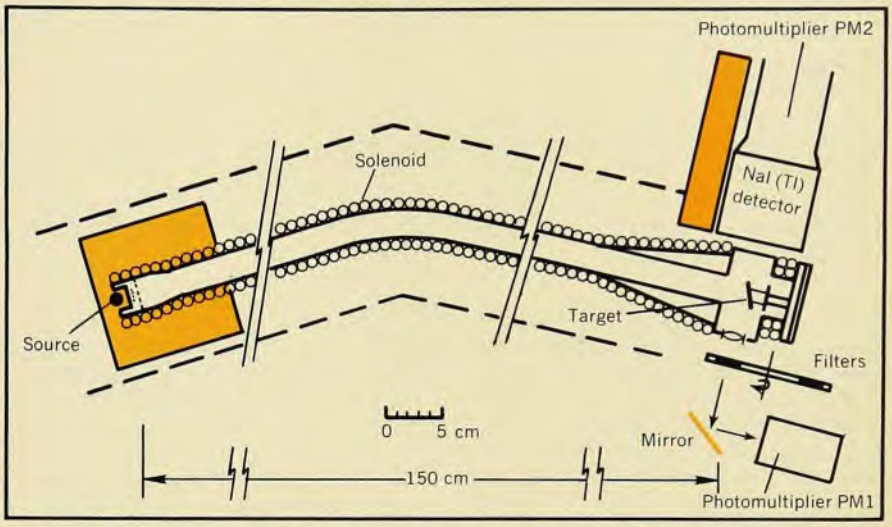
search & discovery

Positronium reveals its first excited state

The way has been paved to test quantum electrodynamical predictions of the Lamb-shift-like transitions in positronium. Karl F. Canter, Allen P. Mills Jr and Stephan Berko of Brandeis University recently observed[1] the long-sought radiation from the first excited state of positronium with a method that makes it feasible to measure the fine structure of the $n = 2$ state. That measurement is now in progress.

The Brandeis experiment is the most conclusive of a long series of attempts to form the excited state of positronium that date back nearly to the discovery of this leptonic atom by Martin Deutsch (MIT) in 1951. Henry Kendall (MIT), as a student of Deutsch in 1954, tried to excite the $n = 2$ state optically from the ground state by shining light into a gas but received ambiguous results. (Positronium had been formed in the gas by a positron source.) Last year a group at Yale University consisting of S. Varghese, Earl S. Ensberg, Vernon W. Hughes and Ingvar Lindgren tried the same experiment but with improved instrumentation, and they claimed[2] positive evidence for the formation of excited positronium. However, a negative result was obtained by Marvin Leventhal, Samuel L. McCall and Albert Passner of Bell Laboratories, who used a modified version of the same technique.[3] Unfortunately, even with unambiguous evidence for positronium formation in the $n = 2$ state, this method does not lend itself to measurement of the fine structure. Large perturbations result from collisions in the gas, so the positronium excited state must be produced at a very low pressure or in a vacuum to allow a significant determination of the splitting by microwave spectroscopy.



Positronium was formed when slow positrons struck target. Signal for formation of the excited state was coincidence between the 2430-Å decay photon, seen by photomultiplier PM1, and the annihilation gamma, detected by the NaI(Tl) counter coupled to PM2. (From reference 1.)

Many other experimenters have searched for excited positronium with different methods and varying results. Quite a few have tried to find excited positronium by slowing high-energy positrons in a gas and by looking for the 2430 Å Lyman-alpha radiation that would signal its decay. However, the $n = 2$ state is most likely ionized or deexcited by collisions in the gas—that would explain the negative results of these searches.

The Brandeis team feels they were successful because they could produce positronium in a vacuum by using a slow-positron beam and a solid target and could separate the region of positronium formation from the radioactive source. Canter, Mills and Berko found last summer that positronium can be formed with high efficiency when low-energy positrons strike a solid,[4] and decided to search for excited positronium formation using the same technique.

In their apparatus, the fast betas

continued on page 20

Analysis shows Skylab tore hole in ionosphere

The launch of Skylab on 14 May 1973 created a temporary, large-scale hole in the ionosphere. The "hole," a depletion of the total electron content of the ionosphere that spanned a spatial region of 1000 to 2000 km and a time period of 2 to 3 hours, was observed and subsequently analyzed by Michael Mendillo (Boston University), Gerald S. Hawkins (Smithsonian Astrophysical Observatory) and John A. Klobuchar (Air Force Cambridge Research Laboratory).[1] They assert that the electrons were lost because of exceptionally rapid chemical recombination of the electrons with oxygen ions that was caused by the molecular hydrogen and water vapor from the exhaust of the Saturn V rocket engines.

Mendillo, Hawkins and Klobuchar analyzed data from the Sagamore Hill Radio Observatory in Hamilton, Massachusetts. This observatory continuously measures the total electron content (TEC), which is a measure of the number of electrons in a vertical column of unit cross section through the ionosphere. The TEC is inferred from Faraday-rotation measurements of the plane of polarization of a very high frequency radio signal from a geostationary satellite. At the time of the Skylab launch from Cape Canaveral, Fla., the TEC dropped very suddenly from 11.3 $\times 10^{12}$ to 5.8 $\times 10^{12}$ electrons/cm^2 (see figure). Similar behavior, delayed in time, was observed at a station in Goose Bay, Labrador (1000 km north), was somewhat weaker at Urbana, Illinois (over 1000 km west) and was barely noticeable at Narssarssuag, Greenland (2000 km away).

Normally, the electrons in the ionospheric F region (from about 200 to about 1000 km) result from photoioni-

tensive study. Historically the first solar cell, the silicon cell has an efficiency up to 16%. However, it must be a single crystal; so its manufacturing cost is high. Another cell, made of gallium aluminum arsenide/gallium arsenide, has demonstrated efficiencies of up to 18% but, like silicon, its potential for production by thin-film techniques is still uncertain. Both are suitable primarily for satellite application or for other areas where cost is not a factor. Recent interest has focussed on cadmium sulfide/copper sulfide cells, in which both layers are thin films. So far such devices have reached efficiencies of about 7% and have exhibited problems in long-term operation. Several laboratories are investigating the replacement of either the copper sulfide or the cadmium sulfide by another compound. One such example now being studied is a cadmium telluride/cadmium sulfide cell.

The combination of layers in a good solar cell must satisfy a long list of criteria and, according to Shay, the two new cells meet all of them. First, the direct band gap of the top layer of n-type cadmium sulfide is wide enough to transmit most of the light to the p-type layer. There, the direct band gap is in the optimal range (1–1.5 eV) for solar power conversion. Next, the bottom layer has a small absorption length of about 1 micron, compared with 10–100 microns for silicon, so that the electrons are produced near the interface. Thus these other materials need not be as pure as silicon, where the electrons must travel further to reach the boundary. A third criterion is that the electron affinity for the bottom layer is smaller than that for the top layer. Because of this the conduction band has no spikes that might prevent electrons from reaching the cadmium-sulfide layer.

The one criterion met solely by the two cells studied at Bell Labs is the excellent lattice match between the two layers. This ensures that little strain results when cadmium sulfide is deposited on indium phosphide or on copper indium diselenide. Otherwise, the layer might peel off or, if it did adhere, the electrons might recombine at the interface. The proper lattice match also makes these devices good candidates for thin-film manufacture because the crystallographic orientation is of little concern.

The most recent efficiency for the copper indium diselenide/cadmium sulfide system was 12%, compared with 12.5% for the indium phosphide/ cadmium sulfide cell. However, the latter is a simpler system; so the Bell Labs group is not yet taking any sides as to which system has greater potential. Both indium phosphide and copper indium diselenide have a quantum efficiency (that is, the ratio of electrons produced in the external circuit to the incident photons) of 70% over a fairly wide range.

The key to whether either of these two devices will be a viable solar cell for terrestrial applications is the demonstration that the cells can be produced by thin-film techniques. That means one must achieve the nucleation of crystal growth on something other than a single crystal. If this hurdle is jumped, Wagner and Shay estimate the cells would produce electricity at a competitive cost. The most expensive component of the cells would be indium, at 5 to 15 cents per gram. Although indium is not presently produced in large quantities, there are sufficient reserves of it in mines in the US, Canada and Peru for this application. It is a byproduct of extraction of zinc from ores. —BGL

References

1. S. Wagner, J. L. Shay, K. J. Bachmann, E. Buehler, Appl. Phys. Lett. **26,** 229 (1975).
2. S. Wagner, J. L. Shay, P. Migliorato, H. M. Kasper, Appl. Phys. Lett. **25,** 434 (1974).

Positronium

continued from page 17

from a Co^{58} source are converted to slow positrons by a gold—magnesium-oxide converter. The positrons are then guided magnetically 1.5 meters along the axis of a solenoid that has a 30-deg bend in the middle. The energy of the positrons was kept at 25 eV by a voltage applied to the gold-foil converter.

The detection system looked for both the 2430 Å photons from the decay of the excited state and the gamma rays from the subsequent annihilation of the ground state; coincidence between these two signals was required. Photons from the target area were focussed onto a photomultiplier through a set of interchangeable narrow-band interference filters whereas the gammas were detected by a NaI (Tl) scintillation counter. Over a ten-day period, the counting rate for the filter that was peaked at the Lyman-alpha line was an average of 1.04 ± 0.13 coincidences per ksec above the average rate in the filters peaked at ±30 Å on either side; this rate corresponds to an excited positronium production rate of roughly one event every four seconds, or one for every thousand that are formed in the ground state.

A major problem with all experimental attempts to find the radiation from the $n = 2$ state has been the large background. Canter, Mills and Berko performed several checks to ensure that the observed signal was not caused either by scintillations induced by the annihilation gamma rays or by scintillations resulting from positron impact on the target. One such check was the measurement of the time interval between observations of the photon and of the annihilation gamma. The time interval showed a distribution corresponding to a lag of the gammas behind the photon, as would be expected if decay of the excited state preceded annihilation of the ground state. From this time measurement they also conclude that the positronium is not bound to the target but deexcites in the vacuum.

The development of the high-flux slow-positron beams that made the Brandeis experiment feasible has been conducted primarily by those interested in positron-atom collision cross sections; the first such measurement was made by D. G. Costello, D. E. Groce, D. F. Herring and J. W. McGowan of the University of Western Ontario.[5] These beams are all based on the observation that, when positrons from a radioactive source are introduced into a solid, a small fraction are reemitted from the surface in the form of a nearly monoenergetic slow positron beam. The particular beam used at Brandeis is patterned after one developed by Canter and P. G. Coleman, Thomas C. Griffith and George R. Heyland of University College London.[6] They made the solid converter in the shape of vanes around the source and found that the yield of positrons was increased by a factor of ten or more when the vanes were coated with a layer of magnesium oxide.

As a purely leptonic atom, positronium is an ideal subject for tests of quantum electrodynamics. Its theoretical predictions have already shown good agreement with the fine structure of the ground state. The $2S \rightarrow 2P$ splitting of the first excited state is of interest because different interaction terms appear when both the S and the P states are involved. This $2S \rightarrow 2P$ splitting was computed to a precision of α^3 Ry as early as 1954 by T. Fulton and Paul C. Martin.[7] The Brandeis team is now trying to test this prediction.

—BGL

References

1. K. F. Canter, A. P. Mills Jr, S. Berko, Phys. Rev. Lett. **34,** 177 (1975).
2. S. L. Varghese, E. S. Ensberg, V. W. Hughes, I. Lindgren, Phys. Lett. **49A,** 415 (1974).
3. S. L. McCall, Bull. Am. Phys. Soc. **18,** 1512 (1973).
4. K. F. Canter, A. P. Mills Jr, S. Berko, Phys. Rev. Lett. **33,** 7 (1974).
5. D. G. Costello, D. E. Groce, D. F. Herring, J. W. McGowan, Can. J. Phys. **50,** 23 (1972).
6. K. F. Canter, P. T. Coleman, T. C. Griffith, G. R. Heyland, J. Phys. B **5,** L167 (1972).
7. T. Fulton, P. C. Martin, Phys. Rev. **95,** 811 (1954). □