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Method for measurements of absolute analyzing powers in nuclear reactions

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A method is proposed to provide an absolute calibration of analyzing powers for spin-$\frac{1}{2}$ particles. The method makes use of elastic scattering of a polarized beam from a spin-zero target at an angle where the analyzing power is large. In this case the polarization of the scattered beam is nearly complete and very accurately known. A measurement of the left-right asymmetry in a second scattering or reaction determines the analyzing power of the second process to an accuracy much below 0.005.

Impressive precision in polarization measurements allowing detection of very small effects has been achieved in nuclear physics experiments. This has been demonstrated, for example, in studies of parity nonconservation in the nucleon-nucleon interaction, where the most accurate measurements[1] yielded a longitudinal analyzing power of $A_z = (1.5 \pm 0.2) \times 10^{-7}$ for proton-proton scattering at 50 MeV. Although the accuracy of these experiments is magnificent, they did not yet reach the level where the uncertainty of the beam polarization determines the overall error of the final result. On the other hand, there are measurements detecting much larger effects, where an absolute precision in monitoring the beam polarization to a level well below 0.01 is desirable. In a recently completed study of the transverse (parity conserving) analyzing power A_y in proton-proton scattering[2] at 50 MeV, an accuracy $\Delta A_y = 1.5 \times 10^{-4}$ was achieved for angles in the vicinity of the maximum of the analyzing power A_y, where A_y reaches the value of 0.03. The impact of these new precise data on phase shift analyses and potential models of the nucleon-nucleon interaction could be greatly enhanced by a more precise determination of the scale uncertainty of the data set. Present data restrict this uncertainty to about 2%. In most experiments, including this one, the polarization of the beam is monitored by scattering from a target with a high analyzing power upstream or downstream from the main experimental setup. Therefore the uncertainty of this analyzing power is reflected in the absolute uncertainties of the measured polarization observables.

In this Rapid Communication we discuss a new method of measuring absolute analyzing powers in a single-stage double scattering experiment. In this new scheme, scattering of spin-$\frac{1}{2}$ particles from a spinless target T_1 with high analyzing power is used to produce a highly polarized secondary beam. The method is general in the sense that such a secondary beam, with *nearly complete* polarization, can then be used to measure analyzing powers with a high absolute precision in *any* scattering or reaction taking place at the second target T_2 [Fig. 1(a)].

For scattering of spin-$\frac{1}{2}$ particles from a spin-zero target, where no depolarization occurs, the polarization of the scattered beam is given by[3]

$$p_2 = \frac{p_1 + A_1}{1 + p_1 A_1},$$

where p_1 is the polarization of the primary beam and A_1 is the effective analyzing power of the scattering. Taking representative values for the beam polarization and the analyzing power, $p_1 = 0.90$ and $A_1 = 0.90$ (e.g., scattering

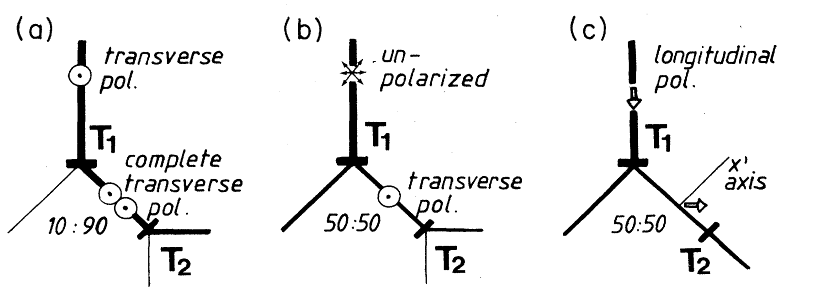

FIG. 1. Schematic representation of three methods used to measure absolute analyzing powers in double scattering experiments: (a) the proposed method; analyzing power of the second scattering is measured; (b) the method with unpolarized beam; (c) spin transfer coefficient, $K_2^{x'}$, method. Left-right detectors are used in methods (a) and (b), while up-down detectors analyze the polarization component along x' axis in method (c). Intensity ratios of the secondary beam scattered to the left and right from the target T_1 are indicated. In all cases a left-right symmetric arrangement with respect to the primary beam axis can be used.

of protons at a suitable angle), the polarization of the scattered beam is very high ($p_2=0.994$). The essential point is that the error of this polarization is very small, even if p_1 and A_1 are not known to a high precision. With the assumptions given above, a typical uncertainty of $\Delta A_1=0.02$ (or a variation of the primary polarization $\Delta p_1=0.02$) results in an error of the polarization of only $\Delta p_2=0.001$. Therefore, even crude knowledge of the analyzing power A_1 (available from the present standards) yields a very accurate value of the polarization of the scattered beam. Such a secondary beam with polarization of almost 100% and a very small uncertainty may be used in a direct determination of the absolute analyzing power A_2 of a subsequent reaction by measuring its left-right asymmetry. With a high analyzing power $|A_2| \gtrsim 0.9$ (usually of practical interest) an error on the order of a few times 10^{-3} may be achieved with modest requirements on the geometrical accuracy of the detection system, internal efficiencies of the detectors, and other systematic errors. Usual precautions such as exchanging left and right detectors can be applied in order to reduce most of these errors significantly.

The two most commonly used analyzers of the proton polarization, ^{4}He and ^{12}C, are very suitable for the production target T_1. They offer high analyzing powers in a very broad energy range[4,5] from ten to a few hundred MeV at forward angles where the cross section is large. At low energies, up to 40 MeV, a ^{4}He polarizer is more effective, while at higher energies ^{12}C has more advantages. Both targets yield a clean secondary beam which is not contaminated by spurious reactions. Neglecting kinematic and straggling effects, the secondary beam is monoenergetic for scattering of low-energy protons from ^{4}He. In the case of ^{12}C, elastically scattered protons are separated by approximately 4 MeV from inelastically scattered protons which have different and, in general, lower polarization. The conditions imposed by the first scattering on the energy resolution of the detection system are therefore very favorable.

For most nuclear scatterings or reactions, the necessary energy resolution will be determined by the process under study in the second scattering and not by background contaminations in the secondary beam. In addition to high cross sections for the first scattering, an intense polarized beam from the accelerator is necessary to make experiments of high statistical precision feasible. Recent progress in ion source technology has resulted in the acceleration of 90% polarized proton beams to an energy of a few tens of MeV with intensities up to 5 μA at the target,[1,2] which can make double scattering calibration experiments with polarized beams superior compared to measurements with unpolarized beams.

In the following, we compare the new method with established procedures to illustrate its advantages and drawbacks. Two methods of measuring absolute polarization standards for polarized protons have often been used in the past. Both of them use a double scattering technique. However, in order to achieve high absolute accuracy each method requires two separate measurements.

In the first method[6] a double scattering experiment with an unpolarized beam is combined with an experiment with a polarized beam. The idea of this experiment is shown in Fig. 1(b). An unpolarized beam scattered from the first target produces a polarized secondary beam with polarization p_2 equal to the analyzing power of the first scattering A_1 (time reversal invariance, $p=A$ theorem). The measured left-right asymmetry of the second scattering is therefore $\epsilon=p_2A_2=A_1A_2$. If both scatterings would occur at the same energy ($A_1=A_2=A_y$), this measurement would yield the analyzing power $A_y=\sqrt{\epsilon}$. However, for two established analyzers of the proton polarization (^{4}He and ^{12}C), the recoil effects are clearly nonnegligible and the measurement discussed above must be supplemented by a second experiment with a polarized beam in which the ratio of two analyzing powers $A_2/A_1=\epsilon_2/\epsilon_1$ is measured. In the latter experiment an energy degrader between the two scatterings must be used. Obviously this method is sensitive to systematic errors associated with the energy loss and straggling in the process of slowing down the beam particles.

The second method[7] [see Fig. 1(c)] relies on the quadratic relation between analyzing power and polarization transfer coefficients $K_x^{x'}$ and $K_z^{x'}$: $A_y^2+K_x^{x'2}+K_z^{x'2}=1$. For an energy and an angle where A_y is large, the necessary precision of the polarization transfer coefficients is not as high as the desired precision of the analyzing power A_y. However, the requirements are still rather stringent. For $A_y=0.900\pm0.003$, an acceptable error in the K coefficients amounts to $\Delta K \approx 0.006$. A measurement of polarization transfer coefficients to this precision is a very difficult task. Clearly, this method loses its power very fast when A_y deviates even slightly from its maximum value of one. Moreover, as in the first method, one encounters problems in measuring the polarization of the incoming and outgoing beam at two different energies. Additionally, the direction of the spin of the incident beam must be precisely controlled (approximately to $\pm1°$ for the errors quoted above) in order to keep systematic errors low.

From the point of view of counting statistics the proposed method is superior in comparison to the others discussed. We present briefly estimates of the relative rates for the experiments considered here, assuming $A_1=A_2=p_1=0.9$, identical geometrical conditions, the same beam current, and a final error of the extracted analyzing power $\Delta A_y=0.003$. As discussed above, the first assumption is representative, e.g., for proton-carbon scattering in a very broad energy range.[5] There are two reasons which make the new method statistically superior. First, the secondary beam is almost completely polarized, so the asymmetry measured in the second scattering is large, and therefore, in general fewer counts are needed in order to achieve a given error in A_y. (We note that the error in the asymmetry $\epsilon=(N_L-N_R)/(N_L+N_R)$ is $\Delta\epsilon=2(N_L\times N_R)^{1/2}/[(N_L+N_R)^3]^{1/2}$ and therefore the total number of counts required is $N_L+N_R=(1-\epsilon^2)/(\Delta\epsilon)^2$.) We illustrate this point using the example of a "spin-rotation" experiment. Assuming equal polarization transfer coefficients, we obtain $K_x^{x'}=K_z^{x'}=0.308\pm0.006$. The asymmetry expected in the second scattering used as an analyzer of the "rotated" polarization amounts to 0.250 ± 0.005. The total number of counts required for both spin-rotation experiments together is therefore approximately 3.5 times bigger than for the proposed "100% polarized beam" experiment. The second advantage is that due to the high analyzing power of the first scattering, the beam impinging on the second target in the proposed method is almost by a factor of 2 more intense than corresponding beams in the two other experiments. One has to bear in mind, however, that this advantage can be offset by the higher intensity of the current available from most accelerators, in the case of experiments with unpolarized beams in which accidental background does not pose a problem.

The three types of experiments discussed above are also sensitive to different systematic errors. The main difficulties of the "unpolarized beam" and spin-rotation type of experiments lie in setting up two different experiments, using energy degraders, monitoring the incoming beam polarization to a high accuracy, and finally propagating all these errors into the final error of A_y. The proposed method is fairly insensitive to the uncertainties in the polarization of the primary beam. Rather, it is sensitive to the background radiation, especially on the low counting rate side of the double scattering polarimeter. We stress, however, that the requirements for clean detection of good events are not tremendous compared to the other procedures; for our assumptions the background rejection in the new scheme must be only by a factor of 2 better than in the unpolarized beam method in order to get comparable quality of the double scattering measurements.

The proposed method combines the high polarization of a primary beam with the high analyzing power in a scattering process to produce a secondary beam with nearly complete polarization. We point out, that in an analogous way it is possible, by using two reactions, both having a high analyzing power A_1 and A_2, to construct a polarimeter with an extremely high and very accurately known analyzing power ("superanalyzer"). Assuming again 0.9 for A_1 and A_2, the resulting analyzing power is

$$A=\frac{A_1+A_2}{1+A_1A_2}\approx 0.994\,,$$

and its value again does *not* depend strongly on the exact values of A_1 and A_2. Obviously, such a "superanalyzer" could be used in a standard way to determine the polarization of a primary beam, and subsequently the polarization data of other reactions with a high absolute precision.

In conclusion, we proposed a simple and very transparent procedure to measure absolute analyzing powers in a single-stage double scattering experiment. Using a polarized beam and a first scattering with a high analyzing power, a secondary beam with nearly complete and very accurately known polarization is obtained. A measurement of the left-right asymmetry in the second scattering or reaction yields the analyzing power of that process. The proposed method is very general. Analyzing powers of *any* scattering or reaction can be absolutely measured in a broad energy range of ten to a few hundred MeV. Their values can then be used for calibration of polarimeters and monitoring the polarization of the beam from an accelerator. Accuracies of 0.001–0.005 can be achieved with a modest effort. This is up to an order of magnitude better than the best standards available at present for polarized proton beams. An experiment along these lines,[8] using a 50-MeV proton beam, is in progress at Paul Scherrer Institute [formerly Swiss Institute for Nuclear Research (SIN)]. The results of this experiment will be reported soon in a separate publication together with a detailed discussion of all systematic errors.

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