relevant if diquarks are to serve as a fusion catalyst.[19]

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[14]This will be true, of course, if $T_c \leq \Lambda$.

[15]If $g \geq 1$, tunneling becomes important, and the result is approximately the same as for $g = 1$.

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Upper Limit for *T*-Invariance Violation in Elastic *pp* Scattering

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A model-independent upper limit on the time-reversal-invariance (TRI) violating amplitude in elastic pp scattering based on a direct experimental reconstruction of the scattering matrix is presented. This analysis is made possible by a set of sixteen polarization parameters measured at the Swiss Institute for Nuclear Research for 579-MeV elastic pp scattering at six center-of-mass angles between 66° and 86°. Less than 1% is found for the fraction of TRI-violating cross section.

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Since the discovery of time-reversal-invariance (TRI) violation in the weak decay of the long-lived neutral kaon,[1] no further evidence of TRI violation in other processes has been found. In the electromagnetic interactions, measurements of the neutron electric dipole moment[2] have shown no violation to a level of about 0.03%, and until recently, tests of detailed balance and polarization experiments[3] in the strong interactions have found agreement with TRI to within about 0.3%. In the past year however, this latter evidence has come under question and much discussion has arisen over the possibility of a violation of TRI in the nuclear interaction. In particular, Conzett et al.[4] have reported the observation of a large difference between the polarization P measured in the nuclear reactions ^{7}Li(^{3}He, p)^{9}Be and ^{9}Be(^{3}He, p)^{11}B at 14-MeV lab energy and the analyzing power A measured in the corresponding inverse reactions. Since TRI requires the equality of P and A, these authors have concluded that TRI is broken in some component of the nuclear interaction. To further strengthen this conclusion, these authors have also examined previous $P-A$ comparisons and found them not to be as sensitive as originally thought. Indeed, the most accurate tests, made on elastic p^3He and p^{13}C scattering, were carried out in a region where $P-A \simeq 0$ even if TRI is not valid. This evidence, of course, stimulates a new interest in testing TRI in the nucleon-nucleon interaction. For indeed, if the effects in nuclear reactions are real and as large as implied, one should expect to also observe a violation in the interaction between the elementary constituents of nuclei.

In a recent paper,[5] we reported the results of a direct experimental reconstruction of the pp elastic scattering matrix at 579 MeV using a set of fifteen complex polarization parameters which we measured at the Swiss Institute for Nuclear Research with the assumption of invariance of the matrix under parity and time reversal. We found these measurements to be more than enough for a complete determination of the resulting five complex amplitudes. In light of the current controversy, it is interesting to ask if this data set would also allow a reconstruction of the more general scattering matrix where TRI is not imposed. In this form, the matrix would contain an additional sixth complex T-noninvariant amplitude. An experimental reconstruction of this amplitude would be of great interest as it would provide direct information concerning any TRI violation in the nucleon-nucleon interaction, information which is not directly accessible in experiments of the $P-A$ type or those testing the relation[6] $\tan\theta_{\rm lab}=(A+R')/(A'-R)$ where only a mixture of T invariant and noninvariant amplitudes can be measured. We have found, in fact, that such a reconstruction is possible, i.e., our set of fifteen polarization measurements, together with the differential cross section and the asymmetry A, is also sufficient to form a "complete" experiment[7] for the determination of six complex amplitudes. In this Letter, we report the results of such an analysis.

If TRI is no longer assumed, the usual elastic scattering matrix for identical spin-$\frac{1}{2}$ particles[8] takes on the new form[9]

$$M(E,\theta)=\{(a+b)+(a-b)(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n})+(c+d)(\vec{\sigma}_1\cdot\hat{m})(\vec{\sigma}_2\cdot\hat{m})$$
$$+(c-d)(\vec{\sigma}_1\cdot\hat{1})(\vec{\sigma}_2\cdot\hat{1})+e(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\hat{n}+m[(\vec{\sigma}_1\cdot\hat{1})(\vec{\sigma}_2\cdot\hat{m})+(\vec{\sigma}_1\cdot\hat{m})(\vec{\sigma}_2\cdot\hat{1})]\}/2,$$

where a TRI-violating amplitude, m, is added to the usual T-invariant amplitudes, a, b, c, d, and e. These variables parametrize the scattering matrix and are functions of reaction energy E and scattering angle θ. The expressions for the pp scattering observables which are functions of these amplitudes are also modified. In particular, m now distinguishes P from A. For comparison, the recalculated expressions for these quantities and the other examples presented in Ref. 5 are given below

$$\sigma=(|a|^2+|b|^2+|c|^2+|d|^2+|e|^2+|m|^2)/2,$$
$$A=A_{00n0}=A_{000n}=[\mathrm{Re}(a^*e)+\mathrm{Im}(d^*m)]/\sigma,$$
$$P=P_{n000}=P_{0n00}=[\mathrm{Re}(a^*e)-\mathrm{Im}(d^*m)]/\sigma,$$
$$D_{w0s0}=[\mathrm{Re}(a^*b)\cos(\alpha+\theta/2)+\mathrm{Re}(c^*d)\cos(\alpha-\theta/2)-\mathrm{Re}(c^*m)\sin(\alpha-\theta/2)-\mathrm{Im}(b^*e)\sin(\alpha+\theta/2)]/\sigma\ .$$

Since our data were originally taken without the possibility of TRI violation in mind, it was necessary in this analysis to carefully reexamine them for instances where an assumption of TRI might have been used in their extraction. Thus, data for the polarization P which were actually measured as polarizations, for example, were carefully distinguished from data which were measured as asymmetries (the parameter A). The only unremedied case was in the original calibration of our polarized beam[10] where the assumption $P=A$ was used. This did not prove to be as crucial as one might expect, however, as will be shown later.

With the distinction between P and A, the num-

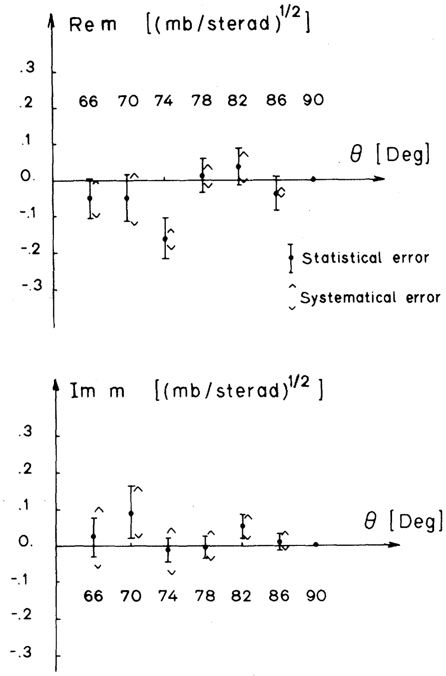

FIG. 1. Re(m) and Im(m) with statistical and systematic errors.

ber of parameters in our data set increased to sixteen. To this we added the unpolarized differential cross section, taken from the Geneva-Saclay phase shift,[11] to make a total of seventeen parameters. A minimum-χ^2 fit of a, b, c, d, e, and m to these data was then performed separately for each of the six angles between 66° and 86° at which the data were measured. The 90° c.m. angle was excluded in this analysis since $m(90°) = 0$ under the Pauli principle. The overall undetermined phase for the six amplitudes was fixed by taking the amplitude e as real and positive. The results of the fit are shown in Fig. 1 and Table I. It is interesting to note that Im(m) was very well determined in this fit even without the use of the data for A. In contrast, however, the real part Re(m) needed both P and A. The solutions for the usual TRI amplitudes a, b, c, d, and e were found to be essentially the same as those in Ref. 5, where TRI was assumed, but with somewhat larger errors. The χ^2 per degree of freedom, averaged over all six angles, was equal to 0.90 in this fit as compared to 0.93 in the fit of Ref. 5 (with the 90° point excluded).

The influence of the systematic uncertainties in our measured observables was also investigated in some detail. Uncertainties in the normalizations of A and P were found to have an important effect on both Re(m) and Im(m), whereas uncertainties on the target polarizations only affected Im(m). Relative systematic errors of 3% on A, 3% on P, and 5% on the target polarization were estimated and used in calculating the systematic errors for Re(m) and Im(m) shown in Fig. 1 and Table I. To study the effect of the beam polarization, where the equality $P = A$ was assumed in its calibration, an additional hypothetical error of 10% relative was assumed for the ratio A/P. Very little increase was observed in the subsequent error on m, indicating no further loss in the precision of the reconstruction. This was due to the tight constraint imposed by the overdetermination of the system. Thus, any uncertainty in the beam calibration is already largely contained in our systematic error estimation.

To set an upper limit on TRI violation, the quantity $|m|^2$ was used. These values are displayed in Fig. 2 and given in Table II. With the assumption of a normal distribution for the statistical errors on Re(m) and Im(m) (which were found to be uncorrelated), the statistical distribution for $|m|^2$ was calculated with use of a Monte Carlo technique.[12] Systematic errors were also entered into this calculation by assuming them to be distributed normally but independent of the statisti-

TABLE I. Numerical values for Re(m) and Im(m) and their errors.

$\theta_{\text{c.m.}}$ [deg]	Re (m) [(mb/sr)$^{1/2}$]	σ_{stat}	σ_{syst}	Im (m)	σ_{stat}	σ_{syst}
66	−0.048	0.053	0.050	0.024	0.054	0.080
70	−0.051	0.065	0.070	0.091	0.072	0.070
74	−0.160	0.055	0.025	−0.012	0.032	0.060
78	0.011	0.047	0.030	−0.003	0.030	0.040
82	0.035	0.051	0.040	0.055	0.031	0.030
86	−0.036	0.048	0.010	0.015	0.027	0.025

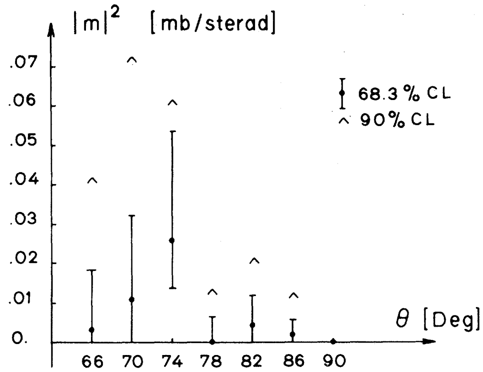

FIG. 2. $|m|^2$ with error intervals corresponding to 68% and 90% confidence levels.

cal errors. The correlation between Re(m) and Im(m) for the systematic errors was also taken into account. At each angle, the value of $|m|^2$ corresponding to a 90% confidence level was then determined by using these distributions. An upper limit on the fraction of TRI-violating cross section, i.e., the ratio of $|m|^2$ to the differential cross section,

$$\tfrac{1}{2}|m|^2/\sigma = |m|^2/(|a|^2+|b|^2+|c|^2+|d|^2+|e|^2+|m|^2)$$

could then be calculated. These limits are given in Table II. The results show no violation of TRI in pp scattering larger than about 1% at any angle. This would appear to be consistent with the validity of TRI and also confirm our original analysis in Ref. 5.

Although the limits given here are larger than those found in some previous tests,[3] such as detailed-balance experiments or those mentioned earlier, it should be noted that these latter experiments have had to rely on additional theoretical calculations in order to be able to untangle the mixture of T conserving and nonconserving amplitudes which are measured. For this reason, these previous results have come under some question. In contrast, our direct reconstruction of the TRI-violating amplitude in pp scattering requires no theoretical input, other than general assumptions concerning the scattering matrix, and provides the first truly model-independent upper limit on time-reversal invariance in strong interactions.

TABLE II. $|m|^2$, its upper limit, and corresponding fraction of TRI-violating cross section.

$\theta_{c.m.}$ [deg]	$\|m\|^2$ [mb/sr]	Upper limit 90% C.L.	$\|m\|^2/\Sigma_{i=1}^{6}\|a_i\|^2$ 90% C.L.
66	0.0029	0.042	0.63
70	0.0109	0.073	1.14
74	0.0257	0.061	1.00
78	0.0001	0.013	0.22
82	0.0043	0.021	0.36
86	0.0015	0.012	0.21

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