the nuclides studied in the mass 100 region. However, the analysis is complicated by the large increase in the amount of spectroscopic information required, and in the amount of missing information that requires a suitable averaging process. The net result is that the spreading widths determined in this mass region and listed in Table II have large uncertainties. Many of the values are preliminary.

VII. INTERPRETATION

As described in Sec. VI the data yield values of the spreading width $\Gamma^{\downarrow}$ defined in Eq. (4) for a number of nuclei. How are these values interpreted? And how is the anomaly in thorium understood?

(i) The values of $\Gamma^{\downarrow}$ lie in the expected range of $\Gamma^{\downarrow}\sim 10^{-6}$ eV. This fact confirms the basic tenets of the statistical approach. For a more detailed test as well as for a better understanding of nuclear structure effects, it is important to establish the dependence of $\Gamma^{\downarrow}$ on mass number A. A recent theoretical estimate (Auerbach and Vorov, 1997) predicts a mass dependence of $\Gamma^{\downarrow}$ given by $A^{1/3}$, with some uncertainty in the exponent. Improved data in the mass range $A\sim 100$ would be of help but might not be decisive since $A^{1/3}$ changes only by a factor 4/3 or so when A ranges from 100 to 240. A novel set of experiments planned (Mitchell and Shriner, 1996) in the spirit of the TRIPLE measurements but using charged particles in the mass region $A\sim 30$ should be able to establish the mass dependence of $\Gamma^{\downarrow}$.

TABLE II. Weak spreading widths $\Gamma^{\downarrow}=2\pi\overline{v^2}/D$ obtained by the TRIPLE Collaboration.

Target	$\Gamma^{\downarrow}(10^{-7}$ eV)
^{93}Nb[a]	$\leqslant 1.0$
^{107}Ag[b]	$5.40^{+3.57}_{-1.99}$
^{109}Ag[b]	$1.30^{+2.50}_{-0.74}$
^{104}Pd[c]	$2.53^{+10.9}_{-1.70}$
^{105}Pd[c]	$1.29^{+2.54}_{-0.83}$
^{106}Pd[d]	$0.49^{+1.16}_{-0.29}$
^{108}Pd[d]	$2.33^{+7.71}_{-1.49}$
^{113}Cd[e]	$16.4^{+18.0}_{-08.4}$
^{115}In[b]	$0.94^{+0.94}_{-0.39}$
^{117}Sn[c]	$0.86^{+1.94}_{-0.54}$
^{121}Sb[f]	$6.45^{+9.72}_{-3.66}$
^{123}Sb[f]	$1.23^{+15.0}_{-0.96}$
^{127}I[f]	$2.05^{+1.94}_{-0.93}$
^{232}Th[g]	$4.7^{+2.7}_{-1.8}$
^{238}U[h]	$1.35^{+0.97}_{-0.64}$

[a]Sharapov *et al.* (1998).
[b]Lowie (1996).
[c]Smith *et al.* (1998).
[d]Crawford (1997).
[e]Seestrom *et al.* (1998). The value for $\Gamma^{\downarrow}$ is dominated by one effect at 289 eV. The analysis assumes that the PNC effect is due to the 289.64-eV resonance observed at ORELA, but not in the present data. Without this effect the value of $\Gamma^{\downarrow}$ $=4.12^{+8.20}_{-2.67}\times 10^{-7}$ eV.
[f]Matsuda (1998).
[g]Stephenson *et al.* (1998).
[h]Crawford *et al.* (1998).

On top of the global mass dependence, there might exist local fluctuations of the spreading width. Such fluctuations have been observed in the spreading width for isotopic spin mixing (Harney, 1986). It is not clear whether the present data set can resolve such local fluctuations. The values given in Table II may suggest their existence (cf. for instance the cases of ^{107}Ag and ^{109}Ag). It is not clear, however, whether the difference between both nuclides is genuine, or is a finite-range-of-data effect. The dependence of the spreading width on excitation energy is another challenging topic. Unfortunately, the experimental approach to parity violation described in this paper does not seem able to address this issue.

(ii) A second important and largely open question concerns the theoretical relation between the experimentally determined value of the spreading width, and the weak parity-violating two-body interaction. The states $|\nu\rangle$ and $|\mu\rangle$ in Eq. (5) both are linear superpositions of a huge number ($\sim 10^6$) of shell-model Slater determinants. The question is: How is the average $\overline{v^2}$ over such complicated states related to the weak interaction? In other words, is it possible to interpret the neutron data in terms of the elementary weak interaction and mesonic couplings? The problem is usually decomposed into two fairly independent parts. In a first step, the effective parity-violating nucleon-nucleon interaction is calculated from the elementary weak interaction by taking into account the nuclear medium surrounding the two interacting nucleons. In a second step, this effective interaction is propagated into the huge shell-model spaces typical for compound-nucleus states at neutron threshold. An account of the present status of the first step may be found in the review by Adelberger and Haxton (1985). This is the only step needed for the interpretation of experiments on parity violation at low excitation energy. In a general context, analysis of the second step was pioneered by French and his school (French *et al.*, 1988a, 1988b). For parity violation there are analyses by Johnson *et al.* (1991), Flambaum and Vorov (1993), and Tomsovic (1997). It was shown that $\Gamma^{\downarrow}$ should be roughly independent of mass number A and excitation energy E, in contrast to both $\overline{v^2}$ and D [cf. Eq. (4)] that depend essentially exponentially on E. This statement does not preclude a polynomial dependence on A and E, and therefore gives only a qualitative indication of the strength and mass dependence of the parity-violating effective nucleon-nucleon interaction at low excitation energies and for small shell-model spaces. Moreover, the work on localization in Hilbert space referred to at the end of Sec. III (Sivan, 1994; Altshuler *et al.*, 1997; Mirlin and Fyodorov, 1997) raises the question of whether the golden rule encapsulated in Eq. (4) is at all applicable. These important questions deserve further study.

(iii) The anomaly found in thorium poses another challenge. The latest measurements confirm the effect in thorium, but are inconclusive for the data taken as a whole. The anomaly may be a special nuclear structure effect in thorium. Many theorists have addressed this problem. For lack of space, we cannot give a complete list of references and mention only some recent ones (Auerbach *et al.*, 1995; Flambaum and Zelevinsky, 1995; Hussein *et al.*, 1995; Auerbach *et al.*, 1996; Desplanques and Noguera, 1996; Sushkov, 1996). Attempts at an explanation have ruled out several possible mechanisms and have focused on the mechanism of a close-lying doorway as the only viable possibility: Some close-lying configuration carries most of the local strength for parity violation. The degree of admixture of this configuration to the p-wave resonance under study largely determines the measured asymmetry. This explains the equality of the signs of the asymmetries in a series of resonances. There is no consensus, however, on the detailed doorway mechanism, nor are there as yet convincing proposals for an independent experimental test of this picture, or solid arguments why the anomaly exists only in thorium.

VIII. SUMMARY

In the last two decades, the study of parity violation in the compound nucleus has made impressive advances. Large enhancement factors were both predicted and observed. The dedicated experiment of the TRIPLE Collaboration has produced values for the asymmetry P of Eq. (3) on a number of p-wave resonances for many nuclei with masses around 100 and 230. Typical values of

P are in the percent region and much larger than the systematic and statistical errors of the data. Except for the thorium anomaly, the data confirm the statistical model. The model predicts that the matrix elements for parity violation and, hence, P, are Gaussian random variables with mean value zero. Thus, it is possible to determine the rms matrix element v and the spreading width $\Gamma^{\downarrow}$ [see Eq. (4)] of the parity-violating interaction directly from the data, without any need to know the wave functions of individual nuclear states. The spreading width is found to lie in the expected range of 10^{-6} eV. Nuclear theorists ascribe the thorium anomaly to a nuclear structure effect specific to thorium. The effect is not yet understood in its details, however.

Future work is expected to address the following points. It is highly desirable to establish the dependence of $\Gamma^{\downarrow}$ on mass number and energy. Experiments on light nuclei with masses around 30 are particularly promising. Likewise, in a given domain of mass number and excitation energy, the spread of the values for $\Gamma^{\downarrow}$ is of interest. Theory must also address these issues. In addition, the quantitative connection between $\Gamma^{\downarrow}$ and the effective parity-violating nucleon-nucleon interaction in nuclei is of central importance. This is a statistical problem, not one of nuclear structure physics. A clarification of the thorium anomaly with an experimentally verifiable prediction would dispel any remaining doubts about the applicability of the statistical model.

Once understood, the study of parity violation in the compound nucleus may pave the way to the more ambitious goal of investigating time-reversal symmetry breaking with the help of similar enhancement factors and statistical concepts.

ACKNOWLEDGMENTS

G.E.M. would like to thank the Alexander von Humboldt Foundation for support, and members of the Max Planck Institute for Nuclear Physics Heidelberg for their hospitality while this manuscript was prepared. G.E.M. and J.D.B. would like to express their appreciation to all of their fellow members of the TRIPLE Collaboration. Over the years, the authors have profited from discussions on the experimental and theoretical aspects of parity violation in the compound nucleus with many colleagues to all of whom we are very grateful. This work was supported in part by the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Grant No. DE-FG02-97-ER41042 and by the U.S. Department of Energy, Office of Energy Research, under Contract No. W-7405-ENG-36.

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