RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 49, NUMBER 2 FEBRUARY 1994

Parity violation in charged particle nuclear reactions

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(Received 9 July 1993)

The potential role of charged particle resonance reactions in the study of parity nonconservation (PNC) in the nucleus is examined in light of recent statistical interpretations of PNC measurements in neutron resonances. Several PNC observables have been calculated using experimental resonance parameters for five *s*-*d* shell nuclei. Longitudinal analyzing powers in $(\vec{p},\alpha_0)$ reactions show strong dependence on energy, angle, and resonance parameters. Measurements of analyzing powers at the 10^{-4} level should provide new information on parity violation in the nucleon-nucleus interaction.

PACS number(s): 11.30.Er, 25.40.Ny, 24.60.Dr, 24.80.Dc

After the first suggestion of parity nonconservation (PNC) in the weak interaction by Lee and Yang [1], experimental confirmation followed shortly in both β decay [2] and in π decay [3,4]. The first positive result for PNC in a nuclear reaction was provided by Abov *et al.* [5] in studies of ^{113}Cd$(\vec{n},\gamma)$. Early PNC measurements with polarized neutron beams are described in a monograph by Krupchitsky [6], and a comprehensive review of a wide range of PNC experiments and their implications has been given by Adelberger and Haxton [7]. Although parity violation has been observed in a number of nuclear systems, it has proven difficult (due to theoretical uncertainties in the nuclear wave functions) to separate nucleon-nucleon PNC effects from nuclear structure effects. For this reason measurements in the *p*-*p* system [8–12] have been emphasized, although these experiments require the measurement of analyzing powers at the 10^{-7} level.

Recent developments have led to a shift in approach to PNC measurements in the compound nucleus. Several authors [13–15] discussed the possibility of large enhancements of PNC observables near $\ell = 1$ neutron resonances in heavy nuclei due to mixing between $\ell = 0$ and $\ell = 1$ states. Large PNC effects were observed in the helicity dependence of neutron total cross sections in several nuclides by Alfimenkov *et al.* [16]. The TRIPLE Collaboration [17,18] has observed parity violation for several resonances in each of the compound nuclei ^{239}U and ^{233}Th and emphasized a statistical interpretation. In this approach, the PNC matrix elements $\{V\}$ for different resonances are independent Gaussian-distributed random variables with mean zero, and the important quantity is the root-mean-square parity-violating matrix element $V_{\rm rms}$. Several recent papers [19–21] have discussed how to relate $V_{\rm rms}$ to the underlying nucleon-nucleon PNC interaction.

A major goal of these polarized neutron measurements is the determination of the mass dependence of the effective nucleon-nucleus weak interaction; Hayes and Towner [22] have recently examined this issue. Another major goal is to clarify the reaction mechanism. This latter issue was raised following the unexpected observation of nonstatistical behavior in the PNC matrix elements in ^{233}Th by Frankle *et al.* [18] and has been considered by a number of authors [22–25]. All of the proposed explanations seem flawed, since they appear to require implausibly large weak matrix elements. As a result, there is appreciable interest in obtaining additional PNC information for compound nuclear resonances in light or medium nuclei. This paper considers PNC effects in charged particle reactions in light of this new statistical interpretation. If a number of parity-violating matrix elements can be determined for a given nuclide, then the distribution of these matrix elements should provide direct information concerning the reaction mechanism.

There have been few experimental parity-violation studies with charged particle resonances. The PNC analyzing powers A_z and A_x have been reported [26–28] for a single 1^+ resonance in the ^{19}F$(\vec{p},\alpha_0)$ reaction (only an upper limit was obtained for A_x). Recent measurements of A_z for the ^{27}Al$(\vec{p},\alpha_{0,1})$ reaction in the Ericson fluctuation regime by Böhm *et al.* [29] also yielded only an upper limit.

At first glance, charged particle resonances would appear to provide a less suitable laboratory for studying parity violation than do neutron resonances, since the neutron resonance studies benefit from several enhancements: "kinematic enhancement" results from the large difference in *s*-wave and *p*-wave penetrabilities for neutrons incident on heavy nuclei; "dynamic enhancement" results from the closeness of the interfering *s*-wave and *p*-wave resonances. These enhancements are not as pronounced for charged particle resonances in light and medium mass nuclei, where the levels are generally much farther apart and the different penetrabilities much closer in magnitude.

However, there are some potentially significant advantages in studying charged particle resonances. Differential cross sections are generally much easier to measure with charged particles, allowing the possibility of angular enhancements. Charged particle resonances with $\ell > 1$ are relatively common, allowing the study of PNC with more than just *s*-*p* resonance pairs. The greater ease of measuring differential cross sections, as well as the possibility of easily studying several reaction channels, makes determination of the nuclear spectroscopy much simpler; this spectroscopic information is essential for extracting a PNC matrix element. Charged particle resonances also offer the possibility of measuring either differential or angle-integrated cross sections; for differential cross sections, one can measure either elastic scattering or reaction channels and use either longitudinally or transversely polarized beams. Each of these combinations yields an observable which is first order in the PNC matrix element. The greater ease of spectroscopic measurements is especially important, since one needs to determine the relevant spectroscopic information for enough resonances to perform a statistical analysis. We believe that a statistical interpretation of these highly excited resonance states is appropriate; this conclusion is based on spacing distributions for a range of nuclei in this mass region [30,31] and spacing distributions of shell model states in this mass region [32]. In each case, there is general agreement of the fluctuation properties with random matrix theory.

To determine the feasibility of such experiments, we have examined a large collection of high resolution proton resonance data measured at Triangle Universities Nuclear Laboratory in the s-d shell. Using experimentally determined resonance parameters, we have calculated A_z and A_x under the various circumstances listed above. Here we focus on measurements of A_z as a function of angle for $(\vec{p},\alpha_0)$ reactions, since these measurements are the most promising and illustrate the important features of our results.

The model we employ is a standard two-state model and assumes a Hamiltonian $H = H_0 + H_{\rm PV}$, where H_0 is the parity-conserving term and $H_{\rm PV}$ is a small parity-violating term. The matrix elements of $H_{\rm PV}$ are denoted by V. Only internal mixing is considered, since that is the process in which the large enhancements occur. Although only two states are included in the present calculations, extension to the n-state mixing problem should parallel the method adopted in the analysis of n-state mixing in the neutron parity violation studies [17,18] , allowing the determination of $V_{\rm rms}$. First-order perturbation theory is used to derive the reduced width amplitudes; details of such derivations have been discussed by Bizzetti and Maurenzig [33] for $(\vec{p},\alpha)$ reactions and by Adelberger, Hoodbhoy, and Brown [34] and Bizzetti [35] for $(\vec{p},p)$ scattering. Differential cross sections for polarized beams were derived following the procedure of Heiss [36]. The resulting expression for the longitudinal analyzing power A_z is a complicated function of resonance energies, partial width amplitudes, and the angular momenta of the target and resonance pair; it is too long to be included here for any of the specific cases under consideration. We note that within this model A_z is proportional to V to first order.

High resolution (p,α_0) resonance data exist for five targets in the s-d shell: ^{23}Na [37], ^{27}Al [38], ^{31}P [39], ^{35}Cl [40], and ^{39}K [41,42]. Each of these data sets covers all or part of the incident energy range E_p=1–4 MeV; partial widths are typically known within 10–20%. These data were searched for adjacent resonances which had the same angular momentum but different parities. Sixty-two pairs of resonances were identified which met this

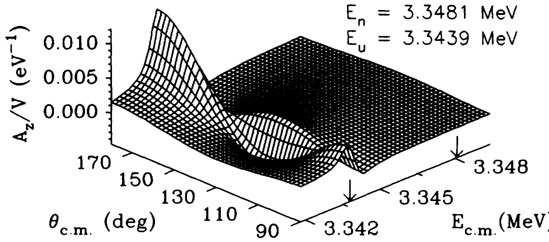

FIG. 1. The ratio A_z/V (A_z is the longitudinal analyzing power and V the parity-violating matrix element) as a function of energy and angle for a resonance pair ($J^\pi = 2^-$ and 2^+) in $\vec{p}$+^{39}K $\rightarrow$ α+^{36}Ar. The arrows along the energy axis mark the locations of the two resonances.

criterion and had a measured alpha width for the natural parity resonance of the pair. The analyzing power A_z was calculated as a function of both energy and angle for each resonance pair using the experimentally measured resonance parameters. These resonance parameters include the resonance energy, total angular momentum and parity, proton entrance channel widths for each channel spin for a given orbital angular momentum value (including the relative sign of the channel-spin mixing), and the alpha width. These parameters were determined by high-resolution resonance elastic and reaction scattering [43]. To simulate the effect of finite beam-energy resolution, the cross sections were convoluted with a Gaussian function of FWHM 500 eV before A_z was calculated. Since V is unknown and $A_z \propto V$, it is convenient to use A_z/V as a measure of the relative enhancement of PNC effects.

The behavior of A_z/V as a function of energy and angle for a typical resonance pair ($J^\pi = 2^-$ and 2^+ in the compound nucleus ^{40}Ca) is shown in Fig. 1. In this case, the largest magnitudes of A_z/V are observed near the lower energy (unnatural parity) resonance. A strong angular dependence is also observed, with the largest magnitude of A_z/V occurring at $\theta_{\rm c.m.} = 180°$. Although the specific behavior of A_z/V differs for each resonance pair, strong dependence on both energy and angle is a generic feature. We have also observed similar strong dependence on energy, angle, and resonance pair in a study of detailed-balance tests of time-reversal invariance with interfering resonances [44].

The maximum values of A_z/V also vary strongly from pair to pair. The pair shown in Fig. 1 has a maximum $|A_z/V|$ of 0.012 eV^{-1}. Maximum magnitudes for the other 61 pairs range from $\sim 10^{-4}$ to $\sim 10^{-1}$ eV^{-1}. The differences occur due both to the different spacings between the resonances and to the specific resonance parameters.

Since the relative enhancements vary so strongly with energy, angle, and resonance parameters, any experiment of this type requires careful evaluation to ensure that the measurement is made at an appropriate energy and angle. Knowledge of the resonance parameters is a necessity, both to determine the most appropriate measurement and to extract a value of V from any measurement.

The quantity A_z/V provides a measure of relative enhancement. However, a large value of A_z/V can occur either because of a large difference in cross sections for different helicities or because of a small cross section. Since a smaller cross section increases the time to reach a given statistical accuracy, the value of the cross section also must be considered in evaluating a proposed experiment. The appropriate figure of merit which combines the requirements of a measurable cross section and a measurable A_z is given by $\beta_P \equiv (A_z/V)^2\, d\sigma/d\Omega$. A larger value of β_P indicates a shorter time to establish a specific statistical uncertainty on V. The quantities A_z/V, $d\sigma/d\Omega$, and β_P are plotted as a function of energy in Fig. 2 for the same resonance pair shown in Fig. 1. In this particular case, the optimal energy for measurement is slightly less than the resonance energy of the unnatural parity resonance. The maximum values of β_P also vary strongly from pair to pair, ranging from $\sim 10^{-9}$ to $\sim 10^{-4}$ mb/sr eV^2.

Since the actual measurement is of A_z, not A_z/V, the size of A_z is the real quantity of interest. Since V is assumed to be a random variable, one cannot determine A_z directly. However, one can estimate $V_{\rm rms}$ and then use the product $(A_z/V)\ V_{\rm rms}$ as an estimate for both the analyzing power and the experimental sensitivity needed to detect nonzero effects in A_z. An estimate for $V_{\rm rms}$ can be obtained from the spreading width: $\Gamma_{\rm PV} = 2\pi\langle V^2\rangle/D$, where D is the average spacing. Spreading widths are known to be "nearly independent of mass number and excitation energy" for isospin violation [45]. We assume that this independence is also true for parity violation and use the average spreading width found for parity violation in heavy nuclei [17,18] for these light nuclei as well; this assumption is consistent with the recent suggestion by Auerbach [46] that $\Gamma_{\rm PV}$ increases as A^δ where $\delta \simeq$1–1.3. The average spacing D was determined from the resonance data as a function of J and E. Knowing both $\Gamma_{\rm PV}$ and D then yields an estimate of $V_{\rm rms}$ for each resonance pair.

The predicted values of $V_{\rm rms}$ range from 50 to 140 meV. [These values are in agreement with the only experimental resonance information available in this mass region. Antonov *et al.* [47] studied the helicity dependence of the ^{35}Cl$(\vec{n},p)^{35}$S reaction and observed parity violation. Assuming two-state mixing, a weak matrix element of 60 $\pm$ 20 meV was extracted.] The estimates of A_z range in magnitude from 2×10^{-5} to 6×10^{-3}; approximately 80% of the pairs have predicted values of A_z larger than 10^{-4}. Therefore, measurements of A_z at the 10^{-4} level could allow determination of $V_{\rm rms}$ for one or more of these light nuclides. This seems feasible, since several previous experiments of a similar nature [26–29] have reported sensitivities of about 10^{-4}. Discussion of some of the systematic errors inherent in such measurements is given in [29].

In summary, the recent measurements of parity violation in neutron resonances in heavy nuclei have led to a different approach to the study of PNC effects in nuclei. These new results (and new questions) make the determination of PNC matrix elements in other mass regions a high priority. We have considered parity violation in the $(\vec{p},\alpha_0)$ reaction and used experimental values for the resonance parameters in five s-d shell nuclei. We obtained explicit predictions for 62 resonance pairs for the values of the ratio of the longitudinal analyzing power to the parity-violating matrix element V. The values of this ratio show a striking sensitivity to energy, angle, and the specific resonance pair. A figure of merit involving both the ratio A_z/V and the magnitude of the cross section was calculated to determine the "best" energy and angle at which to study each resonance pair. Using the value of the parity violating spreading width from the neutron measurements in heavy nuclei and the experimental value of the level spacing, a local $V_{\rm rms}$ was estimated for each resonance pair in each nuclide. Since the large majority of the predicted A_z values are $> 10^{-4}$, these measurements seem well within the range of experimental feasibility. Determination of a number of parity-violating matrix elements in a given nuclide should provide valuable new information about both the mass dependence and the mechanism for parity violation.

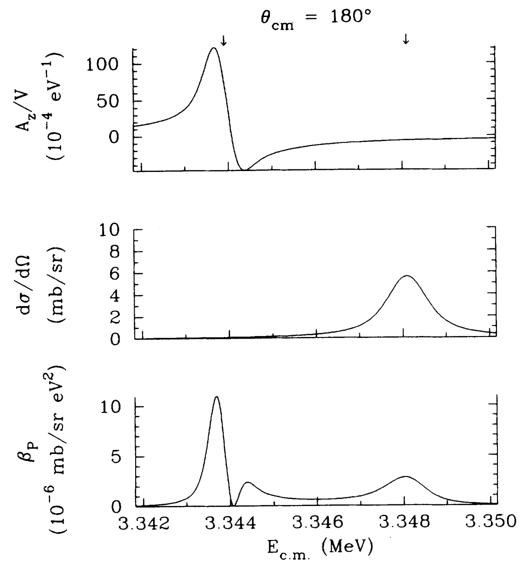

FIG. 2. The quantities A_z/V, $d\sigma/d\Omega$, and β_P as a function of energy at $\theta_{\rm c.m.} = 180°$ for the same resonance pair shown in Fig. 1. The quantity β_P is a figure of merit; a maximum value of β_P indicates the "best" energy at which to perform the experiment. The vertical arrows at the top indicate the locations of the two resonances.

We wish to thank E. D. Davis and C. R. Gould for valuable discussions. This work was supported in part by the U.S. Department of Energy, Office of High Energy, and Nuclear Physics under Grants Nos. DE-FG05-87ER40353 and DE-FG05-88ER40441. One of us (J.F.S.) received support from an appointment to the U.S. Department of Energy Faculty Research Participation Program administered by Oak Ridge Associated Universities.

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