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Faith, Endeavour and Expectations of an Unfinished Quest: A Tribute to Emilio Santos on his Seventieth Birthday

1. BIOGRAPHICAL NOTES

Emilio Santos was born on October 7, 1935 in a small country village of Extremadura, Spain, called San Vicente de Alcántara, but three years later his family moved to Valladolid in the throes of the Spanish Civil War. At Valladolid University he obtained the degrees of M.Sc. and Ph.D. in chemistry in 1957 and 1962, respectively. His Ph.D. research, based on quantum chemistry methods, had the title "Formation Energy of Vacancies in Graphite Crystals" and was part of a collaboration with Prof. Charles Coulson of the University of Oxford, one of the pioneers of quantum chemistry. In 1965, he earned his second Ph.D. this time in physics, with a research topic in analytical mechanics.

From 1964 to 1967 Emilio Santos served as an extraordinary professor at the University of Costa Rica (Central America), but he returned to his native Spain in 1967 to take up a post, first as temporary professor and then as associate professor in atomic and nuclear physics at Valladolid University. Santos became a full professor in theoretical physics in 1976 at Cantabria University, Santander, where he still remains and where he has also been the dean of the faculty of sciences, from 1981 to 1984, and then head of department of modern physics, from 1984 to 1989. In 1998 he was awarded the prestigious Medal of the Spanish Royal Society of Physics.

Any intellectual biography of Emilio Santos, however brief, would be incomplete if it did not also highlight his role as an outstanding teacher. Since the beginning of his academic career, Emilio has devoted great attention to the training of young scientists, notable evidence of which is his supervision of 14 doctoral theses. His guidelines have always been an emphasis on the creative character of scientific research and the rich rewards in terms of personal satisfaction resulting from the generation of new knowledge. He also saw the necessity of establishing competing stable research groups, which he did both at the University of Valladolid—where there exists a strong group in atomic and molecular physics founded by him—and at Cantabria University, which is a center of research on dynamics of complex systems, laser diodes, nuclear physics and nanotechnology. His former students remember Professor Santos for his profound knowledge of physics and its applications, his clear and enthusiastic teaching of the most difficult concepts, his patience and approachability, and for his help and understanding of the difficulties in learning.

2. THE DRIVE TO RESTORE REALISM AND LOCALITY TO THE FOUNDATIONS OF PHYSICS

Due to his wide-ranging interests and motivation, the research areas to which Emilio Santos has devoted his attention are numerous and diverse. We will sort them into four main groups—by chronological order, even though a constant feature is their overlapping in time and Santos's success in focussing his attention on all of them over the years.

The *first* research area is the theoretical study and calculation of the electronic structure of atoms, molecules, and solids, as well as the investigation of the properties of atomic nuclei. Santos's interest in the electronic properties of matter led him to realize immediately the significance and enormous possibilities of methods based on the electron density for the calculation of the electronic structure of materials. Hohenberg, Kohn, and Sham in the mid-1960's generalized these methods, initiated by Thomas, Fermi and Dirac, which established the foundations of what is now called density functional theory (DFT). At that time physicists were applying them energetically to the study of the electronic properties of atoms, molecules, solids, and even nuclei. Around twenty years later, chemists became interested in DFT, making such extensive use of the method that DFT has become the standard theoretical formalism for the investigation of the electronic structure of materials. Working with his students at the University of Valladolid, Emilio Santos started the pioneering work on DFT in Spain in the early 1970s, applying density-based methods to study the surfaces of nuclei and the interaction between layers of graphite. Emilio Santos found that, for separations around the equilibrium distance, the weak binding between planar graphite layers is due to the interaction between the orbitals and can be ascribed to energy lowering due to the electronic rearrangement occurring when the electronic densities of adjacent layers overlap. That is, the binding is not simply a van der Waals interaction.

The *second* significant subject matter of Emilio Santos' research centers around special and general relativity theories. This includes the application of relativistic statistical mechanics and the study of the equilibrium between matter and radiation in multiperiodic relativistic systems. To these pursuits should be added, in recent years, the equilibrium of relativistic stars with local anisotropy.

The *third* area of his research deals with the formulation of stochastic electrodynamics (SED), before 1984, and with that of stochastic optics, after 1984; this last work has been executed primarily in collaboration with T. W. Marshall.

In the summer of 1967, Santos arrived at the principles of SED when trying to understand the stability of the hydrogen atom. He found that the traditional argument against the planetary model of the atom was incomplete on one point. It is true that, according to Maxwell's theory, an electron in orbit around the nucleus would emit energy in the form of electromagnetic radiation, making that configuration unstable and causing the rapid collapse of the atom to nuclear dimensions. However—and this is the important point—this collapse is what would occur if only one atom existed. But in reality there are a huge number of atoms in the universe; and, if all of them radiate, the expectation is that every atom would be immersed in a sea of random electromagnetic radiation, a field that cannot be eliminated even at zero degrees Kelvin, one that has become known as the zero-point field (ZPF). Thus the electron, acted on by this random field, should be restless with a zero-point energy. Hence, as electromagnetic theory predicts, any atom would indeed radiate, but at the same time it would also absorb energy from the ZPF, the ground state of the system corresponding to a distribution in which emission and absorption of energy would cancel on average. From this point onwards, and in the quest of a clear picture of the microworld, Santos understood that the ZPF should have a Lorentz-invariant distribution of frequencies, and he began to study the action of the field on the electron. He had just rediscovered SED, which was originally introduced in 1954 by Braffort and then rediscovered independently by T. Marshall in 1963. However, the failure of SED to provide a proper derivation of Planck's radiation law and to furnish an understanding of the discrete eigenstates of atoms, the Compton effect, and Pauli's principle, along with the difficulties of getting a transparent derivation of the Schrödinger equation, weakened Santos's confidence in SED as a representational tool for interpreting quantum theory.

In the 1980's, as a consequence of the wide interest generated by the work of John Bell together with the reactions to the results of the experiments carried out to test his inequalities (in particular, those done by A. Aspect *et al.*), Santos's attention was re-directed to a study of the performed experiments. The combination of his analysis of the Bell-type experiments with the concepts of the SED led him and T. W. Marshall to the development of stochastic optics (SO). The essential idea of SO is to combine classical wave optics with the presence of the ZPF. In this theory there are no photons, just wave packets superimposed on the ZPF. The corpuscular behaviour of radiation was understood by taking into consideration that, besides the electric field incident, for instance, on a beam-splitter, there is also a ZPF entering into all channels of the beam-splitter. The final consequence of this being that in one outgoing channel the intensity is below the ZPF level and in the other it is above, or vice versa. Assuming that photon counters have a detection threshold just above the ZPF level, it will be possible to detect a signal only in one of the outgoing channels, thus explaining the corpuscular behaviour of light. Along these lines, and using the Wigner function formalism, Santos and T. W. Marshall were able to explain all Bell-related experiments carried out with the help of parametric down-conversion devices. Even entanglement—one of the most intriguing aspects of quantum theory—finds an explanation as a correlation between two light beams involving the ZPF; in classical correlations, the light beams are merely superimposed on the ZPF. From this point of view, quantum optics can be understood as classical optics plus the ZPF. Nevertheless, Santos is exceptionally aware that some challenges are still remain to be resolved within this restricted frame. Among these, he points out that his studies should be extended to the entire electromagnetic spectrum and that a similar scheme should be introduced for the case of the Fermi fields. The scope of his theory must be extended to encompass particles without charge, neutrons for example, and the detection problem (why does the ZPF not give rise to the spontaneous activation of photodetectors?) should be properly addressed.

Although the Santos line of investigation is not part of mainstream research into the foundations of quantum physics, the impact of the developments it has spawned should not be minimized. Indeed, they provide new computational tools, useful for the resolution of some other problems; they furnish an explicit local-hidden variable model in the domain of quantum optics; they also could contribute to a deeper understanding of the connections between classical and quantum theories; and lately (supposing this to be the end of the endeavour) they could result in an alternative interpretation of quantum mechanics.

As outlined above, Emilio Santos obviously is a superb scientist, but to understand the origins of his scholarly achievements, we need to lay bare his underlying vocation. Contrary to what is often maintained, philosophical reflection does not necessarily start with "the doubt" (regarding some previous beliefs), but rather with the adherence to some certainties. Emilio Santos begins with the perceived certainty of some principles and from that basis embarks on his truth-seeking philosophical reflections. One could say that at his core he has the soul of a philosopher. We may introduce this complementary side of his thinking by quoting him verbatim from a recent paper: "*The fact that in several instances accepted theories of physics seem to contradict some general (might I say philosophical?) principles… impressed me deeply since the beginning of my scientific career, to the point that I have devoted most of my research work to try to understand (if not solve) the said contradictions.*" It is in this context where one can discern the *fourth* and last area of Santos intellectual curiosity, the one in which he has perhaps invested his finest efforts.

Which principles are those that could be in conflict with accepted theories of physics? On different occasions Santos has written that these principles are:

(i) *Realism*, that is, the *belief* that physical entities have properties independent of any observation and that the results of any possible measurement depend on these properties. Probabilities must appear then primarily due to our ignorance.

(ii) *Locality*, that is, the *belief* that no influence can be transmitted with a speed greater than that of light.

(iii) Empirical *evidence*, that is, the *fact* that experiments must be the final arbiter.

Nevertheless, these principles, although they are the methodological determining factors, do not all have the same relevance. Realism is, for Emilio Santos, so important that physics itself would be impossible without accepting it. On the other hand, locality derives from our macroscopic experience and might thus be violated without destroying physics. But, in spite of *local realism* being a fundamental principle of physics, Santos would be prepared to reject it *if*, and only if, experiments clearly show that it is untenable. On this basis, his desire for understanding has led him unavoidably to the foundations of physics and, in particular, to the foundations of quantum mechanics: the so called EPR paradox, Bell's inequalities, hidden-variables theories and even quantum logic (research done mainly in collaboration with Jaroslaw Pykacz). All these topics have been for him a real passion during the last 25 years.

Different experiments, carried out to test some predictions of quantum theory, close different loopholes. But, strictly speaking, even after all the checks that have been done in the last 40 years, no investigation has been realized that closes all the loopholes in one and the same experiment. Thus, even if all the loopholes have been closed one by one, Santos maintains that "*the agreement of these experiments with quantum mechanics leaves untouched the question of local realism*." The impulse to restore realism and locality stems from the inconclusiveness he sees in these experimental results.

The challenge of performing a valid and definitive loophole-free test and that of understanding the origin of the quantum correlations (we have given above his solution to this challenge for the particular case of photons), are still open questions. Fortunately, the relevant quest continues undeterred.

Given the extraordinary success of quantum theory, the fundamental relevance of local realism and the nonexistence of a loophole-free test, Santos has, for at least the last 15 years, cherished the idea that may be quantum mechanics and local realism are compatible at the empirical level: "*Time is reinforcing the conjecture that there are fundamental principles preventing the violation of a Bell inequality*." The expectation is that, perhaps, they meet beyond our present horizon. Who knows? Time will tell.

This is where we must leave our brief depiction of Emilio Santos as a scientist–philosopher. But no homage to him would be complete that does not pay due respect to the endearing human qualities of the man behind this picture. Famed for his honest and forthright modesty and known as someone who has an absolute respect for the opinions and points of view other than his own, Emilio enjoys the fondest regard and deepest admiration from all those who have been fortunate enough to meet and know him. Foremost among these are his colleagues who have contributed research papers to this and the next special issues of *Foundations of Physics,* along with our coworkers Ignacio Cirac, Susana F. Huelga, and Marek Zukowski, who have assisted us in organizing this *festschrift*. All of them join us in (belatedly) wishing Emilio a happy 70th birthday. Our fondest hope is that he will, in good health, enjoy an abundance of personally rewarding scientific discoveries in the years ahead.

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