IRPS BULLETIN

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Special Issue: FOCUS on FANO

Ugo Fano pioneered much important work on how electromagnetic radiation and the atoms in matter interact with each other. In the 1930s in his formative years following his doctorate from Turin, he worked in Enrico Fermi's famous Rome group and interacted there not only with Fermi but also with many other famous scientists including Arnold Sommerfeld, Niels Bohr, Edward Teller and George Gamow. Emigrating to the United States, he worked at the National Bureau of Standards (now NIST) for twenty years before taking his Chair at the University of Chicago. Fano's work on the excitation of quasi-bound states of electrons buried in a continuum of energy levels in a solid continues to be widely applied to this day (the Fano line-shape of radiation). Fano received many scientific awards in his lifetime. It is appropriate that one of the most prestigious was the Enrico Fermi Award in 1995, six years before his death in Chicago in 2001.

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Contents of this Journal

From the Editors

Welcome to Volume 30 No 1 of your International Radiation Physics Society (IRPS) Bulletin. This time around we attempt a "special focus issue" on Ugo Fano, the Italian American physicist known for his fundamental contributions to radiation physics. As a group leader at the National Bureau of Standards in the US, he would go around the room in group meetings asking each person three questions:

[1] What are you doing? (Ugo's 1st question)

Our newly-elected IRPS President, Christopher Chantler, thoroughly addresses the "What is IRPS doing?" in his first President's Column beginning on page 4 of this issue. Included are our broad scope and the technical meetings and journals to which this scope has led us thus far. As for this issue of the Bulletin, we dig into the NIST archives and other sources that highlight some of the seminal contributions and accomplishments of Ugo Fano. As usual, you will also find notices of upcoming conferences and calendar items, as well as our standing invitation for news items related to your radiation physics speciality (gravity waves, anyone?) and other interesting activities from your part of the world. In particular, now is the time to register for the 2nd International Conference on Dosimetry and its Applications (ICDA-2), to be graciously hosted by David Bradley and others at the University of Surrey, Guildford, United Kingdom, 3-8 July 2016.

[2] Why are you doing it?
(Ugo's 2nd question)

Here again, our new president references the Society web site

http://www.canberra.edu.au/irps

which states that the primary objective of the IRPS is to promote the global exchange and integration of scientific information pertaining to the interdisciplinary subject of radiation physics. The newly-revised IRPS Constitution provides the current social and technical contexts that motivate our participation in an international radiation physics society. The revised IRPS Constitution may be found beginning on page 35 of Vol. 29 No 2 of the IRPS Bulletin.

[3] Why don't you stop?
(Ugo's 3rd question)

With that, we shall STOP this column so you can get on to the good stuff!

Larry Hudson and Ron Tosh, Editors

FROM THE PRESIDENT

Dear Friends and Colleagues -

As this is my first column as President of IRPS let me remind us of what we come together for, both in the Society and in the International Conferences we sponsor.

[From the Web site and Constitution]: The primary objective of the **International Radiation Physics Society** (IRPS) is to promote the global exchange and integration of scientific information pertaining to the interdisciplinary subject of radiation physics, including the promotion of

1. theoretical and experimental research in radiation physics,
2. investigation of physical aspects of interactions of radiations with living systems,
3. education in radiation physics, and
4. utilization of radiations for peaceful purposes.

Our Council Members and other members clearly get involved in all of these, though likely each member will concentrate in one or another of these key areas.

The Constitution of the IRPS defines Radiation Physics as "the branch of science which deals with the physical aspects of interactions of radiations (both electromagnetic and particulate) with matter." It thus differs in emphasis both from atomic and nuclear physics and from radiation biology and medicine, instead focusing on the radiations.

So we can be excited and gratified by the discovery of [classical] gravity waves announced 12 February, which has been the subject of rumours over the last few months; and we can be excited and gratified about the discovery of the Higgs-like boson, now confirmed as very likely the Higgs boson; and we recognise that these discoveries were all based on detailed and advanced radiation science, sources and detector technology.

We coordinate and sponsor three main conference series: ISRP, IRRMA and ICDA at the moment (see more details elsewhere in this bulletin and get involved as much as you can!). Each of these occurs once every three years, and membership runs for three years, and each of these has discounted registration fees for these conferences as members; so if you only go to one of these, you are likely to fully offset your membership - if you go to all three you will recoup your membership fees and be well ahead!

The International Symposium of Radiation Physics, ISRP: The event is devoted to current trends in the broad area of radiation physics and more than 350 attendees from all over the world may participate. This conference series includes two categories of invited talks. The first one is expected to be a review of a specific area, covering the historical development, the current situation and future perspectives within both experimental and theoretical aspects. The second deals with the hot topics and projects in the Radiation Physics Area. Submitted papers will be presented in oral or poster format.

[Typical] **Conference topics:**

- Fundamental Processes in Radiation Physics
- Theoretical investigation and Quantitative analytical techniques in radiation physics

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- New radiation sources, techniques and detectors
- Absorption and Fluorescence spectroscopy (XAFS, XANES, XRF, Raman)
- Applications of Radiation in quantum control
- Applications of Radiation in Material science, Nano-science and Nanotechnology
- Applications of Radiation in Biology and Medical science
- Applications of Radiation in Space, Earth, Energy and Environmental sciences
- Applications of Radiation in Cultural heritage and Art
- Applications of Radiation in Industry
- Radiation physics and Nuclear fuel cycle

IRRMA: The International Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications *(IRRMA)* is a triennial event organised with the purpose of bringing together scientists and engineers from around the world who share an interest in radiation and radioisotope measurement applications. It is devoted to current trends and potential future issues involving radiation and radioisotopes. The technical sessions will include invited lectures by leading experts in their fields, contributed oral papers and poster presentations of contributed papers.

Attendees have an opportunity to share ideas on industrial uses of radiation and radioisotopes, and also on research and applications in related fields such as Biomedical Applications of Radiation, Art and Cultural Heritage, Monte Carlo Methods and Models, Radiation in Environmental Sciences, Detection of Threat Material and Contraband, Radiation Protection, Shielding and Dosimetry, Radiation Effects on Materials, Radiation Detection and Measurements, and other topics.

International Conference on Dosimetry Applications, ICDA: A new triennial series of conferences, devoted to current trends and potential future issues in ionising radiation dosimetry. The scientific sessions will include invited lectures by leading experts in the field, contributed oral papers and poster presentations of contributed papers. Participants will have an opportunity to share ideas on all theoretical and experimental aspects of dosimetry, and on its applications in radiation protection, the environment, workplaces, medicine and other fields of human activity.

1. Topics: Basic Concepts and Principles in Dosimetry
2. Personnel Dosimetry
3. Accidental Dosimetry
4. High Dose Dosimetry
5. Dosimetry in Environmental Monitoring
6. Dosimetry in Medicine and Biology
7. Dosimetry in the Nuclear Industry and at Accelerators
8. Standardization and Intercomparison in Dosimetry
9. Monte Carlo Calculations in Dosimetry
10. Other Topics

Web-site: We currently have two parallel web-sites

http://www.canberra.edu.au/irps

and

http://radiationphysics.org/index.php

but this should be developed or simplified over the next few months. In the meantime, do feel

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free to browse and make use of e.g. past articles and contributions and to see the number of related conferences involved in the Society. Further, this is where Paypal on-line payment dues will generally be accepted and do note that the costs for students are minimal.

Bulletin: All members receive the periodical Bulletin of the Society, which has announcements of related meetings, topical and review articles and membership pages. It is available on-line and gets posted to the Web-site, and is sent electronically to all members. It is an occasion to keep in touch and some of the articles are excellent reviews or topical comments.

Journals: Members of the Society, and the executive, are strongly involved in numerous high-profile international journals. Perhaps chief amongst these is Radiation Physics and Chemistry, of which I am Editor-in-Chief. This is a great forum for the Society and indeed several of our Conference Proceedings can be published herein. However, one should note at least strong links to Applied Radiation and Isotopes (ARI) and Radiation Measurements, together with other journals that have good relations or editorial responsibilities with our members. So in whatever capacity you might be involved, we welcome you to join and participate in all the activities and outcomes of the Society.

That is certainly an introduction to a few of the key areas of our society, and I look forward to our engagement on any and all topics in the future.

Chris Chantler

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SPECIAL FOCUS ON UGO FANO

From The NIST Archives

A few from the old Radiation Theory Section at Ugo Fano's 1988 NIST Portrait Gallery induction of Distinguished Scientists, Engineers, and Administrators.

From left to right: Steve Seltzer, Martin Berger, Lew Spencer, John Hubbell, Evans Hayward, Ugo Fano (blue tie).

In the 1950s, Fano led Lew Spencer, Martin Berger, and others in developing methods for treating the transport of photons and charged particles in matter. This has resulted in the widely-used radiation interaction cross section databases presently maintained at NIST.

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For an autobiographical reminiscence, see: "The Memories of an Atomic Physicist for My Children and Grandchildren" by Ugo Fano, Physics Essays, Volume 13: Pages 176-197, 2000 .

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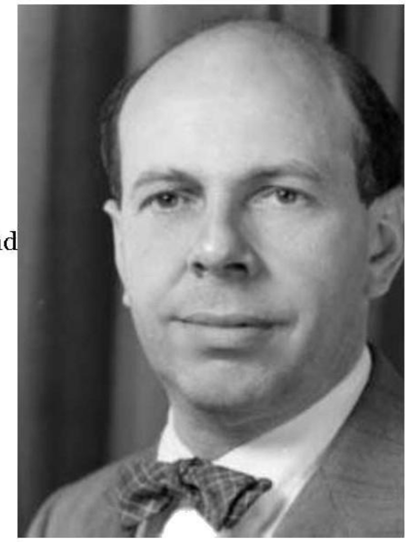

UGO FANO
Inducted: 1988

Citation:
For his service as the first NBS purely theoretical physicist, focusing particularly on atomic physics, and for his efforts in physics education, through his service as Associate Editor of the Reviews of Modern Physics and his authorship of an atomic physics text for non-physicists.

Tenure: 1946 - 1966

Birth: 1912, Turin, Italy
Death: 2001

Education:
University of Turin, ScD (Mathematics), 1934

Principal fields:
Theoretical and atomic physics

Positions held:
Chief, Nuclear Physics Section (later Radiation Theory Section)
Special Research Assistant to the Director
Senior Research Fellow

Honors:
Rockefeller Public Service Award, 1956
U.S. Department of Commerce Gold Medal, 1957
NBS Stratton Award, 1963
Enrico Fermi Award, 1995

Memberships:
American Physical Society (Fellow)
Radiation Research Society
National Academy of Sciences
American Academy of Arts and Sciences
Accademia Nazionale dei Lincei, Rome

Publications:
Author of many technical papers; Associate Editor of *Reviews of Modern Physics*; author of several books, including *Basic Physics of Atoms and Molecules*, Wiley, 1959, a book on quantum physics for non-physicists.

Special Focus on Ugo Fano ... Continued

Article by Antonio Bianconi

Ugo Fano and Shape Resonances

Antonio Bianconi

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Abstract. Ugo Fano has been a leader in theoretical Physics in the XX century giving key contributions to our understanding of quantum phenomena. He passed away on 13 February 2001 after 67 years of research activity. I will focus on his prediction of the quantum interference effects to understand the high-energy photoabsorption cross section giving the "Fano lineshapes". The Fano results led to the theoretical understanding of "shape resonances" (called also "Feshbach resonances") that should be better called "Fano resonances". Finally I will show that today this Fano quantum interference effect is behind several new physical phenomena in different fields.

Ugo Fano was born in Turin, Italy, on 28 July 1912. His father Gino Fano (1871-1952) was professor of mathematics at Turin, Italy, specializing in differential geometry. He has spent his childhood mostly in Verona at "villa Fano" where he developed a love for mountains hiking and rock climbing. He studied Mathematics at University of Turin, but after the "Laurea" he turned his interests on physics following the lectures of Enrico Persico (coming from the Fermi's group in Rome) on theoretical physics and discussions with his cousin Giulio Racah (1909-1965), a theoretical physicist known for the powerful theory of angular momentum. He moved on 1934 to Rome to work with Enrico Fermi where he worked in the period 1934-1936. In these years the Fermi's group shifted from atomic physics to the new experimental nuclear physics. They focused on systematic researches on the absorption and scattering properties of slow neutrons and discovered the artificial radioactivity induced by slow neutrons [1]. The fact that the cross-section is high for small neutron velocities [2] was interpreted as due to the capture of a neutron by a nucleus at a scattering resonance called "risonanza di forma" ("shape resonance").

Fano addressed his interests not on the experimental work, that was the main interest of the Fermi's group, but on the application of quantum theory for interpreting strange looking shapes of spectral absorption lines. Fano investigated the stationary states with configuration mixing under conditions of autoionization introduced by Rice [3] and he pointed out the basic physics of the quantum interference phenomenon between a discrete level and a continuum [4]. This theoretical result in atomic physics is related with the resonant scattering of a slow neutron in a nucleus, the "shape resonances", found by Fermi. In fact it deals with processes inverse to those

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considered in the Fano's theory of autoionization. This is a scattering process, in which the system is formed by combining an incident particle b with the "rest" and then the system breaks up releasing alternatively either the same particle b or another particle c. In this process the interference of resonance and potential scattering amplitudes gives a large reaction cross section. The theory for the nuclear scattering cross-section was developed by Breit and Wigner in 1936 [5].

In 1936-1937 Fano worked in Leipzig with Werner Heisenberg and he visited Arnold Sommerfeld, Niels Bohr, Edward Teller and George Gamow. From Germany Fano moved to Paris with the Joliot - Curie group. Fano returned to the University of Rome as a lecturer in 1938.

In these years Fano started to address his interests to radiation biology and genetics that will become central topics for his later research. It is noteworthy that, after a seminar in Rome by P. Jordan on x-ray effects on genetic material, Fermi had suggested to Fano that the biological action of radiation would be an important and suitable topic for study. He was in close contact with his school friend Salvatore Luria who moved from Turin to Rome where from 1935-1940 was in charge of Medical Physics and Radiology under the direction of Enrico Fermi and Edorado Amaldi. In 1939 Fano married Camilla ("Lilla") Lattes, who collaborated with him in science and worked as a teacher for many years. In the same year the couple immigrated to the United States in 1939 to escape the racial laws.

He was at the University of Michigan summer school at Ann Harbor in 1939 when Werner Heisenberg and Edoardo Amaldi visited Fermi in the states. Once he told me that during a party in August he became aware that for everybody there it was clear that Fermi and Heisenberg would become the leaders of the USA and German projects for the nuclear bomb. At this point he decided not to work in nuclear physics being interested on other science issues. He focused on the interaction of Radiation with matter and in particular on effects of radiation on living organisms (genetic resistance to radiation effects). In 1940-1944 worked with the help of his wife in what was later to be called radiation biology at the Department of Genetics of the Carnegie Institution at Cold Spring Harbor. Fano's papers in this period concerned chromosomal rearrangement mutations, lethal effects, and genetic effects of X-rays and neutrons on Drosophila melanogaster, as well as theoretical analysis of genetic data. His work also included the discovery of bacteriophage-resistant mutants in Escherichia coli, following up earlier studies by Salvador E. Luria who moved to USA in 1939 and visited the Carnegie Institution.

After the war in the years 1946-1966, he joined the staff of National Bureau of Standards (NBS), initially working in the radiological physics group led by Lauriston S. Taylor and after in the basic physics of atoms, molecules, and condensed matter elucidating fundamental physical processes.

In the fifties the scientific interest for "shape resonances" was coming up again, in fact the availability of monochromatic neutron beams at nuclear reactors allowed the measure of the neutron cross section on selected nuclei as a function of neutron energy. The trapping of the slow neutrons for long time inside the nuclei has been clearly shown to be at the origin of resonances for neutron capture. The theory of

 ../Continued

FIGURE 1. Ugo Fano

"shape resonances" in the frame of potential scattering was developed by J.M. Blatt and V. F. Weisskopf [6] and later by Herman Feshbach in 1958 [7] for a general nuclear reaction theory, based on the projection of the nuclear state into direct and compound channels, following the method introduced by Fano [4]

The "shape resonance" occurs when a quantum particle with energy E and wave vector $k=2\pi/\lambda$ is trapped within a potential well with finite barrier of a given size R given by the radius of the nucleus, with the generic condition for the shape resonance: $R = n\,\lambda/2$ where n is an integer. The name "shape resonance" indicates the fact that the shape of the potential barrier determines the energy of the resonance, therefore they have been used in 1949-1954 by Edoardo Amaldi and others to measure the size of the nuclei of several elements with the precision of $\pm 10^{-13}$ cm [8].

In these years the interest of Fano returns to this phenomenon following the extensive investigation of line profiles of high energy levels of excitation in the far-UV absorption spectra in atomic and molecular spectroscopy undertaken by means of far-ultraviolet light of electron bombardment and also of energy transfer in molecular collisions. The Fano prediction and interpretation of the experiments on the excitation of quasi bound states buried in continua was his major outcome in these years [9] and the review paper on the "*The theory of atomic photoionization*" remains as a relevant milestone in the physics of XX century [10]. He has shown that lineshape of the absorption lines (Fig. 2) in the ionization continuum of atomic (and molecular) spectra are represented by the formula

$$\sigma(\varepsilon) = \sigma_a \left[\frac{(q+\varepsilon)^2}{1+\varepsilon^2} \right] + \sigma_b \qquad (1)$$

where $\varepsilon = \frac{E - E_r}{\Gamma/2}$ indicates the deviation of the incident photon energy E from the idealized resonance energy E_r which pertains to a discrete auto-ionizing level of the atom. This deviation is expressed in a scale whose unit is the half-width $\Gamma/2$ of the line

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($\hbar/\Gamma$ is the mean life of the discrete level with respect to autoionization). $\sigma(\varepsilon)$ represents the absorption cross section for photons of energy E whereas σ_a and σ_b are two portions of the cross section corresponding to transitions to states of the continuum that do and do not interact with the discrete auto-ionizing state respectively. Finally q is a numerical index which characterizes the line profile.

Thus, he encouraged Robert P. Madden and co-workers at NBS to use synchrotron radiation for spectroscopic studies. He convinced his old friend Edoardo Amaldi and Mario Ageno to push the Italian scientific community to use the Frascati synchrotron as a synchrotron radiation source for high energy spectroscopy of atoms and solids.

In 1966 he joined the Physics faculty of Chicago where he continued his research on the interaction of radiation with matter. I was still in my twenties when I had the possibility to meet him regularly in the years 1971-1976. He used to come to Rome each summer in June-July, spending his time in Frascati Laboratories with the small group of synchrotron radiation researchers: Adalberto Balzarotti, Emilio Burattini, Mario Piacentini and myself. I remind very nice days discussing the x-ray absorption spectra measured at the new Frascati soft x-ray synchrotron radiation beam line. He informed me on the resonances observed in the scattering of electron on nitrogen molecule that were described by Dehmer and Dill with the same formalism of his "shape resonances". These discussion led me to the interpretation of the x-ray absorption near edge structure (XANES) in complex solids and metalloproteins in term of "shape resonances" of the excited photoelectron within a finite cluster of atoms surrounding the absorbing atom [11,12].

The Fano quantum interference effects have been observed in modern experiments of photo-fragmentation [13]. Here the Fano quantum interference appears when a

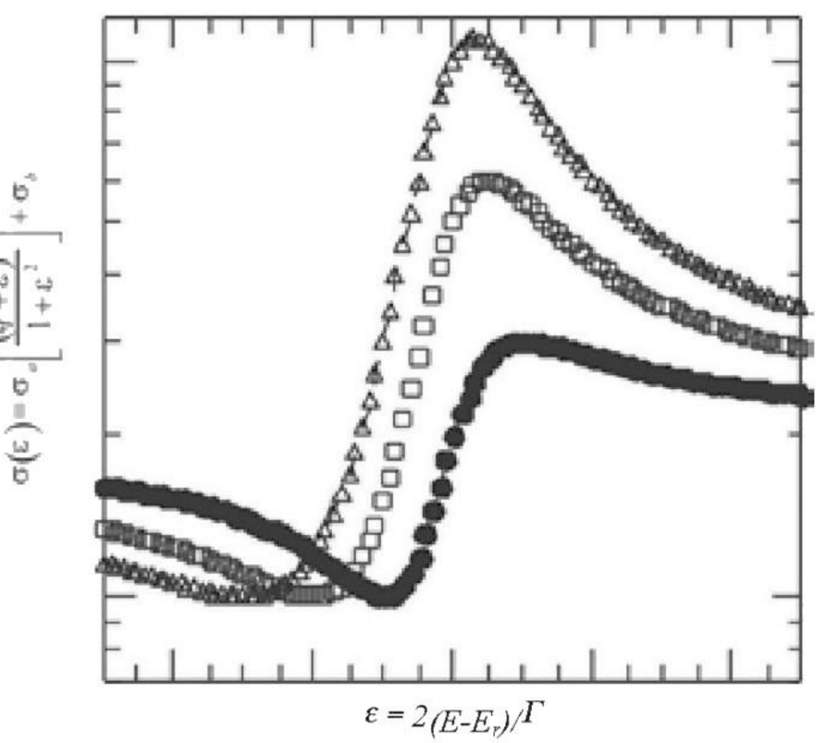

FIGURE 2. The Fano lineshape of the absorption cross near resonance energy E_r of a discrete state buried in the continuum for various values of the q parameter.

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quantum state is formed at the resonance energy E_r above the fragmentation threshold of the system. The variation of the cross section in the neighborhood of the energy of fragmentation resonance follows the Fano lineshape. In the field of photo-fragmentation these resonances are usually classified into "Feshbach resonances" if several (n>1) electronic transitions are required to emit one electron or "shape resonances" if only one electronic transition is required to emit one electron. However this classification makes sense only if the lifetimes of the resonances are not larger than the typical vibrational time of the system, otherwise the distinction is not clear. The quantum mechanical phase shift and consequent interference effects encountered on passing through a shape resonance energy have been studied by many authors and they can be seen as a movie on the web [14].

In 1963 it was pointed out by Thompson and Blatt [15] that the basic physics of the quantum interference between a discrete state and a continuum introduced by Fano predicts the amplification of the superconducting critical temperature in a superconducting film of thickness R if $R=\lambda_F/2$ x integer, where λ_F is the wavelength of the electrons at the Fermi level. This prediction did not work since in a single film phase fluctuations suppress the condensate phase coherence. In 1993 we have shown that the "shape resonance" amplification works in a superlattice of superconducting wires [16] where the enhancement is obtained by tuning the Fermi level at a "shape resonance" of the superlattice of period $L=\lambda_F/2$ x integer. The quantum interference effects between the pairs in a narrow band and in a wide band give two superconducting gaps in two different bands in momentum space and in real space, that has been recently confirmed in the new MgB_2 superconductor made by a superlattice of boron layers [17].

In 1995 the Bose Einstein condensation (BEC) of atoms trapped magnetically in a vacuum and cooled to a few billionths of a degree above absolute zero has been achieved [18]. This ultracold atomic gas is dilute system in which the interparticle interactions are weak and easy to be treated theoretically. It has been found that using a magnetic field it is possible to trap the atoms into Feshbach resonances (19) and it is possible to control the fundamental interactions (20). Moreover the inhomogeneous trapping potential leads to spatial separation oh high- and low-energy atoms, giving rise to a Fermi surface that is manifest in the real as well as in the momentum space. Recently the onset of Fermi degeneracy in a ultracold gas of fermions has been reported [21]. Here the pairing interaction between fermions could be controlled by tuning the system to a "Feshbach resonance" and the condensation of pairs (as in He_3) could become possible, similar to Cooper pair formation in superconductivity. This process will be similar to the T_c amplification by "shape resonance" in high T_c superconductors [16].

The Fano lineshapes have been seen also in the zero bias conductance as a function of the gate voltage in a single electron transistor [22]. Here an artificial atom is created by making a layer of GaAs on top of which is a layer of AlGaAs doped with Si. The electrons from the dopants fall into the GaAs, and the resulting positive charge on the Si atoms creates a potential that holds the electrons at the GaAs/AlGaAs interface, creating a two dimensional electron gas. The quantization of energy and charge makes

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the confined droplet of electrons closely analogous to an atom. The resonance component in the Fano interference appears to come from the single electron charging of the artificial atom interacting with a continuous component.

In conclusion I have shortly focused only on a particular aspect [4,9,10] of the wide scientific activity of Ugo Fano since he had a relevant influence on my personal scientific activity and today its 1935 paper [4] is stimulating new physics.

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Special Focus on Ugo Fano ... Continued

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Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. **110**, 583-587 (2005)]

On the Absorption Spectrum of Noble Gases at the Arc Spectrum Limit

This article can also be found online at : http://dx.doi.org/10.6028/jres.110.083

Volume 110 | Number 6 | November-December 2005

Ugo Fano[1], **Guido Pupillo, Alberto Zannoni, and Charles W. Clark**

National Institute of Standards and Technology,
Gaithersburg, MD 20899-0001

Rydberg spectral lines of an atom are sometimes superimposed on the continuous spectrum of a different configuration. Effects of interaction among different configurations in one of these cases are theoretically investigated, and a formula is obtained that describes the behavior of absorption spectrum intensity. This offers qualitative justification of some experimental results obtained by BEUTLER in studies of absorption arc spectra of noble gases and I^b spectra of some metal vapors.

Key words: absorption spectrum of noble gases; Fano resonance.

Accepted: October 11, 2005

Available online: http://www.nist.gov/jres

1. Introduction

This translation was undertaken to make accessible to readers of English a foundational paper on the theory of spectral line shapes, “Sullo spettro di assorbimento dei gas nobili presso il limite dello spettro d’arco,” U. Fano, *Nuovo Cimento*, *N. S.* **12**, 154-161 (1935).

The results of this paper are widely known via a subsequent publication by the same author in the Physical Review in 1961. [1] The 1961 paper has been cited more than 4500 times, and it was judged to be among the most influential papers published in the history of *The Physical Review* journal series, according to a recent study that examines both numbers and time series patterns of citations. [2] It is, by a considerable margin, the most-cited paper that has been published under the byline of the National Bureau of Standards/National Institute of Standards and Technology (NBS/NIST). [3]

The 1935 paper translated here lacks the generality of the 1961 paper, but its results are identical for an important limiting case, and it should be considered to be the first paper which correctly elucidates the general form of line shapes encountered in the excitation of many important atomic and condensed-matter systems. In particular, it treats the case in which a discrete state coexists in the same energy region as a continuum of states, and accounts for the interaction between the discrete and continuum states, and the interference between their separate excitation amplitudes. The key line-shape formula derived in the 1935 paper is identical in a practical sense to that of the 1961 paper, which is now famous as the “Fano profile”: it does not include a shift in the discrete-state energy due to its interaction with the continuum (as does the 1961 paper), but this is not a direct observable.

In addition to its historic interest, the 1935 paper presents its subject in a remarkably clear way, no doubt reflecting the influence of Enrico Fermi, who was Ugo Fano’s supervisor at the time. It does not use the somewhat formidable mathematical apparatus of the 1961 paper, and it offers insights which may still seem fresh even to those familiar with the subject matter (for

[1] Deceased

example, Fano's observation of how a discrete state with zero excitation amplitude can cause the total excitation probability to vanish at its own energy).

Note on the text: the original publication does not identify equations by number. Equation numbers have been added in the translation for readers' convenience.

The editors are grateful to the Societa Italiana di Fisica for permission to publish this translation, and to Ms. Susan Makar, of the NIST Research Library of the National Institute of Standards and Technology, for much helpful assistance.

2. Text of the Translation [Nuovo Cimento 12, 154-161 (1935)]

On the Absorption Spectrum of Noble Gases at the Arc Spectrum Limit

Ugo Fano

Rydberg spectral lines of an atom are sometimes superimposed on the continuous spectrum of a different configuration. Effects of interaction among different configurations in one of these cases are theoretically investigated, and a formula is obtained that describes the behavior of absorption spectrum intensity. This offers qualitative justification of some experimental results obtained by BEUTLER in studies of absorption arc spectra of noble gases and I^b spectra of some metal vapors.

It is experimentally known that arc spectrum series of noble gases do not converge toward a single limit, but toward two distinct limits. The explanation is that removal of the optical electron from a noble gas atom yields an ion whose ground configuration does not consist of a single level, but rather a doublet ${}^2P^o_{3/2}$, ${}^2P^o_{1/2}$. The interval between the doublet's levels is about 1500 wave numbers for A, 5000 for Kr, and 10000 for Xe. Within this interval, two different kinds of arc spectrum terms can occur: a) continuous spectrum terms represented by the formula $(p^5)_{3/2} + \textit{free electron}$; b) discrete spectrum terms represented by the (*jj* coupling) formula $(p^5)_{1/2}nl$; the latter belong to series that converge toward the ${}^2P^o_{1/2}$ limit. In a recent work ([1]) BEUTLER investigated absorption spectra of noble gases, obtaining the following results. At very low pressure of the noble gas (0.002 mm), continuous absorption with a regular behavior is observed for frequencies greater than the ${}^2P^o_{1/2}$ limit, and also continuous absorption with characteristic intensity modulations is observed between the ${}^2P^o_{3/2}$ and ${}^2P^o_{1/2}$ limits. Absorption between the two limits shows maxima that can be classified into two groups: a more peaked, and a much less peaked one; positions belonging to each of these two groups are Rydberg series that converge to the ${}^2P^o_{1/2}$ limit. With increasing noble gas pressure, absorption peaks grow in intensity and width until they overlap. At the pressure of 0.030 mm the absorption is already continuous and homogeneous, starting from the ${}^2P^o_{3/2}$ limit. In any case absorption due to energy levels below the ${}^2P^o_{3/2}$ limit is smaller in magnitude than absorption above the same limit. The intensity distribution in the absorption spectrum is shown by BEUTLER in a graph whose characteristic appearance is reproduced in Figure 1. He interprets single maxima as lines of the discrete spectrum, much broadened due to the large probability of self-ionization (AUGER effect) $(p^5)_{1/2}nl \to (p^5)_{3/2} + \textit{free electron}$. Wide maxima are assigned to the series $(p^5)_{1/2}nd$, and narrow maxima to the series $(p^5)_{1/2}ns$. The aim of the present work is to show how it is possible to justify such an intensity distribution in a qualitative way, by supposing that positions of discrete terms do not correspond to absorption maxima, but to points located along the steep parts of the curve, which are therefore slightly shifted with respect to the former.

The intensity distribution in the part of the spectrum of interest is obtained by evaluating the squares of dipole matrix elements referring to transitions from the ground state to states whose energy lies between the ${}^2P^o_{3/2}$ and ${}^2P^o_{1/2}$ levels of the ion. If we performed this calculation starting with zeroth-order eigenfunctions, corresponding to single electronic configurations, we would find that absorption is due to superposition of a continuum of almost constant intensity with lines belonging to series that converge to the ${}^2P^o_{1/2}$ limit.

In order to obtain a result in agreement with BEUTLER's experimental data we should start instead with better approximate eigenfunctions, which take into account interaction between different configurations. Ordinarily, eigenfunctions of this type are obtained via perturbation theory; this method is not applicable to our case, as we deal with states belonging to the continuum whose energies are infinitely close to, and also coincident with, the energies of the discrete states. We therefore have to abandon perturbation theory and look directly for eigenfunctions of the SCHRÖDINGER equation. We may assume as a first approximation that states which are not close to each

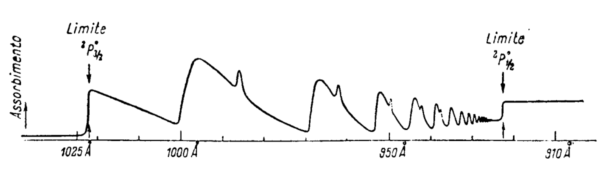

Figure 1:
(From "Zeitschrift für Physik", **93**, 181, 1935)

other do not appreciably interact. Therefore, absorption in proximity of the position of a particular discrete term is obtained considering the interaction only between the term itself and the continuum.

With the problem so outlined, it will be convenient to treat the atom as imbedded in a sphere of very large radius R, in order to simplify the treatment of the continuum. The continuous spectrum is then replaced by a discrete one. The interval τ between two consecutive eigenvalues is almost constant for small energy variations, and is inversely proportional to R. The corresponding eigenfunctions contain a factor related to the free electron, which far from the atom takes the form

$$\frac{1}{2}\sin\left(\sqrt{\frac{8\pi^2 m}{h^2}W}r+\delta\right)f(\theta\phi) \tag{1}$$

so that the normalization coefficient in the $R \to \infty$ limit is proportional to $1/\sqrt{R}$. It follows that if we let R go to ∞ we have to express a factor of $\sqrt{\tau}$ in the normalization coefficient. By invoking the fact that states with very different energies interact weakly, we can finally consider the spectrum of the $(p^5)_{3/2}$ + *free electron* configuration to be produced by the succession of eigenvalues

$$E_n = n\tau, \qquad (-\infty < n < \infty) \tag{2}$$

where the energy of the discrete state under consideration is defined as the zero of energy.

Let ϕ be the zeroth-order eigenfunction corresponding to the discrete term, and ψ_n the one corresponding to the eigenvalue E_n. From the above hypothesis it follows that a perturbed eigenfunction whose energy is close to the discrete term must have the form:

$$\psi = \sum_{n=-\infty}^{\infty} a_n\psi_n + b\phi \tag{3}$$

Let V be the interaction between electrons (which is mainly electrostatic), and define the first-order approximate energy as the energy associated with a given configuration (the sum of the eigenvalue of the equation for independent electrons, the exchange energy, and the diagonal term of V). The SCHRÖDINGER equation for ψ is thus decomposed into the infinite system of equations:

$$Ea_n = E_n a_n + bV_n, \quad Eb = \sum a_n V_n \tag{4}$$

where $V_n = (\phi|V|\psi_n)$ is supposed to be real, for the sake of simplicity.

Let us now introduce a new hypothesis, that is, ψ_n is independent of n at distances from the origin of the order of the atomic radius. It follows that $V_n = q$ is constant, and the last equation reads:

$$\frac{Eb}{q} = \sum a_n \tag{5}$$

while the other equations give:

$$a_n = \frac{bq}{E-E_n} \tag{6}$$

Substituting, we obtain:

$$(*) \quad E = q^2\sum\frac{1}{E-E_n} = q^2\sum\frac{1}{E-n\tau} = \frac{q^2\pi}{\tau}\cot\frac{E\pi}{\tau} \tag{7}$$

which determines the eigenvalues. In order to find b, we impose the following normalization condition (where dv is the element of volume in configuration space):

$$\begin{aligned}1 = \int|\psi|^2\,dv = \sum a_n^2 + b^2 &= b^2\left\{1+\sum\frac{q^2}{(E-E_n)^2}\right\}\\ = b^2\left\{1-\frac{\partial}{\partial E}\sum\frac{q^2}{E-E_n}\right\} &= b^2\left\{1+\frac{q^2\pi^2}{\tau^2}\frac{1}{\sin^2\frac{E\pi}{\tau}}\right\}\\ = b^2\left\{1+\frac{q^2\pi^2}{\tau^2}\left(1+\frac{E^2\tau^2}{q^4\pi^2}\right)\right\}\end{aligned} \tag{8}$$

therefore

$$\psi = \frac{\phi+\sum\frac{q}{E-E_n}\psi_n}{\sqrt{1+\frac{q^2\pi^2}{\tau^2}+\frac{E^2}{q^2}}} \tag{9}$$

Let us consider $X_n = (u|x|\psi_n) = X_c$ to be independent of n, where u is the ground state eigenfunction, and $X_0 = (u|x|\phi)$; the square of the x-component of the dipole matrix element is, taking (*) into account:

$$X^2 = \frac{\left\{X_0+\frac{E}{q}X_c\right\}^2}{1+\frac{q^2\pi^2}{\tau^2}+\frac{E^2}{q^2}} = \frac{\left\{X_c+\frac{q}{E}X_0\right\}^2}{1+\frac{q^2}{E^2}+\frac{q^4\pi^2}{E^2\tau^2}} \tag{10}$$

Having obtained this result, we have to take the limit $R \to \infty$. Matrix elements X, X_c and q contain a factor of $\sqrt{\tau}$, because of their definition; it is therefore convenient to set $X = \bar{X}\sqrt{\tau}$, $X_c = \bar{X}_c\sqrt{\tau}$, $q = \bar{q}\sqrt{\tau}$. Actually the quantity we are interested in is $\bar{X}^2$, since $(\bar{X}^2 + \bar{Y}^2 + \bar{Z}^2)dE$ determines the transition probability from the ground state to a state of energy in the range dE. Therefore, we have:

$$\bar{X}^2\tau = \frac{\left\{\bar{X}_c + \frac{\bar{q}}{E}X_0\right\}^2}{1+\frac{\bar{q}^2\tau}{E^2}+\frac{q^{-4}\pi^2}{E^2}}\tau \qquad (11)$$

and taking the limit $\tau \to 0$

$$\bar{X}^2 = \frac{\left\{\bar{X}_c + \frac{\bar{q}}{E}X_0\right\}^2}{1+\frac{\bar{q}^4\pi^2}{E^2}} \qquad (12)$$

The same formulae hold for $\bar{Y}^2$ and $\bar{Z}^2$. Setting $D = (\bar{X}, \bar{Y}, \bar{Z})$, $D_c = (\bar{X}_c, \bar{Y}_c, \bar{Z}_c)$, $D_0 = (X_0, Y_0, Z_0)$, we obtain:

$$|D|^2 = \frac{|D_c + \frac{\bar{q}}{E}D_0|^2}{1+\frac{\bar{q}^4\pi^2}{E^2}} = \frac{|D_c|^2}{1+\frac{\bar{q}^4\pi^2}{E^2}} + \frac{\bar{q}^2|D_0|^2}{E^2+\bar{q}^4\pi^2} + \frac{2E\bar{q}}{E^2+\bar{q}^4\pi^2}D_c \times D_0 \qquad (13)$$

In a small enough range of frequencies, this quantity can be regarded as proportional to the absorption intensity.

In order to discuss this formula, it is convenient to examine the three-term expansion. The first two terms have a well defined physical meaning, since $|D|^2$ reduces to them if D_0 or D_c goes to zero, respectively. Therefore we observe that if the dipole matrix element associated with the continuous spectrum is zero, we obtain as the absorption spectrum a line which is broadened due to the AUGER effect, and whose width is given by $\nu = \frac{2\pi\bar{q}^2}{h}$, as expected. If instead the matrix element associated with the discrete spectrum term is zero, the term itself affects absorption by the continuum, in that the latter vanishes at the position of the former. The third term is truly distinctive, as it results in net absorption being not simply obtained as a superposition of absorptions due to discrete and continuum terms, albeit mutually influencing each other; this term represents a shift of absorption intensity, or, in other words, it diminishes the intensity on one side of the discrete term's position, and increases it by the same amount on the other side.

In Figure 2, $|D|^2$ is depicted as a function of E for some values of $|D_0|$, $|D_c|$, $D_0 \times D_c$, $\bar{q}$ (the parameters that determine the curve); values have been chosen to show that *the curve itself can have a behavior that justifies theoretically the results obtained by Beutler*. Characteristic features of the curve that readily result from the discussion of its equation are: *a*) the curve goes asymptotically to $|D_c|^2$ for $E \to \pm\infty$; *b*) the ordinate of the intersection of the curve with the $E = 0$ axis

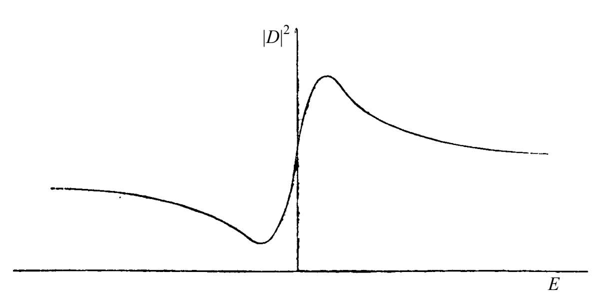

Figure 2:
$|D_c| = 2$; $|D_0| = 4.2$; $\bar{q} = 0.6$; $D_c \times D_0 = 6$; $\frac{|D_0|^2}{\bar{q}^2\pi^2} = 5$ arbitrary units

depends only on $|D_0|$ and $\bar{q}$, as it is equal to $\frac{|D_0|^2}{\bar{q}^2\pi^2}$; *c*) the curve has a maximum and a minimum on opposite sides of the $E = 0$ axis; in particular, if D_c is parallel to D_0, the minimum is equal to zero; *d*) the difference between the abscissa of the maximum and of the minimum is of the order of $\bar{q}^{\,2} \approx \frac{h}{2\pi\tau}$, where τ is the lifetime of the discrete term with respect to the AUGER effect (estimating τ as 10^{-14} sec, one gets $\bar{q}^{\,2}/hc \sim 500$ wave numbers).

Obviously, due to the simplifying assumptions that we used, the result obtained has merely a qualitative value, which is to show the behavior of the curve.

That the derived formula fails to fulfill the sum rule is to be attributed to the hypothesis adopted, since it indeed should yield:

$$\lim_{U\to\infty}\left\{\int_{-U}^{U}|D|^2\,dE - 2U|D_c|^2 - |D_0|^2\right\} = 0. \qquad (14)$$

In fact, we assumed the presence of a continuous spectrum of infinite extent, with $|D_c|$ constant, which is physical nonsense as it would result in an infinite number of dispersion electrons. This incorrectness is particularly evident in the limiting case $D_0 = 0$, where it appears that the number of dispersion electrons of the continuum is reduced by a factor of $\frac{1}{1+\frac{\bar{q}^4\pi^2}{E}}$ in the vicinity of the perturbing discrete term, without being correspondingly increased in other parts of the spectrum, so that the total sum of dispersion electrons does not change.

A trial calculation has shown that the derived formula is not even susceptible to a rough numerical evaluation, due to the large number of electrons that must be included for noble gases, and the poor approximation achievable in evaluating individual integrals.

Application of the obtained formula to line broadening phenomena in I^b absorption spectra. - I^b spectra, obtained by excitation of an electron belonging to the outermost closed shell, have been studied by BEUTLER in a series of important works ([2]). Superposition of discrete terms of I^b spectra upon continuum terms of ordinary arc spectra gives rise to the same situation that occurs in noble gases' spectra between the two limits of the arc spectrum. Nevertheless, the phenomena look different, since, up to the present, in known cases absorption due to the continuum: *a*) is much less intense than absorption due to discrete terms of I^b spectra, and *b*) decreases very rapidly in intensity with increasing frequency.

BEUTLER observed that some I^b series have bright and narrow lines superimposed upon the continuous spectrum. He explains this phenomenon by showing that interaction among terms belonging to these series and to the continuum vanishes. On the other hand, other series have diffuse lines, which he describes as asymmetrically broadened. In every diffuse series, lines tend to become symmetric again and to narrow as frequency increases, as the intensity of the continuum on which they are superimposed decreases.

In Figure 3 two different graphs of $|D|^2$ as a function of E are shown; curve 1 is obtained taking a value of $|D_c|^2$ small compared to $\frac{|D_0|^2}{\bar{q}^2\pi^2}$, curve 2 is obtained for the same values of $|D_0|$ and $\bar{q}$, and with $D_c = 0$. Line shape peculiarities in diffuse series of I^b spectra can therefore be explained, since the data relative to lower frequency lines are those utilized to obtain Figure 1, while by increasing frequency we get closer to conditions corresponding to Figure 2. Narrowing of the lines with increasing frequency is probably due to the fact that the $\bar{q}$ interaction tends in general to decrease with increasing total quantum number of the corresponding discrete term.

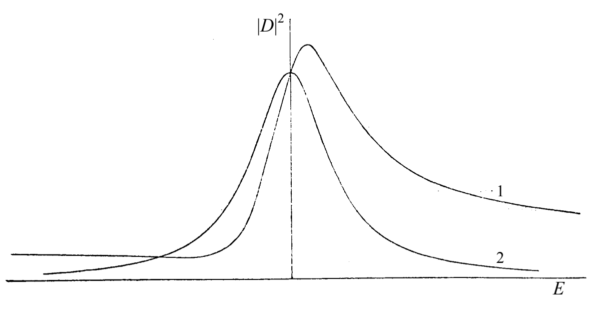

Figure 3:
Curve 1: $|D_c| = 1$; $|D_0| = 4.2$; $\bar{q} = 0.6$; $D_c \times D_0 = 3$; $\frac{|D_0|^2}{\bar{q}^2\pi^2} = 5$
Curve 2: $|D_c| = 0$; $|D_0| = 4.2$; $\bar{q} = 0.6$; $D_c \times D_0 = 0$; $\frac{|D_0|^2}{\bar{q}^2\pi^2} = 5$
arbitrary units

I want to deeply thank Prof. FERMI who guided and helped me throughout this work. *Rome, Istituto di Fisica della R. Università, February 1935-XIII.*

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About the authors and translators: *Ugo Fano (1912-2001) was a physicist at the National Bureau of Standards (NBS), now NIST, from 1946 to 1966, and subsequently a professor of physics at the University of Chicago. He is the author of the most-cited paper written by an NBS/NIST scientist, of which the present paper is a predecessor. Guido Pupillo was a Guest Researcher at NIST from 2001 to 2005, while completing his Ph.D. degree in physics at the University of Maryland, College Park. He is currently a postdoctoral research associate at the University of Innsbruck, Austria. Alberto Zannoni was a Guest Researcher at NIST from 1999 to 2000. He is currently the proprietor of an internet services company in Ravenna, Italy. Charles W. Clark has been a physicist at NBS/NIST since 1981, and is currently Chief of the Electron and Optical Physics Division of the NIST Physics Laboratory. Ugo Fano was the supervisor of his Ph.D. thesis at the University of Chicago. The National Institute of Standards and Technology is an agency of the Technology Administration, U.S. Department of Commerce.*

Reports from Vice President, Prof. M.A. Gomaa

Africa and Middle East

Visit to Gamma Irradiation Facility, Alexandria, Egypt

Members of National Network of Radiation Physics (NNRP) and members of IRPA-Egypt (Radiation Protection Group of the Egyptian Society of Nuclear Sciences and Applications) accepted an invitation from Chairman of National Center for Radiation Research and Application (NCRRT). The new Gamma Irradiation Facility in Alexandria belongs to NCRRT, and NCRRT belongs to Egyptian Atomic Energy Authority.

A meeting was held on 14 January 2016 at one of the Facility conference halls. We were welcomed at the main Reception Hall (see photos below) in preparation of the forthcoming 12th Radiation Physics and Protection Conference to be held next November at Gamma Irradiation Facility Conference Hall

Among the activities was a visit of the Facility with radioactive Co-60 source in the storage position. The activity of the source was 500 kCi one year ago. Furthermore, a lecture was given by the Chairman of NCRRT and the Chief Engineer of the facility about the capabilities of the facility to cover the needs of industrial section at Alexandria and nearby cities.

../Vice President's Reports continued

The 11th ESNSA Conference and 2nd IRPA-Egypt Workshop

Professor M. A. Gomaa

The conference and workshop were held (20-24 February, 2016) at Sonsta Pharaoh Hotel , Hughada , Red Sea, Egypt.

The conference and workshop was attended by 200 participants, and the number of research papers orally presented were 140 papers.

The main participants of the conference and workshop were Egyptians from Atomic Energy Authority Centers, Nuclear Material Authority, Nuclear Power Plant Authorities, Nuclear and Radiological Regulatory Authority and from several Egyptian Universities. From abroad, participants from Romania, United states of America , Russia, Tunisia and Qatar attended the conference and workshop.

Three sessions were devoted to the workshop, namely Radiation Protection Invited talks, Radiation Protection Research papers and Medical Radiation Protection Sessions.

Seventeen sessions were devoted to the conference in the fields of nuclear and radiation chemistry; theoretical and experimental physics; reactors; analysis of nuclear material; medicine, biology, agricultural application in the nuclear fields.

Among the activities of the conference and workshop was a special session devoted to throw light on the achievements carried out by Egyptian atomic energy scientists from 1955 to 2016.

Four Egyptian Radiation Physicists who attended ESNSA-11 Conference and presented papers and posters :
Left to right : Talaat Salah El Deen, Wael Badwy, Tarek Morsi, Safwat Salma

Conferences

4th International Conference on Radiation and Applications in Various Fields of Research

University of Nis, Faculty of Electronic Engineering, Nis, Serbia

23rd - 27th May, 2016

The aim of the Conference is to provide the forum for researchers and professionals from various fields of biology, chemistry, physics, medicine, environmental protection, electronics, etc, involved with ionizing and non-ionizing radiation, as well as other areas connected to them, to exchange and discuss their findings and experiences.

The Conference program includes topical invited lectures, a limited number of oral presentations, and poster presentations. The official language of the Conference is English.

For further information : **http://www.rad-conference.org**

Calendar - 2016

10 – 16 April, 2016 **RANC-2016**

1st International Conference on Radioanalytical and Nuclear Chemistry

Budapest, Hungary

Full information and contact details on page 33 of the June 2015 Bulletin

23 – 27 May, 2016

4th International Conference on Radiation and Applications in Various Fields of Research

University of Niš, Serbia

***Described above, and full information* http://www.rad-conference.org**

3 – 8 July, 2016 **ICDA-2**

2nd International Conference on Dosimetry and its Applications

University of Surrey, Guildford, UK.

Full information on page 36 of the December 2015 Bulletin

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INTERNATIONAL RADIATION PHYSICS SOCIETY

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The Constitution of the IRPS defines Radiation Physics as "the branch of science which deals with the physical aspects of interactions of radiations (both electromagnetic and particulate) with matter." It thus differs in emphasis both from atomic and nuclear physics and from radiation biology and medicine, instead focusing on the radiations.

The International Radiation Physics Society (IRPS) was founded in 1985 in Ferrara, Italy at the 3rd International Symposium on Radiation Physics (ISRP-3, 1985), following Symposia in Calcutta, India (ISRP-1, 1974) and in Penang, Malaysia (ISRP-2, 1982). Further Symposia have been held in Sao Paulo, Brazil (ISRP-4, 1988), Dubrovnik, Croatia (ISRP-5, 1991) Rabat, Morocco (1SRP-6, 1994), Jaipur, India (ISRP-7, 1997), Prague, Czech Republic (ISRP-8, 2000), Cape Town, South Africa (ISRP-9, 2003), Coimbra, Portugal (ISRP-10, 2006), Australia (ISRP-11, 2009), Rio de Janiero, Brazil (ISRP-12, 2012) and Beijing, P.R.China (ISRP-13, 2015) The IRPS also sponsors regional Radiation Physics Symposia.

The **IRPS Bulletin** is published quarterly and sent to all IRPS members.

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../Continued

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