Proton structure seen in a new light

New evidence of two-photon exchange could reconcile discrepant measurements of the proton's inner construction.

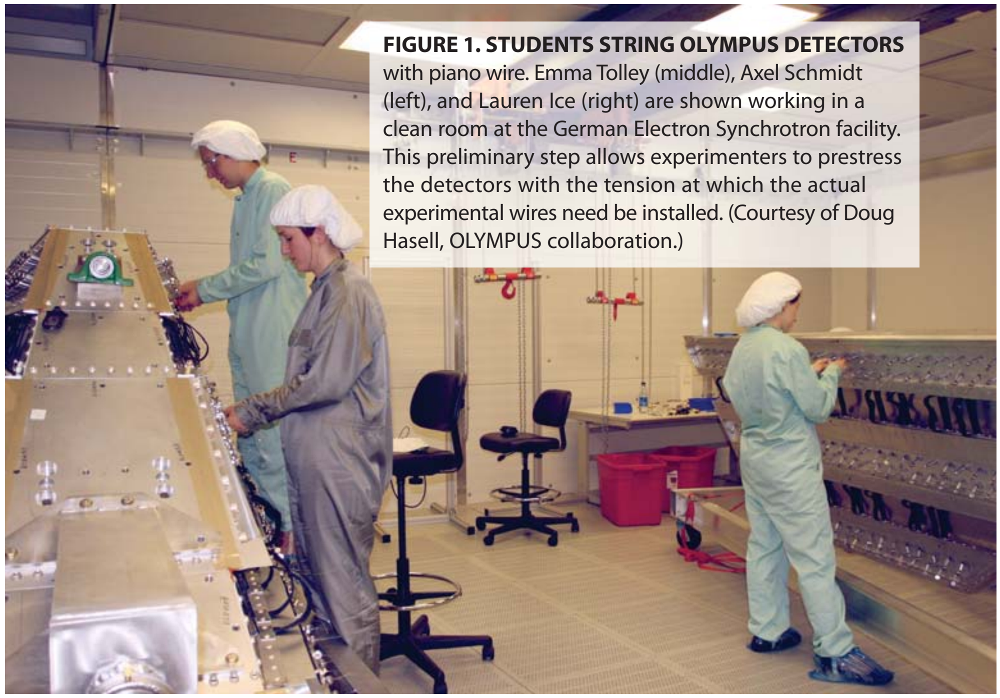

FIGURE 1. STUDENTS STRING OLYMPUS DETECTORS with piano wire. Emma Tolley (middle), Axel Schmidt (left), and Lauren Ice (right) are shown working in a clean room at the German Electron Synchrotron facility. This preliminary step allows experimenters to prestress the detectors with the tension at which the actual experimental wires need be installed. (Courtesy of Doug Hasell, OLYMPUS collaboration.)

The proton is not a point particle; nor is it an unvarying composite. Inside the proton are three valence quarks—two up quarks and one down quark—accompanied by massless gluons and a sea of other quarks that flit in and out of existence. Particle physicists characterize the proton's structure with so-called form factors. The two most significant of those relate to the charge- and magnetic-moment distributions in the proton. Their determination is important not just for describing the internal structure of the proton but also for understanding quark–gluon interactions within it and for interpreting experimental determinations of, for example, the proton radius.

The two form factors can be extracted from measurements of elastic scattering of unpolarized electrons off protons. Surprisingly, polarized-electron scattering experiments conducted about 15 years ago at the Thomas Jefferson National Accelerator Facility contradicted the apparently well-established results obtained earlier with unpolarized electrons.[1] Theorists soon proposed a reason for the observational mismatch: Interpretations of the experiments ignored processes in which the electron and proton exchange two virtual high-energy photons whose wavelengths are comparable to the scale of the proton's structure and whose interactions with the proton are therefore sensitive to that structure.

Two-photon exchange also comes into play when positrons scatter off protons. But because the charges of electrons and positrons are opposite, the relative sign of the one-photon- and two-photon-exchange contributions to the scattering amplitude is also opposite. The theoretical models that reconcile the discordant form-factor measurements predict that except for a small range of forward scattering angles, two-photon effects should cause the ratio of positron-to-electron scattering events to increase as the scattering angle and momentum transferred to the proton increase.

Several years ago, three collaborations endeavored to test that prediction. The findings of the CLAS experiment at Jefferson Lab and VEPP-3 experiment in Novosibirsk, Russia, were published two years ago.[2] The more definitive OLYMPUS results came out in March of this year.[3] All three experiments observed the general trend predicted by theory, and together they provide evidence that two-photon exchange is germane to understanding the previous measurements of proton form factors. The OLYMPUS experiment, however, garnered a sufficient quantity of precise data to generate tension with predictions of some theoretical models.

BLAST off

In the OLYMPUS experiment, an electron or positron beam passes through a 0.6-m open-ended tube that receives a steady supply of hydrogen gas. The scattered beam particle and recoiling proton are detected by means of a pair of drift-chamber detectors filled with argon and carbon dioxide gas; thousands of wires that create an electric field; and 954 additional tungsten wires a mere 25 μm in diameter, whose job is to sense particle positions. As a charged particle passes through a drift chamber, it ionizes the argon atoms within. The newly liberated electrons drift toward the thin sensing wires; once an electron approaches to within about 1 mm, it is greatly accelerated by a strong electric field. The accelerated electron ionizes so much argon that the resulting cascade of liberated electrons produces a measurable signal in the wire. From observations of the sensing-wire signals, other detector clues, and simulation work, OLYMPUS scientists could re-create the tracks of the beam particle and proton. From those tracks they deduce the momentum transferred to the proton and the scattering angle of the beam particle.

The OLYMPUS drift chambers began life as the BLAST detector at MIT's Bates laboratory. For years BLAST researchers had been investigating nucleon structure—though not two-photon physics—but funding for the project ran out in 2005. At the end of 2009, the German Electron Synchrotron (DESY) facility in Hamburg approved a proposal by BLAST

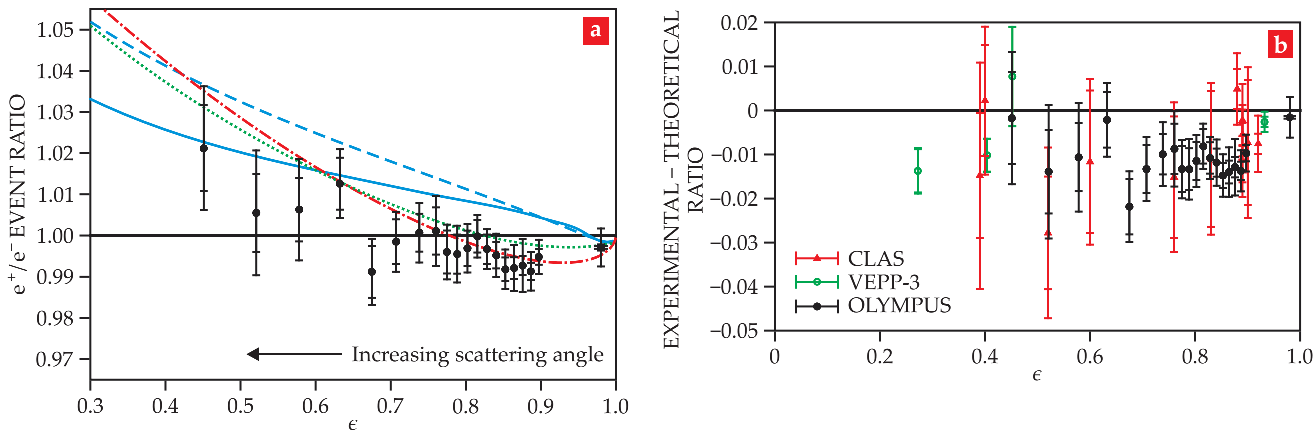

FIGURE 2. THE RATIO OF POSITRON EVENTS TO ELECTRON EVENTS increases as the scattering angle increases. **(a)** Here ϵ is a function of scattering angle that decreases with increased scattering. The blue dashed and solid curves come from theoretical calculations without free parameters. The red and green curves give the predictions of models with parameters based on experiments that predate the CLAS, VEPP-3, and OLYMPUS efforts. **(b)** The parameter-free theory[5] that generated the solid blue curve in panel a seems to overpredict the ratio of positron counts to electron counts. The discrepancy is particularly pronounced for the OLYMPUS data at high ϵ. Error bars indicate statistical uncertainties (inner bars) and statistical-plus-systematic uncertainties (outer bars). (Adapted from ref. 3.)

investigators and international colleagues to look for two-photon effects, and shortly thereafter the US Department of Energy came through with funding. Almost immediately, the MIT team began disassembling the device in preparation for shipping it overseas. All of the thousands of detector wires had to be removed and replaced at the drift chambers' new European home. Figure 1 shows some of the team's student members at the tedious task of stringing the detectors.

The OLYMPUS team had to work fast; the German government had decided that DESY's DORIS storage ring—the source of the OLYMPUS electron and positron beams—would permanently shut down at the end of 2012.

Most of the OLYMPUS data were collected in a run beginning in October 2012. It was scheduled to end on 20 December, but the OLYMPUS scientists prevailed on their DESY colleagues to give up their Christmas and New Year's holidays so that the experiment could squeeze in an additional two weeks. In the end, OLYMPUS collected about 25% more data than anticipated. Analyzing the complicated runs involved collecting cosmic data for background analysis and devising particle tracking algorithms that could handle the detector's inhomogeneous magnetic fields. All told, the data analysis took well over two years.

Trend spotting

Figure 2a presents the OLYMPUS results and predictions of several theoretical models. From right to left, the momentum transferred to the proton and the scattering angle of the beam particle both increase. Theory predicts that, except for the smallest scattering angles, the positron-to-electron count ratio should also increase from right to left. University of Manitoba theorist Peter Blunden, who helped derive the two blue model curves shown in the figure, is gratified by the data. "There's definitely a slope in the data at higher momentum transfer," he observes, "and it's at about the right magnitude to be consistent with theory. To me, that's the big story." After the OLYMPUS data came out, Blunden joined members of the OLYMPUS and CLAS collaborations to analyze the joint data from the three experiments that compared positron and electron scattering. Their conclusion: The hypothesis that two-photon exchange is not contributing to the observed data can be ruled out with more than 90% confidence.[4]

Blunden's most sophisticated calculation, carried out with Jefferson Lab's Wally Melnitchouk,[5] overestimates the OLYMPUS data, especially at lower scattering angles. Figure 2b, which shows the difference between the experimental data and the prediction of the two theorists, also includes the CLAS and VEPP-3 data. The tension between theory and data points, however, is just a standard deviation or two. The fact that the discrepancy seems most pronounced at low momentum transfer is noteworthy; two-photon effects, at least, are not expected to be significant in that regime. Says Blunden, "It's not a result to be dismissed, but it would indicate there's some more complicated reaction mechanism in a region where it's unexpected."

The OLYMPUS experiment modestly expanded the range of momentum transfers that were explored by CLAS and VEPP-3. But the form-factor measurements made at Jefferson Lab with polarized electrons extended to far greater momentum transfer. Measuring the ratio of positron-to-electron scattering events in experiments that extend to higher momentum transfers could go a long way toward clarifying whether two-photon effects truly suffice to reconcile all the form-factor data, or whether new physics must be entertained. Unfortunately, obtaining good positron-scattering statistics at high momentum transfer and large scattering angle requires an intense positron beam. Creating such a beam is an enormous challenge, but that has not deterred working groups from starting to discuss experiments that might go beyond OLYMPUS. At the moment, though, no such experiments are on the drawing board.

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