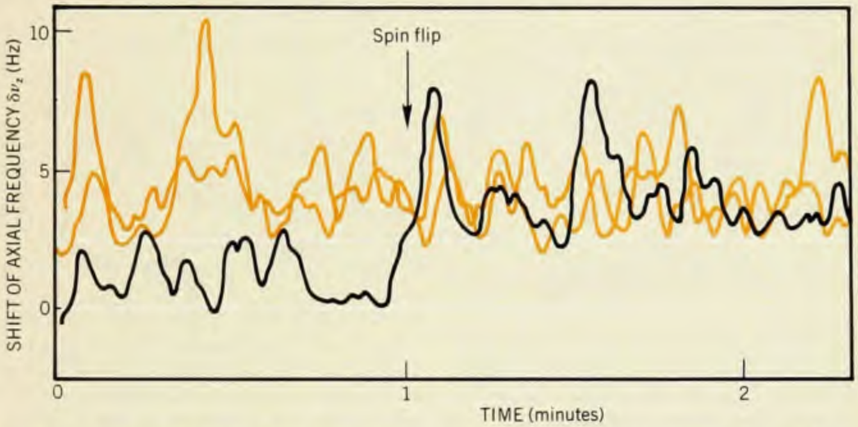
search & discovery

New measurement of magnetic-moment anomaly tests QED

Once again quantum electrodynamics, which has already earned itself the description "the most successful dynamical theory in all of physics," comes under close scrutiny as further refinements in experimental technique provide data sufficiently precise to test this highly respected theory. Hans Dehmelt (University of Washington) reported at the Chicago meeting of the American Physical Society last month on measurements made in collaboration with Robert Van Dyck Jr and Paul Schwinberg of the magnetic moment anomaly of the electron. Brief notes on the experimental method had appeared earlier in *Nature*;[1] a more extensive paper on the new measurement is in *Physical Review Letters*.[2]

The new experimental value is known to two parts in 10^7; it agrees with current calculations of this quantity (made on the basis of QED theory), which have a precision of only three parts in 10^7. Experimenters and theoreticians both believe that they will be able to improve on their accuracy in the near future.



Spin flip of a single electron in the Penning trap at the University of Washington. Because of the random fluctuations in the thermally excited cyclotron motion, the axial frequency shift shows an unsymmetric fluctuation, always staying above a fixed "floor" for a given spin direction. The floor suddenly changes when the spin is flipped. Three superimposed traces are shown here, with only the black one showing the spin flip. The axial frequency shift is about 2.5 Hz in this case.

Penning trap. Dehmelt and his colleagues have succeeded in levitating single electrons with very low energy (about one millivolt) for several days at a time in a Penning trap at liquid-helium temperatures. The Penning trap as used in this experiment is a device that combines a strong magnetic field with an electric

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Budget includes three centers for synchrotron radiation

The growing interest in using synchrotron radiation has led to a shortage of facilities for such experiments. Former President Ford's budget request for FY 1978, submitted to Congress in mid-January, calls for building dedicated sources at Brookhaven National Laboratory and the University of Wisconsin and improving the Stanford Synchrotron Radiation Project. SSRP operates symbiotically with SPEAR, which is primarily used as a high-energy physics storage ring.

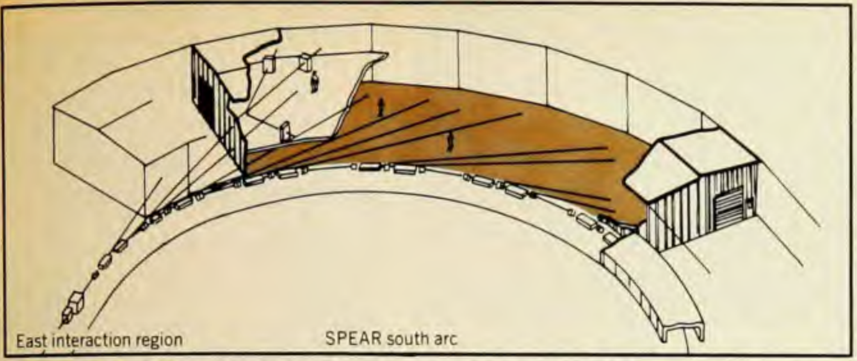
The budget has a line item requesting that ERDA be authorized to spend $24 million for a dedicated facility at Brookhaven scheduled to be completed in Fall, 1981. Meanwhile NSF has asked for an increase in construction funds of $4.2–4.3 million to be used for synchrotron-radiation sources. It is considering proposals from both Wisconsin and Stanford. Wisconsin would like to spend $3 million for a new storage ring over a three-year period. Stanford would like to spend $6.7 million spread over three years to upgrade SSRP. NSF is requesting Congress for funds for the first year. In addition, NSF has asked for funds to convert the Cornell University synchrotron to a high-energy storage ring, which would have provision for synchrotron-radiation research.

Panel recommends. These budget requests appear to be responding in part to the recommendations of a National Research Council group, the Panel to Assess the National Need for Facilities Dedicated to the Production of Synchrotron Radiation, a part of the Solid-State Sciences Committee. The panel was headed by Robert W. Morse (Woods Hole Oceanographic Institution).

The panel noted that existing facilities in the US (at Wisconsin, Stanford, Cornell and the National Bureau of Standards) have seven x-ray and 17 vacuum-ultraviolet stations. A conservative analysis, the panel says, of projected needs indicates that by 1986 there will be a demand for approximately 60 x-ray stations serving users requiring radiation in the range 1–50 keV (12–0.25 Å) and 40 soft x-ray vacuum-ultraviolet stations serving users requiring radiation in the range 0.01–1.0 keV (1200–12 Å). The panel observes that even if existing facilities were fully expanded and dedicated, they would only meet one-third of the increased need estimated to be required by 1986.

The panel urged that there be a balanced geographical distribution of synchrotron-radiation capabilities to serve the largest number of active participants. Morse said that the need could be satisfied by three geographically distributed major facilities, at least two of which would have x-ray capability. (All three would have vacuum-uv capability in any case.)

The Brookhaven facility would require appropriations of $5 million, $10 million, and $9 million over the next three years, construction taking three and a half years from commitment. The facility, to be known as the "National Synchrotron Light Source," would consist of a 2.5-GeV



Proposed layout of beams in the new two-level experimental hall on SPEAR's south arc.

will be forthcoming. That would provide for part of the new building and a start on two beam lines. Doniach notes that because SSRP is already running, it can provide an interim solution to the demand for synchrotron radiation, particularly in the x-ray region, whereas it will take a few years for the other US machines to start experiments.

One reason for the great interest in soft x rays, obtainable at the new installations proposed and at SSRP, is microlithography, for fabrication of submicron integrated circuits. It should allow 100 times more capacity on a single chip. The University of California at Berkeley and Stanford Research Institute have each proposed to NSF building a microlithography research center, which would employ radiation from SSRP. Meanwhile Wisconsin is proposing to NSF to build a National Research and Resource Facility for Submicron Structures, which would be located near Aladdin and use one or two of its beams for x-ray lithography.

Cornell University is planning to convert its 12-GeV electron synchrotron to an electron–positron storage ring, each beam having 8 GeV. Conversion funds would come from operating expenses. Over a three-year period the incremental cost for conversion would be about $10 million, according to director Boyce McDaniel. Cornell has plans to build three exit ports for synchrotron radiation plus some working space. No money is being requested at this time to equip the beam lines or provide support facilities. The facility would produce x rays from a few keV up to as high as 100 keV, with a critical energy of 35 keV. —GBL

Magnetic-moment anomaly

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quadrupole field to confine low-energy electrons in microscopic metastable orbits. The researchers refer to the system, one electron plus trap, as "geonium"—an atom in which the Earth can be regarded as taking on the function of the nucleus.

Dehmelt's group uses a superconducting magnet to provide an 18-kilogauss field, and hyperbolic electrodes—top cap, ring electrode, and bottom cap—for the electric quadrupole field. This system gives rise to an axial electric potential well and a radial hill. The presence of electrons is detected by monitoring the signal induced to the end caps at the characteristic axial oscillation frequency ν_z, in this case about 60 MHz. The magnitude of this forced resonance signal is proportional to the number of electrons trapped. Each experimental run is initiated by firing a high-energy electron beam through the trap to ionize background gas by collision, and it is the slow secondary electrons that are trapped. By suitable adjustment the high-energy beam can be made to produce a small number—say zero through four—of slow electrons in the trap per pulse, and the number trapped in a particular run is inferred by examining the quantized magnitude of the induced end-cap current, in a way very reminiscent of the Millikan oil-drop experiment.

The magnetic moment anomaly a_e of the electron is defined as the dimensionless ratio of frequencies $(\nu_s - \nu_c)/\nu_c$, where ν_c is the cyclotron frequency and ν_s the spin precession frequency for the electron in a magnetic field in the nonrelativistic limit. In the case of an electron in a Penning trap the presence of the electric field shifts the cyclotron frequency slightly to a value $\nu_c' = \nu_c - \nu_m$, where ν_m is the magnetron frequency. The path of a trapped electron can be visualized as consisting (in addition to the axial oscillation at frequency ν_z) of small circular cyclotron orbits executed at frequency ν_c, centered on a point that moves around the much bigger magnetron orbit at frequency ν_m. In the present version of the experiment ν_c and ν_m are about 51 GHz and 35 kHz respectively.

The shift in the cyclotron frequency can be determined either from ν_z and ν_c' or from ν_m. By doing it both ways and showing the two results to be in good agreement, the assumption of axial symmetry for this trap is shown to be satisfactory. An analysis by Lowell S. Brown (University of Washington) confirms this conclusion.

The crucial problem is to detect radiofrequency resonances at the cyclotron frequency ν_c' and the spin–cyclotron beat frequency $\nu_a' \equiv \nu_s - \nu_c'$. In the sensitive indicator scheme devised for this experiment, cyclotron and spin motions are slightly coupled to the axial mode by means of a weak magnetic bottle realized by a nickel wire wound around the ring electrode. The depth of the resulting shallow magnetic potential well augmenting the principal axial electric well is proportional to the total magnetic moment of the electron and to $(n + m + \frac{1}{2})$, where $n = 0,1,2,3 \ldots$ and $m = \pm \frac{1}{2}$ are cyclotron and spin quantum numbers respectively. Consequently the axial frequency, which is continuously monitored, is now given by $\nu_z = \nu_{z0} + (n + m + \frac{1}{2})(1.0\ \mathrm{Hz})$, and so provides continuous information on the combination $(n + m)$. Because the cyclotron resonance changes n and spin flips change m, the detection problem is solved.

Putting the magnetic bottle to a totally different use, spin flips are now induced by making the electron see a resonant magnetic rf field at a combination frequency equalling ν_s. To an electron in a thermally excited cyclotron orbit centered on the bottle axis the radial components of the bottle field appear as a magnetic rf field rotating at ν_c', which is further made to change its sign periodically at the frequency ν_a' for an auxiliary forced axial motion. This effect creates a spectral component at $\nu_c' + \nu_a'$, which on resonance (i.e., when it equals ν_s) causes spin flips, thus allowing ν_a' to be measured.

At 4 K temperature the recognition of spin flips is somewhat obscured by the rapidly varying thermal excitation of the first four or so n levels. For a weak ν_a' drive, a graph of ν_z against time accordingly shows a random fluctuation, rather like noise, but with a "floor" that represents the cyclotron ground state with an occasional major shift corresponding to a spin flip.

With $\nu_c (= \nu_c' + \nu_m)$ and $\nu_s - \nu_c (= \nu_a' - \nu_m)$ known, a_e, the magnetic-moment anomaly, can be calculated from $(\nu_s - \nu_c)/\nu_c$. The present value for a_e obtained by Dehmelt's group is $(1\,159\,652\,410 \pm 200) \times 10^{-12}$. The previous best measurement of a_e was by Arthur Rich's group at the University of Michigan, in 1971, which had an uncertainty of three parts in 10^6.

QED. P.A.M. Dirac's original theory of the electron predicts the value 2 for the g-factor of the free electron. But the quantity a_e, defined by $a_e \equiv (g - 2)/2$, differs from zero by about one part in 1000 when QED corrections are applied to the Dirac model.

T. Kinoshita and P. Cvitanovic (Cornell) have calculated a_e from QED to an accuracy of three parts in 10^7, and the agreement with the new measurements is very good. Other QED calculations (by M. J. Levine of Carnegie-Mellon University and J. Wright of the University of Il-

Penning electron trap in which Hans G. Dehmelt and his colleagues can levitate single electrons in microscopic metastable orbits for periods of several days. This tube has a 4-cm diameter.

linois, and by R. Carroll of the University of Michigan), though not quite so precise, are also in agreement. In these results, analytical values for some Feynman diagrams obtained by Levine, R. Roskies (University of Pittsburgh), E. Remiddi (CERN) and others are incorporated.

Comparison between different experiments is most conveniently done by computing α, the fine-structure constant, from theory and experiment. The new measurement of a_e by Dehmelt's group, together with the QED calculation, leads to a value of α good to three parts in 10^7.

The fine-structure constant can be obtained independently from the Josephson effect, to two parts in 10^7. (No other method for α is currently within a factor of three of this precision.) The agreement between the two values of α is very good. The conclusion is that QED is very sound to this order, and that Bardeen-Cooper-Schrieffer theory (*via* the Josephson effect) is sound also—unless, of course, QED and BCS theory are both in error to the same extent, which appears unlikely.

What are the prospects for further improvement? QED calculations are expected to improve by a factor of ten or so when more of the 72 Feynman diagrams in the sixth-order calculations are solved analytically; 51 of them have been solved so far. Four years ago, when Kinoshita completed his calculation of a_e, only a few were known analytically, and he did them all numerically. Merely by pushing the numerical method further, Kinoshita thinks he can get a five-fold improvement in the calculation. Meanwhile, analytic evaluation is also being pushed vigorously.

Dehmelt's group expects further improvement in their data, too. They point out that their dimensionless ratio ν_s/ν_c is already the most precisely known characteristic parameter of any elementary particle, but they confidently expect even further refinement in the method to yield accuracies of a few parts in 10^8 in a_e. In the near future they hope to make the same measurements on the positron, to yield the most accurate comparison of a particle–antiparticle parameter. "There's not much competition in that field," Dehmelt told PHYSICS TODAY, noting that the only measurement since the early work of Rich's group at Michigan is an electron–positron comparison, made in the storage rings at the Nuclear Physics Institute at Novosibirsk, yielding accuracies only around one part in 10^5.

—JTS

References

1. R. Van Dyck Jr, P. Ekstrom, H. Dehmelt, Nature **262**, 776 (1976); H. G. Dehmelt, Nature **262**, 777 (1976).
2. R. S. Van Dyck Jr, P. B. Schwinberg, H. G. Dehmelt, Phys. Rev. Lett. **38**, 310 (1977).

Shuttle has space for long-term experiments

Opportunities for getting experiments aboard the Long Duration Exposure Facility (LDEF) are now being offered by the Universities Space Research Association, under the sponsorship of NASA.

In 1979 NASA will begin launches every half year of LDEF, which is a large unmanned structure capable of carrying over 70 experimental packages. This satellite will be carried aloft by the Space Shuttle, left to orbit for a period of 6–9 months and then brought back to Earth where experimental packages will be returned to the experimenters for analysis. The orbital environment provides weightlessness, high vacuum, and fluxes of solar radiation, micrometeoroids and charged particles over a large energy range.

Experiments are being sought in all fields of science and technology, but particularly from academic scientists. Physicists are encouraged to submit proposals in astrophysics, cryogenics, plasma physics and fluid dynamics. The Universities Space Research Association plans to reserve space for experiments from student groups.

Once a proposal has been approved, the Association will assist experimenters in obtaining research funding and in all other phases of experiment development and management. NASA will provide preflight acceptance testing, orbital flight and return for experiments.

Outlines for proposals and ideas should be sent to M. H. Davis, USRA, PO Box 3006, Boulder, Colo. 80307.

NASA seeks ideas for solar-energy conversion

The National Aeronautics and Space Administration has issued a request for ideas, concepts and suggestions that would assist the agency in formulating research objectives in solar-energy conversion in space. Research at present is based on photovoltaic devices and thermal engines and, according to NASA, approaches other than these may be more effective and could make better use of the environment in space.

Ideas and concepts that are sent to NASA should center on systems that are located in space (near Earth) and, in principle, are capable of highly efficient energy conversion. Systems scalable to megawatt and gigawatt power levels are needed for potential applications in space and for transmission of energy to Earth.

NASA considers this solicitation a planning phase and, therefore, only sufficient information to permit consideration of ideas as part of an overall planning effort is required. NASA may, if further effort is justified, issue a separate announcement-of-opportunity or a request-for-proposals to pursue those objectives developed in this planning phase.

Ideas should be submitted no later than 31 March to NASA Headquarters, Code RR, Washington, D.C. 20546. Any concept description that would disclose proprietary information should not be submitted as it may serve as the basis for a further solicitation of proposals.

in brief

The CERN Super Proton Synchrotron began experiments on 7 January with nine experiments on the floor. On 13 December a 400-GeV beam had been extracted with an intensity of 4×10^{12} protons/pulse.

Among the building expenditures associated with the PEP Project (a joint effort of SLAC and Lawrence Berkeley Laboratory), ERDA has approved a $28-million contract for the design and construction of housing for research equipment. This contract was signed by Stanford University and the joint venture of Kaiser Engineers (Oakland, Calif.) and Parsons, Brinckerhoff, Quade and Douglas Inc (San Francisco, Calif.)

The 100-inch Irénée du Pont Telescope of the Hale Observatories was recently dedicated at Las Campanas Observatory in Chile. □