PROCEEDINGS OF SCIENCE

Proposed experimental study of wave-particle duality in p,p scattering

---

Richard M Talman[*]

Laboratory for Elementary Particle Physics
Cornell University, Ithaca, NY, USA

E-mail: richard.talman@cornell.edu

Of all nuclear physics experiments none are more fundamental than "elastic" p, p and, secondarily, p, d or d, d scattering. Recognizing that these particles are themselves composite, "elastic" scattering may be accompanied by temporary internal rearrangement with undetectably small energy loss. This paper argues that correct calculation of the spin dependence of p, p (and other charged particle) elastic scattering, must account for a previously-neglected relativistic effect of "G", the anomalous magnetic dipole moment (MDM) of the scattering particles. The paper describes storage ring scattering configurations capable of confirming this contention. Especially important experimentally for protons is the existence of "perfect" (greater than 99%) proton-carbon scattering polarimetric analyzing power A at K=183.1 MeV laboratory kinetic energy and correspondingly high nearby. Possibilities: (i) In a storage ring collider with counter-circulating proton beams, each with energy up to K=200 MeV, the final spin states of coincident scattered protons can be determined with high probability for a significantly large fraction of all scatters, both prompt and delayed. For comparison with current descriptions based on proton scattering from a hydrogen target fixed in the laboratory, this corresponds roughly, to proton kinetic energy K=400 MeV in the laboratory frame, barely below the pion production threshold. (ii) In a "DERBENEV-style" figure-8 storage ring, independently polarized, diametrically opposite bunches on orthogonal orbits can collide at the beam crossover point with symmetric $K'' \approx 200$ MeV energies in a slow (transversely) moving frame. (iii) Alternalively, p and d beams can counter-circulate at the same time in a small racetrack shaped ring with superimposed electric and magnetic bending. In this case the scattering would be "WOLFENSTEIN-style", with collinear incident orbits (at the cost of significantly inferior polarimetry for the deuteron beam). To investigate the consistency of quantum mechanics and special relativity it is proposed to implement options (ii) and (iii) in the COSY beam hall.

19th Workshop on Polarized Sources, Targets and Polarimetry (PSTP2022),
26-30 September, 2022
Mainz, Germany

---

[*] Speaker

PoS(PSTP2022)039

1. Introduction

This paper is a companion to two published papers with related subject matter [1][2], and a planned paper on storage ring study of nuclear transmutation. An expanded version, including statistical analysis of the experiment, can be obtained at reference [3] .

As everybody knows, for laboratory kinetic energies up to approximately 100 MeV (at which point, as shown in Figure 1 (top left), the proton deBroglie wavelength is slightly greater than the proton diameter) the quantum (QM) and classical (CM) (i.e. Rutherford) descriptions of elastic p, p scattering agree splendidly. This agreement clearly could not, and does not continue beyond, say, 400 MeV, when pions begin to appear. The approximate match of deBroglie wavelength with proton size can scarcely be simple coincidence. It represents a nominal transition point from wave to particle description of p, p scattering, like the transition from geometric to wave optics. At higher energy π-mesons are needed to account for excess energy while conserving momentum at the local velocity. For correlation with, say, rainbows, refer to Van-de-Hulst[4]; a further empirical numerical factor, $\pi(m-1)$ of order 1, multiplying the diameter, is required, where m is the "index of refraction" of the nuclear medium. Since the failure is sudden, while the wavelength variation is smooth, one has to blame the discontinuous behavior either on spin or on new particle threshold, neither of which Rutherford had anticipated.

For present purposes this justifies modest extrapolation, using classical Hamilton-Jacobi theory, while continuing to treat "particles" as particles, rather than as waves, at least for purposes of approximate description. This is illustrated in Fig. 1(top right), which shows a sequence of prompt eikonal trajecories up to the point where subsequent trajectories are captured into a still mysterious compound nucleus. As in accelerator injection, filamentation evades violation of Liouville's theorem. By the fourth sector it has become ambiguous (classically) or probabilistic (quantum mechanically) whether a particle is detectable immediately or has been "mutually captured" by the other nucleus. Semicircular arrows indicate the sense of azimuthal advance (which is necessarily opposite for the two scattering particles. The epoch represented begins just before and ends just after the actual collision. Inset graphs show horizontal plane quadrants, viewed (for example) from above; the shadings represent the sequencing of events. Individual orbits can be labeled by "azimuthal time", with one "typical" prompt orbit shown in each of the first three quadrants after the collision. For Newtonian description this represents the complete story. For QM the subsequent evolution remains predictable, but only in a statistical sense—for example, a fourth scatter may, or may not, result in an event in the fourth quadrant. Rest mass appears to be transformed tempoarily into rotational energy during the "prompt" phase; then back again during compound nucleus decay.

An intuitively attractive way of merging these conflicting theoretical pictures is to segregate scattering events temporally into "prompt" and "delayed" categories, with the expectation that the prompt events are well described by both CM and QM, while "delayed" events require QM. One visualizes "prompt events", for which classical physics provides definitive (but eventually incorrect) results, and "delayed events" for which quantum mechanics QM is required. QM (i.e. wave mechanics (WM) at quantum, nuclear or atomic length scale) has the more challenging task of providing "long term" description of nuclear scattering, elastic plus inelastic which can, however, only be probabilistic. Resonance, Heisenberg time uncertainty, and barrier penetration go hand in hand during the delayed phase.

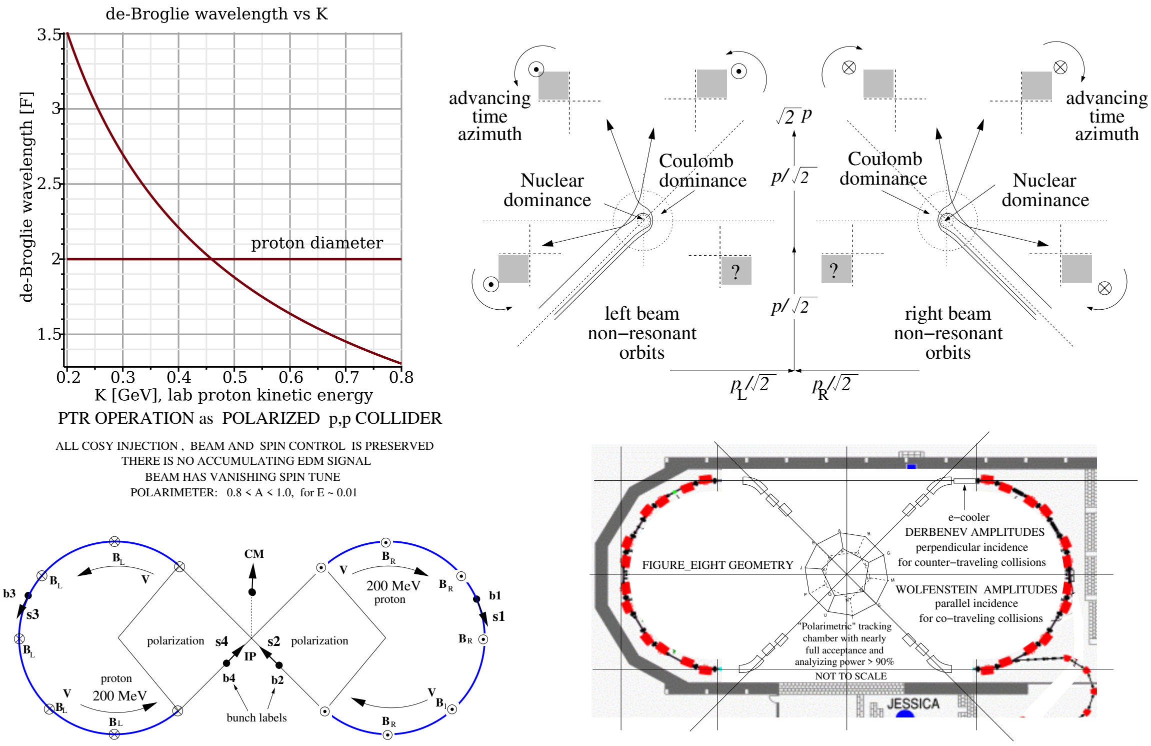


Figure 1: Top Left: DeBroglie wavelength[fm] of an incident proton versus its total laboratory kinetic energy. **Top Right:** "Prompt" classical orbits (or Hamilton-Jacobi "wave eikonal curves") representing a sequence of three particles (or wave packets) sequentially following the mutual scattering of a pair of protons, one from each beam, one into each of three azimuthally (in a periodic angular sense) advancing sectors. **Bottom Left:** Skeleton design plan for a 200 MeV (kinetic, laboratory) energy polarized p, p figure-eight collider. Both incident beam spins states at the collision intersection point (IP) can be pure, and scattered particle momenta and polarizations are measured with analyzing power in excess of, say, 0.7 analyzing power as each proton slows through 183 MeV energy, for which $A = 1$. **Bottom Right:** COSY semicircular arcs are preserved exactly as at present, but powered oppositely to account for the reversed bending.

It has long ago been shown experimentally that QM subsumes (beyond a reasonable doubt) the correct classical description of low energy Rutherford scattering. What remains to be investigated experimentally is the degree to which the segregation into "prompt" and "delayed" categories is useful. For prompt behavior, one expects agreement with high probability between deterministic classical treatment and probabilistic quantum mechanical treatment. On longer time scales, especially in the light of barrier penetration by "tunneling" and new particle production, one can only expect theory to produce a probabilistic description of the subsequent evolution[5].

The purpose of the proposed experiment, starting from proton beams in pure spin states, is to study experimentally spin correlations of the eventual decay back into elastically scattered, polarized protons. The paper concentrates on the detection, in a colliding beam storage ring, of coincident scattered protons coming to rest in graphite polarimeter chambers which provide nearly full directional coverage. This makes it practical to test the quantum mechanical description of low energy nuclear physics with unprecedented sensitivity. The polarization of every proton scattered at the IP, and scattered again in one of the near crystalline graphite foil (or construction grade graphene) plates of the detection chamber, will have been determined with unprecedented accuracy, irrespective of scattered proton direction. This will provide high quality positive elastic signature for every elastic scatter. The total stopping ranges of most protons, including weakly inelastic scatters, will be used to reject inelastic scatters. See Table 1 .

With such cleanly matched pairs of elastic scatters, the comparison of time-forward and (effectively) time-reversed scatters can be performed with unprecedented accuracy on an event by event basis. For example, the equality of scattering probability P and analyzing power A (as required to be equal by time reversal symmetry) can be checked for matched pairs of protons. Furthermore, (with sufficient incident spin orientation control) by altering the incident pure polarization states, the reversed-time version of any observed forward-time scatter can be re-created. In other words, truly forward-time and backward-time scatters can be compared.

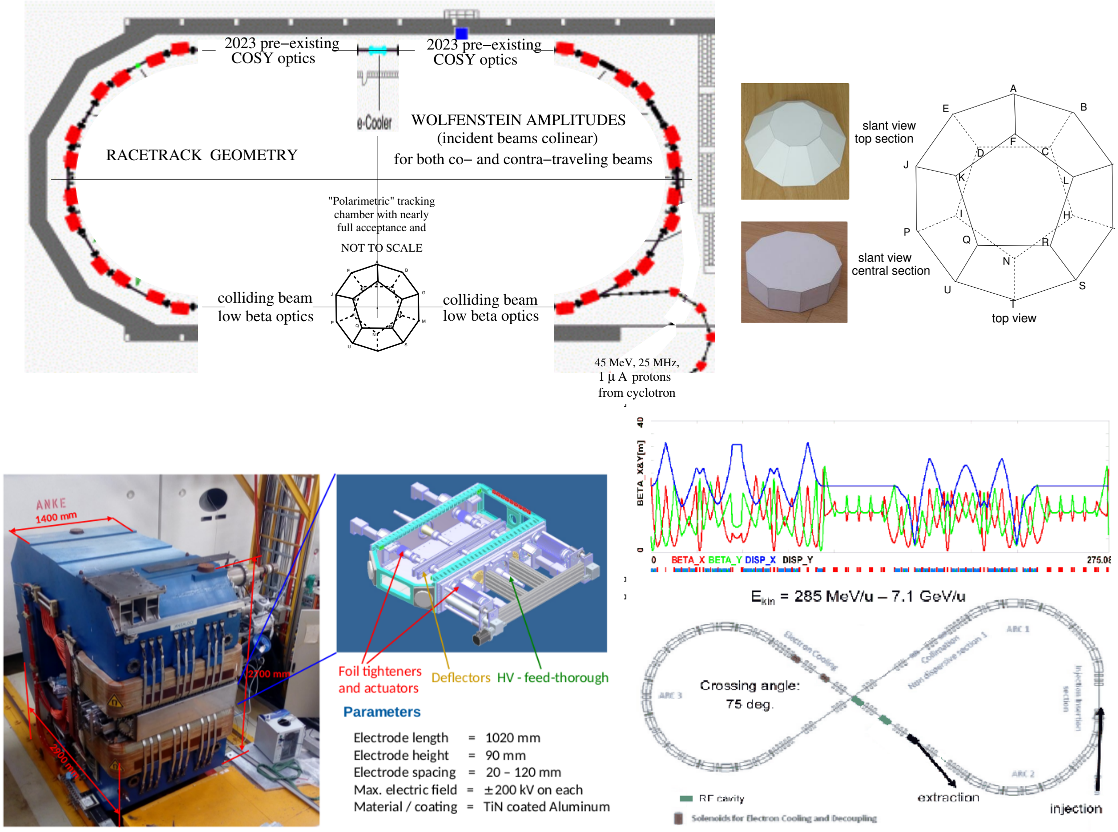
This paper concentrates on testing experimentally the quantum mechanical treatment of low energy nuclear physics, with special concentration on the role of nuclear spin in elastic scattering. This includes, for example, investigating the possibility that the entanglement of scattered protons be detected. Special attention is also paid, possibly for the first time, to the influence of the anomalous magnetic moment in p, p scattering.

2. Description of the proposed accelerator configuration

Several ring configurations need to be described. COSY is a low energy proton or deuteron storage ring in Juelich, Germany, whose days are numbered. Reference [7] is a detailed CERN yellow report, slightly pre-dating COVID, describing plans to upgrade COSY to measure (T-violating) proton EDM. This design is updated here. Two (mutually compatible) storage ring designs are described. One is race-track shaped, the other like a figure-8. These rings cannot operate at the same time, but interchanging configurations can be arranged to be routine. Together, they are more powerful than contemplated in Reference [7]. The circular arcs of the COSY ring are retained in place, common to both storage rings, and present COSY injection is retained. Along with invaluable personnel experience, roughly 2/3 of the value invested previously in COSY is retained unchanged.

Bottom left Figure 1 provides a skeleton view of a figure-eight storage ring for which a more detailed design is shown bottom right. We designate this configuration as DERBENEV who introduced figure-8 design based on spin considerations. Most significant for this configuration for present purposes is the fact that a single beam can "collide with itself" or, rather, that bunches separated by half the circumference collide at the crossing point, with orthogonal incident orbits. *This feature of* DERBENEV *configuration contrasts with all previous scattering configurations for which colliding bunch orbits are collinear.*

A second configuration, compatable with the first, referred to as WOLFENSTEIN racetrack, is shown upper left in Figure 2. Simultaneously counter-circulating beams (for example clockwise proton and counter-clockwise deuteron) beams are supported. This requires electric bending superimposed on the existing magnetic bending, as illustrated lower left in the same figure, which displays an insertion constructed by Grigoriev and others, whose purpose is to superimpose electric bending within every existing COSY bending magnet. It is this electric/magnetic superposition which will enable the simultaneous co- and counter-circulation of stored beams. This capability is required to implement item (iii) of the abstract. Lower right in the same figure shows the design for JLEIC-BOOSTER, the injector accelerator intended for the Jefferson Lab electron-ion collider. This figure-eight ring has roughly the same size as the DERBENEV ring described previously and serves comparable beam energies. The ring elements and lattice optics can be expected to be similar to the lattice functions shown.



Parameters

Electrode length = 1020 mm
Electrode height = 90 mm
Electrode spacing = 20 – 120 mm
Max. electric field = ±200 kV on each
Material / coating = TiN coated Aluminum

Figure 2: Top left: This figure shows COSY (as of 2022) after incorporation of the superimposed electric bending shown below left. The semicircular arcs are preserved exactly as at present, except the arc magnets are powered individually, to compensate appropriately for the superimposed electric bending. " Co-traveling bunches" (needed for resonant nuclear transmutation) have same sign, collinear incident momenta. "Counter-traveling bunches" (needed for p, d scattering) also have collinear incidence momenta. **Top right:** Artist's conceptions of almost full-acceptance tracking/stopping/polarimeter chambers at the intersection point. **Bottom left:** Grigoryev prototype electric field insert in COSY bending magnets for 200 MeV (kinetic, laboratory) energy operation of COSY with electric bending superimposed on existing magnetic bending. **Bottom right:** Lattice and lattice optics for the Jefferson Lab JLEIC figure-eight booster injector. The figure-eight lattice shape can exploit, but does not require, superimposed electric and magnetic bending.

3. Near perfect analyzing power

Circulating beam energies as great as 200 MeV are such that both elastically scattered proton laboratory energies are greater than 183.1 MeV for all elastic scattering events, briefly exceeding the energy at which the graphite analyzing power exceeds 99%, as established by von Przewoski, et al.[6]. As the protons slow down through 183.1 MeV; their polarizations will be detected by left/right (or up/down) scattering asymmetry with analyzing power greater than, say, 0.7 for an appreciable fraction of their full range. Graphite chamber thickness great enough to stop all of these scatters is easily achieved, irrespective of scattering angle. See Table 1.

K.E.	Stopping	Power, MeV cm^2/gm	$dK/d(\rho_0 l)$	range, $\rho_0 l$ gm/cm^2	20 col3/col4
MeV	electronic(e)	nuclear(n)	total(t)		n-prob.
20	2.331E+01	1.006E-02	2.332E+01	4.756E-01	0.00862
40	1.331E+01	5.221E-03	1.331E+01	1.662E+00	0.00784
60	9.642E+00	3.553E-03	9.645E+00	3.453E+00	0.00736
80	7.714E+00	2.703E-03	7.717E+00	5.786E+00	0.00700
100	6.518E+00	2.186E-03	6.520E+00	8.616E+00	0.00670
120	5.701E+00	1.838E-03	5.703E+00	1.190E+01	0.00644
140	5.107E+00	1.587E-03	5.109E+00	1.561E+01	0.00621
160	4.655E+00	1.398E-03	4.656E+00	1.971E+01	0.00600
180	4.299E+00	1.250E-03	4.301E+00	2.418E+01	0.00581
200	4.013E+00	1.130E-03	4.014E+00	2.900E+01	0.00563
sum					0.06761

Table 1: Stopping power for protons stopping in graphite, density 1.70 gm/cm^2. Column 6 gives the probability of nuclear scatter in the approximation that nuclear energy loss (in this energy range) is always negligible compared to electric energy loss. The binning error associated with wide kinetic energy bins is quite small because the probabilities vary slowly. Though the polarization detection efficiency E, is 7% percent, the analyzing power will exceed, say 70%, for perhaps an order of magnitude smaller efficiency.

4. Spin-flip T-violation detection

Anticipated data rate performance is based on calculated storage ring luminosity of 10 inverse millibarns per second, producing $N_0 = 2 \times 10^9$ clean scatters per (nominal) year. Of these events, a number $N_1 = 10^7$ will provide p-carbon polarimetry for one or other of the final state protons; we refer to these events as "silver-plated". Approximately $N_2 = 25,000$ "gold-plated" events will have both final state proton spins having been measured. These rates are tabulated in Table 2.

Note, however, that in a certain sense, irrespective of polarimetric inefficiency, the kinematics, including incident spin state averages, of every one of the $N_1 = 10^7$ single polarimetric-detected events will be theoretically predictable, based on existing experimental data. This assumes time-reversal symmetry, along with the expectation that time-reversal violation will occur only at perhaps the one percent level. From these data rates it is not obvious which class of events holds the best statistical power for detecting T-violation.

event class	symbol	formula	fraction	symbol	events/year
p, p scatter	N_0	1	1	N	2×10^9
single spin measured	N_1	$2/E$	2/400	N_1	1×10^7
both spins measured	N_2	$2/E^2$	2/400^2	N_2	0.25×10^5

Table 2: Anticipated event rates with increasing detection quality per nominal year running time for polarimetric detection efficiency $E = 1/400$.

Let us consider the experimental problem of detecting a correlation between initial and final spin amplitudes, on the one hand, and scattering directions on the other. Based on many historic experiments, experimentally measured cross sections have been parameterized to best fit, PCTC (P and T-conserving) theoretical production models. These distributions have been and can now be digitally reproduced with high accuracy by Monte-Carlo simulation, as parameterized by best fit partial wave expansion coefficients. One now speculates that, hidden in this data, is a PCTV, time-reversal violating contribution with differential cross section at perhaps the one percent level, which has so far evaded detection. We propose, therefore, to study the same process by direct measurement. This might be called “analog Monte-Carlo determination”. The reason we have to acknowledge the stochastic nature of the measurement, is that we have only beams with less than 100% polarization and polarimetry with less than 100 percent analyzing power.

A requirement of T-symmetry is that, if one spin flips, so also does the other. The PCTC (P-conserving, T-conserving) fit presumably satisfies a constraint N_u=$N_{\rm null}$ where $N_{\rm null}$ is the (dominant) theoretical rate, calculated from already-known “measured cross sections” with no apparatus equipment prejudice concerning the fractional contribution of T-violating or P-violating processes, but the theoretical expectation that these contributions have been smaller than some small value, such as one percent.

In our proposed experiment frozen-spin monochromatic protons in independently adjustable (almost) pure spin states collide, with both scattered particles stopping in nearly full-acceptance tracking chambers. Some will undergo nuclear scatters in the tracking chamber plates. The anticipated polarimetry is calculated to detect fractional T-violation at the 10^{-4} level, at least two orders of magnitude better than existing limits.

References

[1] R.M. Talman, *Superimposed Electric/Magnetic Dipole Moment Comparator Lattice Design,* ICFA Beam Dynamics Newsletter #82, Yunhai Cai, editor, 2021 JINST 16 P09006

[2] R. Talman, *Difference of measured proton and He3 EDMs: a reduced systematics test of T-reversal invariance,* arXiv:2205.10526v2 [physics.acc-ph], https://doi.org/10.1088/1748-0221/17/11/P11039

[3] R. Talman, *Proposed experimental study of wave-particle duality in p,p scattering*, https://arxiv.org/abs/2302.03557 .

[4] H. C. van-de-Hulst *Light Scattering by Small Particles,* Dover Publications, 1981 (originally, John Wiley and Sons, Inc. NY), 1957

[5] J. Gomez-Camacho, et al., *Time scales in nuclear structure and nuclear reactions of exotic nuclei,* Il Nuovo Cimento, 42, C, 2019

[6] B. von Przewoski, et al., *Absolute measurement of the p+p analyzing power at 183 MeV,* Phys. Rev, C, **44**, 1, p44, 1991

[7] CPEDM Group, *Storage ring to search for electric dipole moments of charged particles Feasibility study,* CERN Yellow Reports: Monographs, CERN-2021-003, 2021