PHYSICAL REVIEW C VOLUME 25, NUMBER 3 MARCH 1982

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Manuscripts submitted to this section are given priority in handling in the editorial office and in production. A Rapid Communication may be no longer than 3½ printed pages and must be accompanied by an abstract and a keyword abstract. Page proofs are sent to authors, but, because of the rapid publication schedule, publication is not delayed for receipt of corrections unless requested by the author.

Time reversal and charge symmetry studies in single nucleon transfer reactions in the $A = 5$ system

A. L. Sagle, F. P. Brady, and J. L. Romero
Crocker Nuclear Laboratory and Department of Physics, University of California, Davis, California 95616

B. E. Bonner, N. S. P. King, and M. W. McNaughton
Los Alamos Scientific Laboratory, Box 1663, Los Alamos, New Mexico 87545

H. E. Conzett
Lawrence Berkeley Laboratory, Berkeley, California 94720

(Received 17 August 1981)

Time-reversal invariance and charge symmetry have been studied in polarization measurements of single-nucleon transfer reactions in the mass five system. First, we experimentally established the equality of the proton analyzing power, A, for $^4\text{He}(\vec{p},d)^3\text{He}$ at 32 MeV and the polarization, P, of the inverse reaction, thereby checking time-reversal invariance. Then in a double scattering experiment using the reactions $^3\text{H}(d,\vec{n})^4\text{He}$ and $^4\text{He}(\vec{n},d)^3\text{H}$ at $\theta_{\text{c.m.}} = 38.6°$ and assuming $P = A$ (from time-reversal invariance) we obtained a polarization of 0.480 ± 0.016 for the 50 MeV neutrons. When this value is used, good agreement is found between the analyzing power distributions of $^4\text{He}(\vec{n},d)^3\text{H}$ and $^4\text{He}(\vec{p},d)^3\text{He}$ at 50 MeV, which is consistent with charge symmetry.

[NUCLEAR REACTIONS $^4\text{He}(\vec{p},d)^3\text{He}$, $E_p = 32$ and 50 MeV; $^4\text{He}(\vec{n},d)^3\text{H}$, $E_n = 50$ MeV. Measured $A_y(\theta)$, $\theta = 25°-150°$ c.m. Inferred neutron polarization for reaction $^3\text{H}(d,\vec{n})^4\text{He}$ at $E_d = 37.1$ MeV, $\theta = 38.6°$ c.m.]

Time-reversal invariance (TRI) and charge symmetry (CS) are such important fundamental postulates in the description of nuclear interactions that any significant test of their experimental consequences should be pursued. Very recent reports of spin-polarization experiments in some nuclear reactions show results which differ substantially from those expected on the basis of TRI and CS, so it is clear that additional tests of these symmetry principles are most appropriate.

Concerning TRI, Slobodrian *et al.*[1] reported on comparisons of the polarization (P), in the $^7\text{Li}(^3\text{He},\vec{p})^9\text{Be}$ and $^9\text{Be}(^3\text{He},\vec{p})^{11}\text{B}$ reactions, with the analyzing power (A) in the inverse reactions. Large differences between P and A of $\cong 0.4$ were found. For the case of the $^9\text{Be}(^3\text{He},\vec{p})^{11}\text{B}$, preliminary results at Los Alamos indicate no P-A differences.[2] Since the P-A equality follows directly from TRI,[3] confirmation of the result of Ref. 1 or corroborative P-A differences in other reactions would, indeed, constitute firm evidence for violation of TRI. Additionally, Conzett[4] has examined all of the previous polarization tests of TRI in nuclear scattering and reactions, and he shows that almost all of them are really nontests of TRI and that the remaining ones are inadequate due either to lack of precision or lack of sensitivity to a violation of TRI. In view of these developments, it is now particularly important that new tests of TRI be made, and reactions can provide a more sensitive test than elastic scattering.[4]

With respect to charge symmetry, a similar P_n-A_p equality, which follows from the combination of TRI and CS, has been established in (p,n) transitions between the mirror nuclear states of an isospin doublet.[5] Here P_n is the neutron polarization in the $(p,\vec{n})$ transition and A_p is the proton analyzing power in the $(\vec{p},n)$ transition with polarized protons. This, however, is not an exact equality since the Coulomb force breaks the charge symmetry. Early P_n-A_p differences were reduced to equalities by later more precise measurements,[6,7] but surprisingly large differences were found[7] in the $^{15}N(p,n)^{15}O$ reaction for proton energies in the region of 5 to 9 MeV, where resonance structure is prevalent. Even though the magnitude of these differences has been produced in a continuum shell-model calculation with a standard two-nucleon interaction that includes noncentral and Coulomb components,[8] a quantitative description of the P_n-A_p differences is yet to be achieved. Thus, tests of CS in nuclear reactions, as well as TRI, are now of particular interest.

We report here extensive use of the P-A equality in measurements of single-nucleon transfer reactions in the mass-5 system. In one set of measurements this theorem is checked by comparing the analyzing power of $^4He(\vec{p},d)^3He$ with the polarization of $^3He(d,\vec{p})^4He$ at equivalent center of mass energies and angles. In a second experiment an absolute measurement is made of the neutron polarization in a double scattering experiment with the reactions $^3H(d,\vec{n})^4He$ and $^4He(\vec{n},d)^3H$. The analyzing powers of the charge-symmetric reactions $^4He(\vec{p},d)^3He$ and $^4He(\vec{n},d)^3H$ are then compared and found to be in agreement.

In the first experiment the analyzing powers were measured for the reaction $^4He(\vec{p},d)^3He$ at 32, 40, 50, and 52.5 MeV at the Lawrence Berkeley Laboratory using polarized protons from the 88-inch cyclotron. In Fig. 1 we compare the analyzing power for this

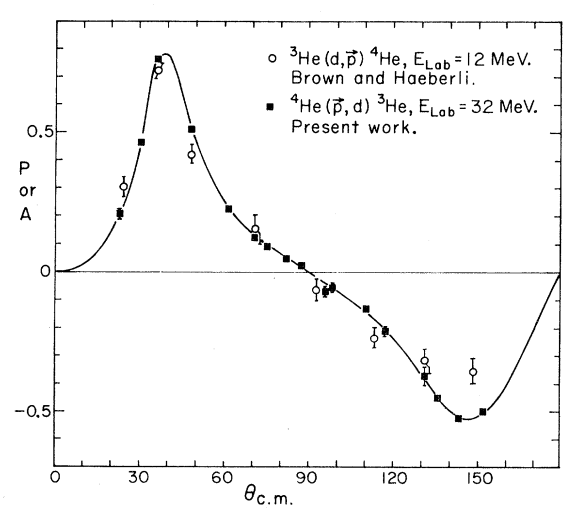

FIG. 1. Analyzing power angular distribution for the $^4He(\vec{p},d)^3He$ reaction (solid squares) compared with the polarization measurements of the $^3He(d,\vec{p})^4He$ reaction (Ref. 9) at the same (compound nucleus) center of mass energy. The plotted data of Ref. 9 do not include an estimated 5 to 10% uncertainty in the analyzing power of their polarimeter (Ref. 9). The curve is a Legendre polynomial fit to the $^4He(\vec{p},d)^3He$ data.

reaction at $E_p = 32$ MeV with earlier measurements[9] of the proton polarization in the inverse reaction $^3He(d,\vec{p})^4He$ at 12 MeV. These energies are equivalent in the center of mass because of the large reaction Q value (18.6 MeV). Although there is general agreement between P and A, the datum for $^3He(d,\vec{p})^4He$ at $\theta_{c.m.} = 148°$ is higher than the trend of the $^4He(\vec{p},d)^3He$ data. This disagreement, however, may not be significant because of the large uncertainty in the value of the p-^{12}C analyzing power used by Brown and Haeberli.[9] The protons for this datum had an energy of 12.7 MeV at the center of the ^{12}C target and recent measurements[10] have shown large fluctuations in the p-^{12}C analyzing power near 13 MeV. For the other data, the protons from $^3He(d,\vec{p})^4He$ had higher energies at the ^{12}C target and no large fluctuations were observed in these newer analyzing power measurements. A rather similar situation exists in a recent P-A comparison in the $^{13}C(\vec{p},d)^{12}C$ reaction and its inverse near $E_p = 14$ MeV,[11] where P-A differences have been observed at backward angles. Again, the older $^{12}C(d,\vec{p})^{13}C$ polarization measurements[12] at these backward angles may be uncertain. While the backward angle $^3He(d,\vec{p})^4He$ and $^{12}C(d,\vec{p})^{13}C$ polarizations should be remeasured, there appears to be no evidence for a violation of TRI in these reactions at forward angles.

In the second experiment an absolute measurement of the polarization was made with the 50-MeV polarized neutron facility[13] at the Crocker Nuclear Laboratory 76-inch cyclotron by using a double scattering technique first proposed by Barschall.[14] The polarized neutrons produced at $\theta_{lab} = 29.7°$ from the reaction $^3H(d,\vec{n})^4He$ passed through a spin rotation magnet and then impinged on a liquid nitrogen cooled ^4He gas cell. Simultaneous left-right measurements were then made of the deuterons from the reaction $^4He(\vec{n},d)^3H$ at $\theta_{lab} = 25°$ with a pair of plastic scintillation counter telescopes. At these angles, the center of mass energies and angles are the same for these inverse reactions and the polarization of the neutrons produced in the first reaction is equal to the neutron analyzing power of the second reaction from the P-A equality.

Another pair of telescopes measured the analyzing power at other angles while the absolute measurement was being made at 25°. Data were taken in a series of consecutive spin-up and spin-down runs. The left, right, spin-up, and spin-down yields were combined in the usual way[15] to obtain the measured asymmetry, ϵ. Possible systematic effects in the measurement at 25° were investigated by interchanging detectors. The telescope pair used at other angles was moved to 25°. In addition, the left and right telescopes within a pair were interchanged.

The kinematic conditions necessary for the absolute measurement were checked experimentally. The scattering angle of the production reaction was set at

TABLE I. The asymmetry for ^{4}He($\vec{n}$,d)^{3}H at $\theta_{lab}=25°$.

Detector pair	$\epsilon_{measured}$	$\epsilon_{corrected}$[a]
1,2	0.236 ±0.016	0.248 ±0.017
3,4	0.207 ±0.020	0.218 ±0.021
1,2	0.203 ±0.022	0.214 ±0.023
2,1	0.252 ±0.021	0.265 ±0.022
1,2	0.199 ±0.018	0.205 ±0.019

[a] $\epsilon_{corrected}$ is the measured asymmetry corrected for the finite acceptance of the targets and the detectors.

29.7 ±0.03°. The neutron beam energy was measured by a time of flight technique[16] and found to be 50.0 ±0.1 MeV. The error in the angle of the detected deuteron is estimated to be ±0.1°.

The results of the absolute measurement are given in Table I. In the column labeled detector pair, the first number represents the left detector and the second number represents the right detector. For the first four measurements, the 6.4-cm $\phi \times 15.2$-cm height ^{4}He gas cell had a 102-μm-thick Al window and the target to detector distance was 67 cm. For the fifth measurement, the ^{4}He gas cell had a 38-μm-thick nickel window and a target to detector distance of 81.6 cm. Typical sizes and thicknesses were $11 \times 5 \times 0.12$ cm for the ΔE detectors and $10.1 \times 5.1 \times 2.5$ cm for the E detectors. The measured asymmetry, ϵ, is corrected for the finite extent of the targets and detectors. The angular distributions of the analyzing powers and the unpolarized differential cross sections for ^{4}He(p,d)^{3}He were used for this small correction. The corrected and uncorrected values of ϵ are shown in Table I for each configuration. The errors are dominated by statistical uncertainties although they include contributions from uncertainties in the scattering angle ($\Delta\epsilon_\theta = \pm 0.002$) and the finite acceptance correction ($\Delta\epsilon_f = \pm 0.002$). The weighted average of ϵ is 0.231 ±0.009. To check for internal consistency, we form a χ^2 from the deviations of the five measurements from their weighted average. We find $\chi^2 = 6.18$ which corresponds to a central confidence limit of ~20% for four degrees of freedom. A weighted average of $\epsilon = 0.231 \pm 0.015$ corresponds to a central confidence level of 68% and we use this latter value to extract the analyzing power ($\epsilon = P^2 = A^2$) of 0.480 ±0.016.

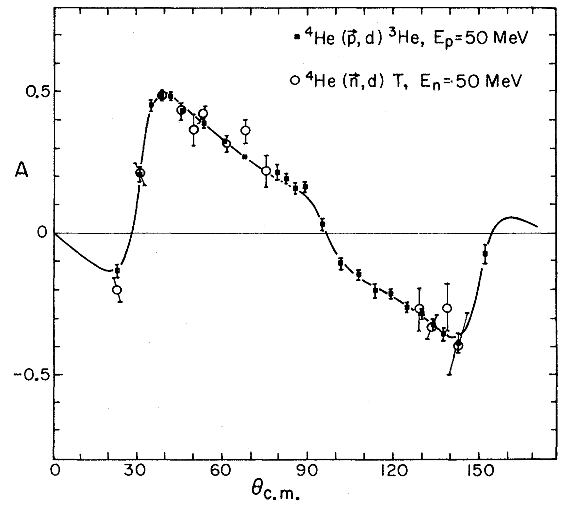

FIG. 2. The angular distribution for the ^{4}He($\vec{n}$,d)^{3}H analyzing power at 50 MeV compared with the charge symmetric reaction. The curve is a Legendre polynomial fit to the latter.

The datum for the analyzing power at $\theta_{lab}=25°$ is also a measurement of the 50-MeV neutron beam polarization if the P-A equality is valid. We have verified this equality at forward angles and at a lower energy for the charge symmetric reaction ^{3}He(d, $\vec{p}$)^{4}He and its inverse. When we use the absolute measurement of the neutron polarization, the angular distributions for ^{4}He($\vec{n}$,d)^{3}H and ^{4}He($\vec{p}$,d)^{3}He at 50 MeV agree quite well as shown in Fig. 2. We thus conclude that our set of measurements for these (nucleon, d) reactions are all consistent (within experimental errors) with time-reversal invariance and charge symmetry.

We thank R. M. Larimer, Ch. Leemann, W. Dahme, and W. B. Broste for their assistance during these experiments. This work was supported by the National Science Foundation Grants No. NSF-PHY-77-05301 and No. 79-26282 and by the Director, Office of Energy Research, Office of Basic Energy Sciences, Nuclear Sciences Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

[1]R. J. Slobodrian, C. Rioux, R. Roy, H. E. Conzett, P. von Rossen, and F. Hinterberger, Phys. Rev. Lett. 47, 1803 (1981); H. E. Conzett, in *Polarization Phenomena in Nuclear Physics—1980,* edited by G. G. Ohlsen *et al.*, AIP Conf. Proc. No. 69 (AIP, New York, 1981), p. 1422.

[2]P. W. Keaton, R. A. Hardekopf, P. W. Lisowski, and L. R. Veeser, Bull. Am. Phys. Soc. 26, 623 (1981).

[3]R. J. Blin-Stoyle, Proc. Phys. Soc. London Ser. A 65, 452 (1952); G. R. Satchler, Nucl. Phys. 8, 65 (1958); L. C. Biedenharn, *ibid.* 10, 620 (1959).

[4]H. E. Conzett, in Ref. 1, p. 1452; (unpublished).
[5]H. E. Conzett, Phys. Lett. 51B, 445 (1974); L. G. Arnold, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions,* edited by W. Grüebler and V. König (Birkhäuser Verlag, Basel, 1976) [Experientia Suppl. 25, 503 (1976)]; Bull. Am. Phys. Soc. 22, 588 (1977).
[6]T. R. Donoghue, Sr., M. A. Doyle, H. W. Clark, L. J. Dries, J. L. Regner, W. Tornow, R. C. Byrd, P. W. Lisowski, and R. L. Walter, Phys. Rev. Lett. 37, 981 (1976).
[7]R. C. Byrd, P. W. Lisowski, W. Tornow, and R. L. Walter, Bull. Am. Phys. Soc. 22, 587 (1977); R. L. Walter and R. C. Byrd, in *The (p,n) Reaction and the Nucleon-Nucleon Force,* edited by C. G. Goodman *et al.* (Plenum, New York, 1980), p. 469; R. C. Byrd and R. L. Walter, *Polarization Phenomena in Nuclear Physics—1980,* edited by G. G. Ohlsen *et al.*, AIP Conf. Proc. No. 69 (AIP, New York, 1981), p. 1475.
[8]R. J. Philpott and D. Halderson, in *The (p,n) Reaction and the Nucleon-Nucleon Force,* edited by C. D. Goodman *et al.* (Plenum, New York, 1980), p. 491.
[9]R. I. Brown and W. Haeberli, Phys. Rev. 130, 1163 (1963).
[10]H. O. Meyer, W. G. Weitkamp, J. S. Dunham, T. A. Trainor, and M. P. Baker, Nucl. Phys. A269, 269 (1976); and W. G. Weitkamp (private communication).
[11]B. L. Burks, R. E. Anderson, T. B. Clegg, R. L. Varner, J. F. Wilkerson, and H. Shieck, Bull. Am. Phys. Soc. 26, 624 (1981).
[12]A. Budzanowski, L. Freindl, W. Karcz, B. Lazarska, and W. Zipper, Nucl. Phys. A161, 610 (1971).
[13]A. L. Sagle, M. W. McNaughton, N. S. P. King, F. P. Brady, and B. E. Bonner, Nucl. Instrum. Methods 129, 345 (1975).
[14]H. H. Barschall, Helv. Phys. Acta 29, 149 (1956).
[15]G. G. Ohlsen and P. W. Keaton, Jr., Nucl. Instrum. Methods 109, 41 (1973).
[16]F. P. Brady, S. W. Johnsen, and W. J. Knox, Nucl. Instrum. Methods 89, 309 (1970).