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Hydrogen Spectroscopy and Fundamental Physics

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"Dann muss man doch bescheiden sein."

Albert EINSTEIN [1]

"One must be modest" is an appropriate quotation to describe laser spectroscopy of the hydrogen atom. This is a field of modest scientific accomplishments, despite its awesome technical machinery. To illustrate, the first demonstration of laser spectroscopy in hydrogen was made by HÄNSCH, SHAHIN, and SCHAWLOW in 1972. [2] Now, sixteen years later, the most precise laser measurement of the Lamb shift in the ground state of hydrogen is by the Oxford group and is known to one part in ten thousand. [3] This is just equal to that achieved by LAMB and coworkers thirty-five years ago. [4] In the meanwhile, radio frequency and other techniques have pushed the measurement of the H(2S) Lamb shift an order of magnitude beyond the accomplishments of laser spectroscopists. [5]

This talk will concentrate on the relation of the hydrogen atom to fundamental physics. It will start with laser spectroscopy of hydrogen and determination of R_∞. It will then discuss other systems, in particular the electron-positron system, as possible new tests of fundamental physics.

1. Laser Spectroscopy of Hydrogen and the Measurement of R_∞

The Rydberg constant is the scale factor that connects all theoretical calculations and experimental measurements of energy levels in any system involving electrons. This includes all atoms, molecules and condensed matter. In simple systems, such as hydrogen, positronium, muonium, and possibly helium, the theoretical accuracy is comparable to that of experiments. In this case, experimenters can be said to measure the Rydberg constant, if not to test theory. Laser spectroscopy, at the moment, is the method par excellance to measure R. Measurement of the Rydberg constant R is a simple matter. One measures the wavelength or frequency (the velocity of light is defined to be 299 792 458 m/sec) in a system, such as hydrogen, where theoretical calculations are expected to be accurate to within the experimental error. One then compares this measurement (in Hz or cm^{-1}) with the theoretical calculation (in atomic units), thereby finding the atomic unit in Hz or cm^{-1}. Half of the atomic unit is the Rydberg

The Hydrogen Atom Editors: G.F. Bassani · M. Inguscio · T.W. Hänsch

constant. At present, the most precise measurements of R are in the H,D system in a variety of states. All current measurements agree within experimental errors (see Table I). Within the near future, one might expect improvement in both measurements and calculations in the helium atom to provide an alternative determination of the Rydberg constant.

Table I. Comparison of measurements of Rf_r=R-10973 731 m^{-1}, errors and variances[a]

Group	Transition	R_{fr} (error)	Variances (parts in 10^{20})				
			Standard	Relative Wavelength (frequency) measurement	Statis-tical	Other	Total
Yale-NBS	2S - 3P	0.569(7)	3	10	25	5	42
Stanford	1S - 2S	0.571(7)	16	18	3	---	38
Paris	2S-8D,10D	0.571(2)	3	---	---	---	3
Yale-NBS	2S - 4P	0.573(3)	3	---	2	2	7
Oxford	1S - 2S	0.573(3)	7	1	---	1	9

a. see references 3,9 and other talks in this session

2. Where Are We Now? Where Are We Heading?

Table I breaks down the variance $V = \sigma^2$ of the different measurements of R. Figure 1 shows this graphically. This gives insight into the current status of the field and could be used to address several questions about the future.

One could ask, "What would be the contribution of using special techniques, such as two-photon spectroscopy, to take advantage of the potentially high precision of ultra-narrow lines, such as the 1S-2S transition in H (width = one Hertz)? The statistical part of the variance in Figure 1 reflects the "Q" (ratio of frequency of line width) of the lines used by the various groups. Narrowing the line width does lower the variance, as is shown by the improvement in the results of the Yale-N.B.S. group in going from Balmer-α to Balmer-β with its threefold higher Q. But there are limits. These are shown most graphically in the case of the Paris group, which exploited the narrowness of the 2S-8D, 10D, 12D lines to the fullest. The rest of their variance is negligible. Their result has reached the best possible accuracy achievable by laser spectroscopy, less than two parts in 10^{10}. Further improvement is not possible without a better frequency standard in the optical region.

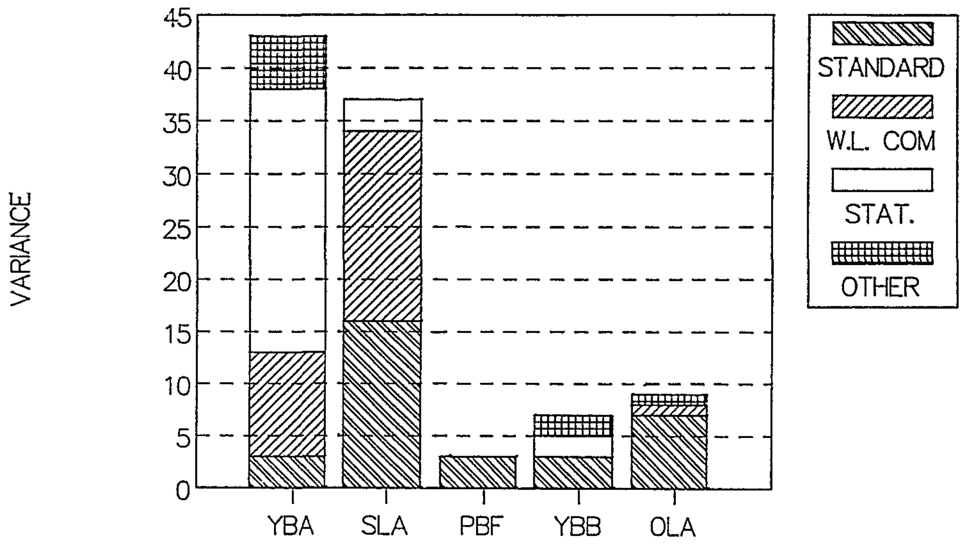

Figure 1. Comparison of variance = σ^2 (units of 10^{-20}) of the Rydberg constant

Legends:

YBA - Yale - N.B.S. Balmer α (reference 9)

SLA - Stanford Lyman α (two photon. See talk by T. Hänsch)

PBF - Paris 1S - 8D,10D (two photon. See talk by F. Biraben)

YBB - Yale - N.B.S. Balmer β (reference 9)

OLA - Oxford Lyman α (two photon - see ref. 3)

Sources of variance:

Standard - frequency or wavelength standard

W.L. COM - Comparison of measured wavelength with standard

Stat - Statistical errors

Other - Other sources of error, such as energy level shifts

3. Possible New Directions for Research

We consider, as an example, the determination of the Lamb shift in the ground state of hydrogen. The theoretical uncertainties are about a factor of ten smaller than the experimental error. [3] Thus an order of magnitude improvement in the experimental precision is necessary before laser spectroscopy can be said to be interesting. We consider a few possibilities:

1. Measurement of ratios. An example of this type of measurement was given by WIEMAN and HÄNSCH, [6] who successfully measured the ground state Lamb shift of H and D by comparing a laser at Balmer β at 4860 A with another dye laser which was doubled to look at the two-photon transition 1S-2S, Lyman α. The measured

values of 8151(30) and 8188(30) MHz agree both with theory and the results of BOSHIER et al., which have a 40-fold higher precision. [3] This procedure has the advantage of eliminating the standard, but it involves the additional complexity of two simultaneous measurements.

2. Direct chain to the visible. This possibility involves improving the chain from the Cs frequency standard into the visible, preferably near an atomic hydrogen line. For example the 486 nm laser, useful for Balmer β or doubling for the 1S-2S line, is quite near the seventh harmonic of the He-Ne(CH_4) line at 3.39μ and is an attractive possibility for a direct link from Cs to a hydrogen line.

3. Use of improved standards in the infra-red and radio frequency regions. Currently, standards based on the osmium tetroxide and CH_4 absorptions at 10.8μ or 3.39μ, respectively, are at the level of a few parts in 10^{11} or better. [7] Measurement of a hydrogen line near one of these standards could improve the accuracy of the Rydberg constant by an order of magnitude. By measuring transitions between two high lying states in the radio frequency region, one has the potential accuracy of the Cs clock at a few parts in 10^{14}. [8]

In either case, by using the hydrogen lines in different wavelength regions, one would then have a new set of standards throughout the entire frequency spectrum. [9]

4. Exotic Atoms. Muonium

The purely leptonic hydrogen atom, muonium, consists of a positive muon and an electron. It is the ideal atom, free of the nuclear structure effects of H, D and T and also of the difficult, reduced mass corrections of positronium. An American-Japanese group has observed the 1S-2S transition in muonium to a precision somewhat better than a part in 10^7. [10] Because there were very few atoms available, the statistical errors precluded an accurate measurement. The "ultimate" value of this system is very great, being limited by the natural width of the 1S-2S line of 72 kHz, set by the 2.2 μsec lifetime of the muon.

5. Positronium

Positronium (e^+e^-) is a purely leptonic system, free of nuclear structure effects, but suffers from reduced corrections in the worst possible case of equal masses. This makes the system difficult to treat, since quantum electrodynamical calculations start from an infinite nuclear mass and treat reduced mass effects as a perturbation.

Many experiments have been performed on this system, since its historic discovery by DEUTSCH.[11] Table II shows a sample of these measurements, with the level of agreement between theory and experiment shown. It is a mixed bag, with several cases of highly significant difference between Q.E.D. theory and experiment.

Table II. Positronium. Comparison of experimental theory, and deviation between the two, expressed in experimental standard deviations

Quantity	Value	Dev(σ)
1S hfs	203.3991 Th	
(GHz)†	203.3849 Exp	12
	203.3870 Exp	
n=2, fs(MHz) S ↔ P†		
J=1 ↔ J=2	8625 Th	
	8620 Exp	1.9
J=1 ↔ J=1	13 011 Th	
	13 001 Exp	2.4
J=1 ↔ J=0	18 496 Th	
	18 504 Exp	0.8
Decay Rate	7.038 30 Th	
of O-Ps	7.051 6 Exp	10
(per μs)†		
1S - 2S	1233 607 202 Th	
Interval	1233 607 143 Exp	5.4
(MHz)†		

† Ref. 14

How should one view these disagreements? Certainly one should never be complacent. Nevertheless, it seems likely that in most cases, the problem lies in the difficulty of the Q. E. D. calculations, which have not been carried out to a high enough order. Perhaps, a totally new type of calculation is needed. [12] In the case of the 1S-2S interval, there is some doubt about the correctness of the experimental values and remeasurements are underway. [13,14]

6. The Electron-Positron system. A New Elementary Particle?

We have seen that the electron-positron system, positronium, shows irregularities in its ground and excited states. However, we have questioned whether or not the discrepancies between theory and experiment have any real physics. On the other hand, there are remarkable phenomena in this system at energies of a few hundred KeV, as shown by the heavy ion experiments at G. S. I. in Darmstadt, Germany (see Figure 2). [15] At the risk of being accused of introducing irrelevant material in a focussed symposium, I shall discuss these interesting events here. The reason is there has been little or no systematic investigation of the e^+e^- system at these energies and the results are provocative. It is possible that, unlike most other studies of the hydrogen atomic system with a well-understood Hamiltonian, these events could represent really new physics. [12] On the other hand, the author will explore the possibility that these bizarre events have a conventional explanation.

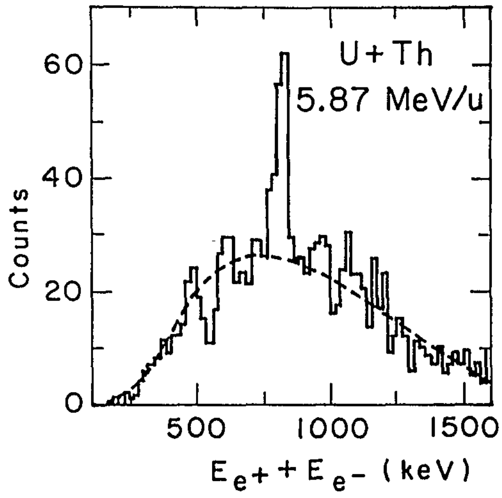

Figure 2. Distribution of the sum of coincident electron and positron kinetic energies in heavy ion collisions at G.S.I. (ref. 15)

The G. S. I. group measured the sum of the kinetic energies of electron-positron pairs produced in heavy ion collisions at GeV energies. The remarkable feature of these experiments was a sharp peak in the energy distribution, summed over the e^+e^- pair (Fig. 2). This lead to speculation as to the origin of this mysterious peak. A large number of papers have been written on the subject. [15]

The original discussion of this problem was based on the solution of the ground state solution of the Dirac equation for the hydrogenic atom consisting of a point nucleus of charge Z and a single electron:

$$E = [1 - (\alpha Z)^2]^{1/2} mc^2$$

At Z> 1/α = 137, this solution "dives" into the electron sea of the positron continuum and no real solution exists. This has been interpreted as an unstable state which, if vacant, can be filled by "autoionization" from the positron continuum. [16]

In 1969, Gershtein and Zeldovich noted that a slow collision would cause the diving of the lowest bound level into the positron continuum. This caused great excitement and a rash of papers and experiments attempting to calculate the properties and observe these "escape" positrons. [16] The G. S. I. experiments grew out of this early stage of development.

A remarkable paper at this stage of the field was by RAFELSKI, MÜLLER and GREINER [17], who predicted a sharp line in the positron continuum, as a result of a reaction between the colliding nuclei. This would produce a time delay which would allow the spontaneous emission of the positron with a sharp line shape. Early observations of this positron line seemed to verify this prediction. The fact that there was only a single energy of the emitted positron, independent of the charge of the colliding nuclei, seemed to rule out the nuclear physics explanation, [15] and furthermore lead to a new possibility.

This was considered by COWAN et al. [18] who hypothesized "a common source of the monoenergetic positrons in the two-body decay of a previously undetected particle... A clear signal for a neutral particle could be provided by the detection of a monoenergetic electron in coincidence with the peak positrons." This particle, at first assumed to be the axion, a pseudoscalar of zero spin, has had various names, one of which is the "X_0". For the second time, a remarkable discovery, the observation of electron-positron pairs [15,19] (see Figure 2), confirmed a speculative hypothesis dramatically. The experimenters, although phrasing their interpretation cautiously, could hardly resist considering the possibility that they had indeed observed "a neutral particle which decays into an e^+e^- pair... The signature for such a process, when viewed from the particle rest frame, would be back-to-back colinear emission of monoenergetic electrons and positrons.... Features associated with the electron-positron decay of a slowly moving particle appear to be reflected in the observations involving electron-positron coincidences." [19] A new flurry of experiments, this time by particle physicists, started a frantic search for the X_0 but it never was found. Another problem with the new data was that the e^+e^- coincidence peak no longer occurred at a single energy. It has been seen at three different energies, and even more than one energy for a given collision pair. [15]

Many discussions have been in the literature about the nature of this new particle. Some have assumed that it was the axion; others have ruled out the standard axion, but have not ruled out non-standard axions. In fact, the particle physicists concluded that they had ruled out a new elementary particle. It seems rather improbable now that such a particle exists at all. [20]

The theorists, who never lack for ingenuity and inventiveness, no longer seem to be writing about the X_0 particle. However, there have been several discussions about a new phase of quantum electrodynamics, an even more radical interpretation of the G. S. I. results. [21]

Many other attempts to observe this new excited state of positronium have been made. Indications of correlated, equal energy, two-photon decay with a summed energy of 1062 keV have been found by DANZMANN et al. [22] in the same reaction as produced the electron-positron pairs. [15, 18, 19] The authors believe that this line, at a new, fourth energy, may belong to the same neutral system which produced the correlated electron-positron pairs. [22]

Many groups have searched directly for this entity by Bhabha electron-positron scattering, the inverse process to the decay of the postulated entity. Although this is the definitive experiment in principle, the technical problems are great. As of the present time, no group has yet produced convincing results. [23]

7. The Conventional Explanation of the G. S. I. Results

The author and A. Robatino have pointed out that the sharp positron spectrum resembles electron spectra found in atomic collisions by Niehaus and coworkers. [24,25] The quantum mechanics in both cases is analogous. In our point of view, the sharpness of the spectra arises from interferences arising at avoided crossings of potential curves of the molecules formed by the collision partners. In particular, such a model is consistent in a natural way with the multiple summed energies found by the G. S. I. experimenters. [15,16,19] The molecular model predicts very different angular distributions than those of the particle model. [26] The more recent discovery of electron positron pairs is equally consistent with the molecular model, as with more exotic explanations. [26]

A recent analysis of the G. S. I. experiments shows that the design of the experiments did not decide between the particle explanation [18,19] and the conventional, atomic physics model of the collisions. [27] Furthermore, the kinematic data of these experiments is incomplete. The sharpness in the summed energy of the electron positron pair is not unambiguous evidence of a back-to-back decay mechanism of a particle or other entity. Neither the equality of the e^+, e^- energies nor the equal but opposite momenta are directly observed. These experiments give too little information about the angular distributions or the relative energies of the electron-positron pair.

It seems to the author that a conventional explanation, which follows the principle of scientific parsimony, is preferable as a point of departure, before postulating new entities, involving totally new principles of physics. As experimenters still pursue with undiminished enthusiasm the possibility of a new physics, the investigation of the atomic alternative awaits the definitive test. Such a test would involve a study of the angular distribution of the electrons and/or positrons with a different geometry than that used by the G. S. I. EPOS group. [15]

Such an investigation would produce more than positive or negative results, proving or disproving the particle (or new Q. E. D. phase) explanations. If the

G. S. I. results in fact arose from molecular interactions, this would be the beginning of a new field of atomic physics, involving for the first time excitation from the negative energy, positron continuum into the positive energy, electron continuum. [27]

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