single-particle process similar to the one proposed here for the (d,p) reaction.

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Time-Reversal Invariance in Nuclear Scattering

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WE report here some experimental tests of time-reversal invariance, or of parity conservation, or both, in high-energy nuclear scattering. The work was carried out because of the discovery of the failure of parity conservation in weak interactions.[1]

If parity conservation is assumed,[2] which recent experiments have shown to be a good approximation for strong interactions,[3] then one can show quite straightforwardly that time-reversal invariance requires the equality of P and e,[4,5] where P is the polarization produced in the scattering of unpolarized protons and e is the asymmetry produced when fully polarized protons are scattered. Furthermore, in the case of p-p scattering, it has been shown[6] that, at angles near 45° cm, $|P-e|$ is maximum and of the same order of magnitude as the ratio between the coefficients of the two parts of the scattering matrix which are noninvariant and invariant, respectively, under time reversal. It has been estimated that in strong interactions, present experimental data set an upper limit of 10–20% to the relative strength of forces which are noninvariant with respect to time reversal.[7]

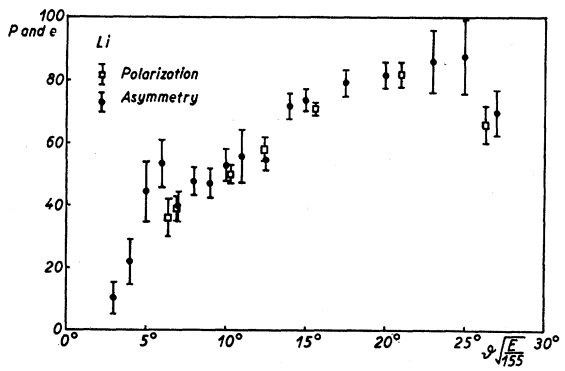

FIG. 1. Asymmetry (energy 155 Mev, angular resolution 0.6°) and polarization (energy 180 Mev, angular resolution 0.6°) for lithium.

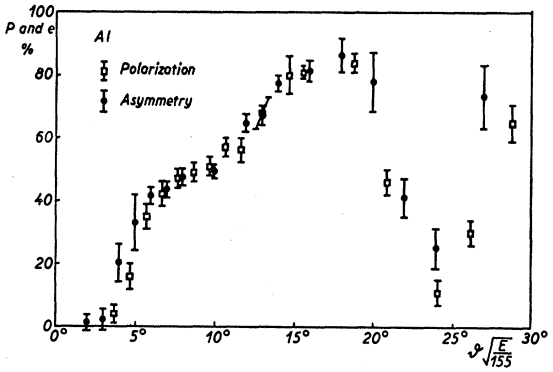

FIG. 2. Asymmetry (energy 155 Mev, angular resolution 0.5° for $\vartheta \geqslant 6°$; 0.9° elsewhere) and polarization (below 15°; energy 156 Mev, angular resolution 1.0°; above 15°; energy 175 Mev, angular resolution 1.3°) for aluminum.

We have compared e and P for hydrogen, lithium, beryllium, and aluminum, chosen for their high spin-to-mass ratios, since a failure of $e=P$ in spin-zero nuclei would necessarily violate parity conservation.[5] No measurements of P have previously been performed for these elements. Values of e are available near our energy only for hydrogen. We have measured P for hydrogen, P and e separately for lithium and aluminum, and e/P for beryllium and aluminum, using the unpolarized 185-Mev external beam of the Uppsala synchrocyclotron. All the measurements of e and e/P were made with the range equipment of Alphonce, Johansson, and Tibell,[8] and those of P with the analyzer magnet setup described by Hillman, Johansson, and Tyrén.[9]

The values of e/P for beryllium and aluminum were determined in the standard double-scattering arrangement at one angle only, 14.2° in the lab system, by interchanging first and second targets, one of which was always carbon. All targets were 15 Mev thick, and a first-order correction was made for the energy degradation by having the second scattering take place at $(177.5/162.5)^{\frac{1}{4}}\times 14.2°=14.8°$. In one case the measured asymmetry is $\epsilon_1=P_C e_\nu$ and in the other $\epsilon_2=P_\nu e_C$, where ν stands for either Be or Al. However, carbon has spin zero, so if parity is conserved $e_C=P_C$, and so $\epsilon_1/\epsilon_2=e_\nu/P_\nu$.

The values of P for hydrogen were measured with polyethylene, but the good energy resolution of the magnet used meant that the subtraction was less than 10%. In the cases of lithium and aluminum, some inelastically scattered particles were included in both the e and, to a lesser extent, the P experiment, but the spectra measured by Tyrén and Maris[10] indicate that these contributions may be not more than a few percent, at least at the smaller angles.

The results for lithium and aluminum are given in Figs. 1 and 2. The errors shown are statistical standard

TABLE I. The polarization in p-p scattering compared with an interpolation among available asymmetry data.

Scattering angle cm	Angular resolution cm	Mean lab energy	Target thickness	P measured	e interpol.	$P-e$
30.9	1.4°	176 Mev	19 Mev	0.264±0.014	0.257±0.018	0.007±0.023
50.0°	1.2°	179 Mev	12 Mev	0.276±0.013	0.265±0.018	0.011±0.022

deviations, and do not include errors in e of about 2% due to uncertainty in the beam polarization, and in P of about 0.05 because of the uncertain analyzing power. These errors are to some extent correlated, thus reducing the error in $|e-P|$.

The values of e/P for beryllium and aluminum were

$$e_{\mathrm{Be}}/P_{\mathrm{Be}}=1.005\pm0.024, \quad e_{\mathrm{Al}}/P_{\mathrm{Al}}=1.047\pm0.019,$$

where the errors quoted are of purely statistical origin, and the systematic errors of the measurement should be small.

Table I gives the results of P for hydrogen together with values of e estimated by interpolation among available data at 130, 170, and 210 Mev,[11] at 142 Mev,[12] and at 148 Mev.[13] The errors on P are statistical standard deviations. The absolute error is thought to be less than about 0.01 due to special care taken in determining the analyzing power for these measurements.

The only significantly positive results appear for aluminum. However, we attribute the small difference between e and P near 6° to the thicker target in the P experiment causing a larger contribution of multiple scattering, and that near 25° to the energy difference and to the larger fraction of inelastic scattering included in the e experiment. The energy difference between the two scatterings might also explain the small deviation of $e_{\mathrm{Al}}/P_{\mathrm{Al}}$ from unity.

With respect to complex nuclei, one should note that even in inelastic scattering, where the two experimental situations are evidently not time reversals of each other, no differences between e and P have so far been observed,[9] which is equivalent to the absence of an asymmetry in any spin-flip scattering[14]; and the mechanism responsible, such as a scattering without spin flip, might also be present in elastic scattering.

It can be seen that the measurements are all based on the assumption that $e=P$ for carbon, so that a positive result could have been attributed to a failure of time-reversal invariance *and* parity conservation in carbon. If any positive result had been observed, it would have been possible to have checked whether or not it originated in the failure of parity conservation, by experiments of the type suggested by Bell and Mandl.[4]

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