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TRENDS IN EXOTIC-ATOM RESEARCH*

Richard M. Lambrecht

Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973

and

Dezső Horváth

TRIUMF, University of British Columbia, Vancouver, B.C.,

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ABSTRACT

An attempt was made to analyze the trends in the development of exotic-atom research on the basis of a recently compiled bibliography [1]. The analysis of nearly 4000 publications demonstrated that:

- exotic atoms are nuclear probes used in every field of physics, from the test of quantum electrodynamics (QED) to chemical physics, to materials sciences;
- the role of nuclear and atomic physics in exotic atom research is decreasing (although it is still significant), while that of materials sciences and chemical physics is exponentially increasing;
- prior to 1980 most investigators were mainly interested in atoms with negative muons, while during the last few years the positive muon (μSR) studies have dominated exotic atom research.

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INTRODUCTION

Exotic atoms can be considered as new nuclear probes in the physical sciences. A peculiar quality distinguishes the exotic atom method from other methods of subatomic origin. Nuclear probing methods such as neutron diffraction, charged particle and neutron scattering, nuclear magnetic resonance, Mossbauer effect, and positron annihilation are utilized almost exclusively in the materials sciences and chemical physics. However, exotic atoms have been used in practically all fields of the physical sciences including theoretical, elementary particle, nuclear, atomic, solid state and chemical physics. The first application of exotic atoms in the biological sciences appeared in 1979.

The various types of exotic atoms are identified by the particles which make them exotic. Thus, there are muonic ($\mu^{\pm}$), pionic (π^{-}), kaonic (K^{-}), antiprotonic ($\overline{p}$), and Σ^{-}hyperonic, etc. atoms. Muonic atoms are distinguished from hadronic atoms, the exotic atoms with strongly interacting particles. The formation of exotic atoms is unavoidable when charged particles are stopped in gases or condensed substances. The particles are obtained at 0.5–10 GeV proton accelerators. Muons are emitted in the decay of charged pions and disintegrate via electron emission. Pions, kaons and antiprotons are formed in the collision of protons with atomic nuclei.

We recognized the exponential growth of publications dealing with exotic atoms in 1975. Knowing that the scientific literature in this esoteric field was weakly indexed and often appeared in obscure sources, we decided to attempt the compilation of a complete bibliography on exotic atoms. It is our hope that the document [1] will stimulate new chemical and physical applications of exotic atoms, and aid researchers entering the field.

There are excellent reviews on the various aspects of the physics and chemistry of exotic atoms with extensive literature lists. Y.N. Kim's book [2], for example, enlists the widest coverage of the scientific literature on exotic atoms with 460 references. Our bibliography [1] presents 1341 entries published prior to 1971, and nearly 4000 entries for the period 1939-1982.

RESULTS AND DISCUSSION

The trends of development of the physics and chemistry of exotic atoms can be analyzed from various points of view. In Figs. 1 and 2 the numbers of publications are presented against the year of publication. Figure 1 depicts the details of publications by particles used. A brief glance at Fig. 1 reveals that the majority of publications on exotic atoms are related to muons. The roles of positive and negative muons are far from symmetric. Figure 2 depicts the fields of physics investigated. Figures 1a and 2a present absolute numbers, while Figs. 1b and 2b are expressed as percentages. The numbers have been obtained by reading abstracts or guessing the particles and the orientation of the papers from the titles. Although these data are estimates, they reflect the trends in research with exotic atoms.

The μSR (muon spin relaxation, resonance, or rotation) methods involve stopping polarized positive muons in the sample and counting the decay positrons in a given direction as a function of the time the muon survived in the medium (see the papers presented at this conference).

The interest in positive muons arose in 1957 with the first investigations involving a search for the existence of muonium, and on muon depolarization. Since then the annual publication rates have grown exponentially having out-numbered even the negative muon studies (see Fig. 1). For the muonic and hadronic atoms formation probabilities, particle depolarization, Auger electron and X-ray yields, lifetimes, cascade transition energies, level widths and shifts, transfer rates, nuclear capture rates, and nuclear reactions connected with interactions with the exotic particle are usually measured or calculated. The interest in muonic (μ^-) atoms has been rapidly growing in a more-or-less linear fashion. Among the hadronic atoms the π^- and K^- atoms appear the most frequently, the interest in pionic atoms is steadily growing. However, the share of muonic atoms in the literature on exotic atoms is slowly decreasing. Virtually, this effect can be attributed to the rapid growth of scientific activity on μSR.

The use of exotic atoms is based on their unique properties associated with the instability, great mass, and possibly the strong interaction of the exotic particle. The information from exotic atoms may be delivered by decay products as in the case of muonium, by reaction products from nuclear capture, or by the hard X-rays from cascade transitions.

The experimental test of quantum electrodynamics (QED) is rather troublesome in usual, electronic atoms as there the QED effects are extremely small. As the muon is a heavy lepton, muonic atoms present a unique information source on QED. Thus far all the tests have proved the correctness of QED to a precision of about 0.25%. Theoreticians are expected to improve their calculations as the present experimental accuracy is about 0.04-0.06%.

The energy levels of an exotic atom sensitively depend on the properties of the involved particle. It is possible to use exotic atoms for the experimental determinaton of certain particle data (mass and magnetic moment) with high accuracy and for studying other phenomena in particle physics such as neutral currents, anomalous interactions, etc. Theoretical and particle physics oriented publications on exotic atoms have shown steady annual growth since 1970. The percentage of exotic atom publications on this area is decreasing (Fig. 2).

Near the ground state the particle of the exotic atom very sensitively probes the nuclear structure and properties. Using muonic X-rays, one can investigate the radial shape of nuclear charge distribution in detail. In hadronic atoms, due to the strong interaction between the hadron and the nucleus, the levels are shifted and broadened as compared to muonic atoms with a strong dependence on the nuclear charge. The proton and neutron distributions inside the nucleus can be separately analyzed by means of combined muonic and hadronic atom data as the muon interacts mainly with the protons and the hadrons with both types of nucleons.

The absorbed negative particle excites the nucleus and can induce nuclear fission reactions. On the other hand, the muon lives long enough in hydrogen to form muonic molecules. Due to its great mass the muon, approaching the molecular ground state, compresses the hydrogen nuclei (proton, deuteron, or triton) of the molecule thereby inducing a nuclear fusion process.

As seen in Figs. 3 and 4, the research with exotic atoms until the early 1970's was dominated by nuclear physicists. Since then the annual rate of nuclear physics oriented exotic atom publications has gradually leveled off and given way to emphasis in atomic and chemical physics, and materials testing.

The remarkable area of exotic atoms which can be related to atomic physics consists of: (i) process of atomic capture of the particles; (ii) particle transfer from exotic hydrogen atoms to other atoms; and (iii) formation of muonic hydrogen molecules. The role of atomic physics in exotic atom research is slowly decaying, although the absolute number of publications is increasing. Atomic physics is still one of the most important fields of exotic atom research.

The most striking feature in Figs. 4 and 5 is the very rapid, exponential growth of the publications in solid state physics and chemistry. It is mainly asociated with positive muons: i.e., muon spin research in solids and muonium investigations in chemical systems, especially in solutions and gases. Nevertheless, other topics include negative muon depolarization, the search for chemical effects in muonic and hadronic atoms, and studies of pion capture by protons in hydrogen-containing samples. Applications in biological sciences are very recent and are predicted to grow. A related area of research involves negative pions for cancer radiotherapy and fundamental investigations in radiation biology.

CONCLUSION

In conclusion we emphasize the shift of publications on exotic atoms to positive muons, and to applications in solid state physics and chemistry. From the point of view of some theoretical particle physicists, the muon may be a superfluous particle whose removal practically would not affect the physical laws. However, we see the muon as an extremely useful nuclear probe in all fields of physics, and in the chemical and biological sciences as well.

REFERENCES

[1] D. Horváth, R.M. Lambrecht, Exotic atoms: A bibliography 1939-1982, (Elsevier Scientific, Amsterdam) 1983 (in press).

[2] Y.N. Kim, Mesic atoms and nuclear structure (North-Holland, Amsterdam) 1971.

FIGURE CAPTIONS

Fig. 1 Annual publication rates on exotic atoms with the following particles: positive muon (μ^+), negative muon (μ^-), pion (π^-), kaon (K^-), antiproton, Σ^--hyperon, etc. ($\bar{p}$, Σ^-, ...) and with unspecified particles; (a) in absolute numbers, (b) in percents.

Fig. 2 Annual publication rates on exotic atoms concerning the following topics: test of quantum electrodynamics (QED), particle physics, nuclear physics, atomic physics, solid state physics and chemistry, and methodical problems including review articles.

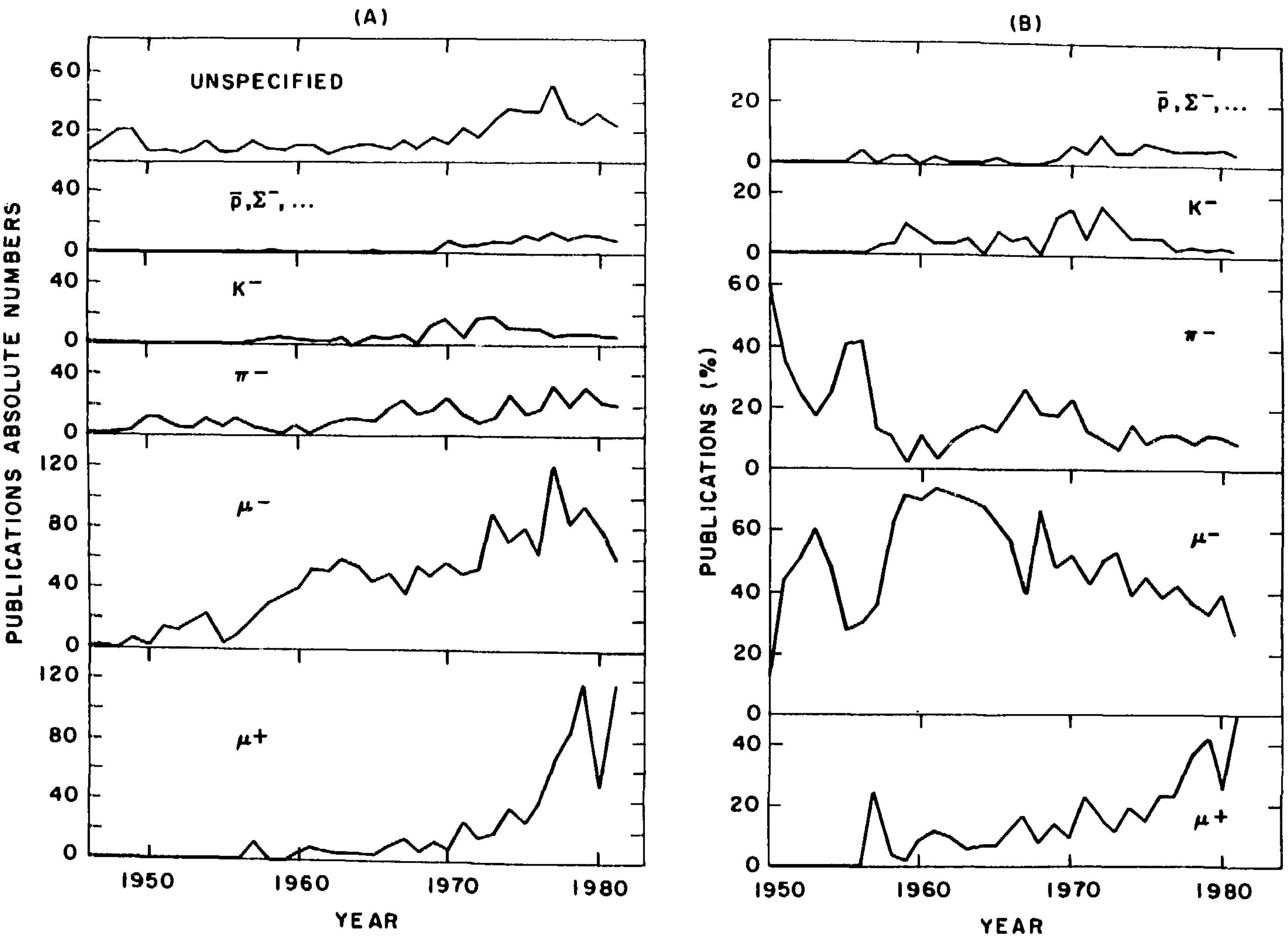
(A)
UNSPECIFIED
p̄, Σ⁻, ...
K⁻
π⁻
μ⁻
μ+
PUBLICATIONS ABSOLUTE NUMBERS
YEAR
(B)
p̄, Σ⁻, ...
K⁻
π⁻
μ⁻
μ+
PUBLICATIONS (%)
YEAR

Fig. 1.

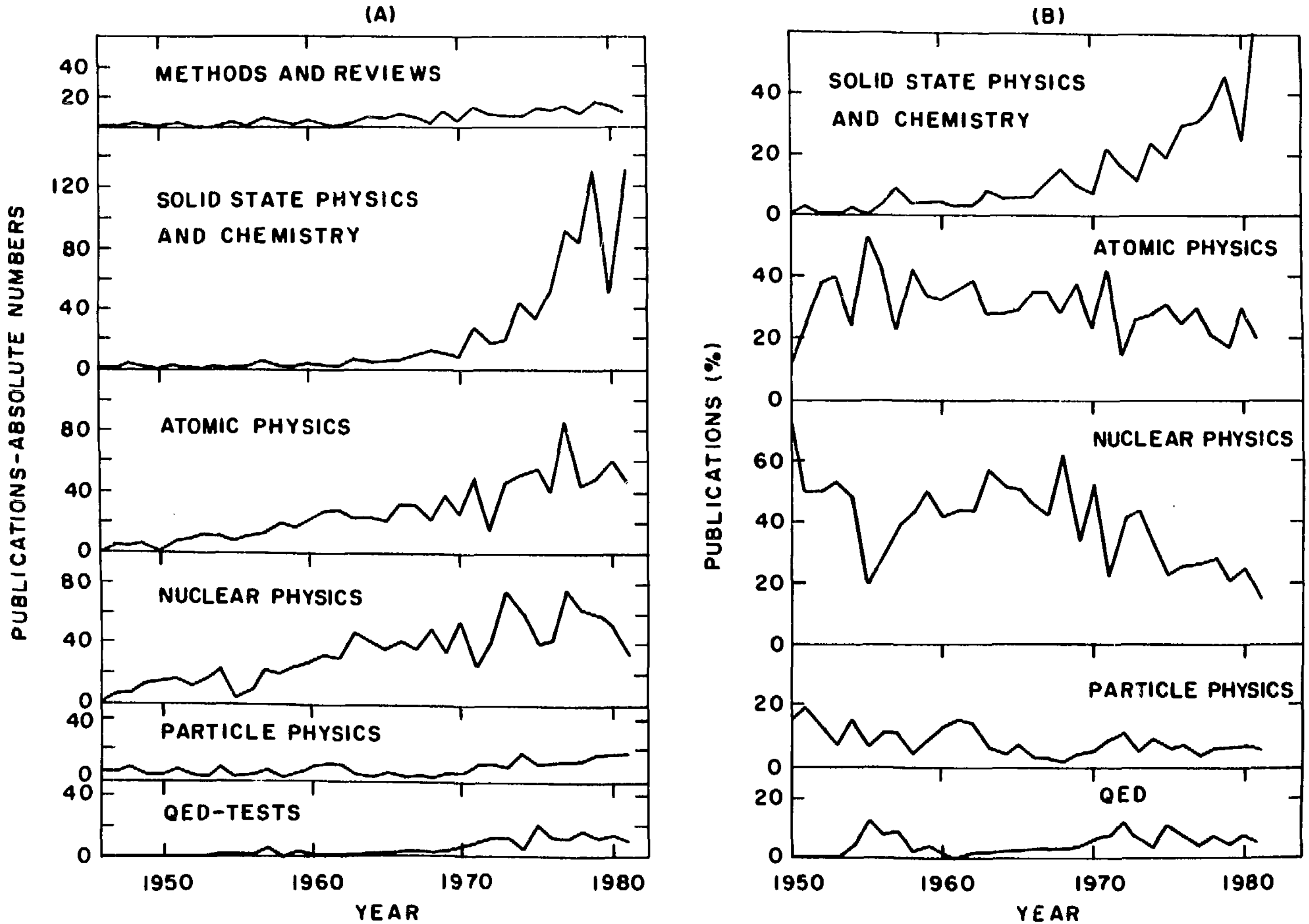
(A)
METHODS AND REVIEWS
SOLID STATE PHYSICS AND CHEMISTRY
ATOMIC PHYSICS
NUCLEAR PHYSICS
PARTICLE PHYSICS
QED-TESTS
PUBLICATIONS-ABSOLUTE NUMBERS
YEAR
1950
1960
1970
1980
(B)
SOLID STATE PHYSICS AND CHEMISTRY
ATOMIC PHYSICS
NUCLEAR PHYSICS
PARTICLE PHYSICS
QED
PUBLICATIONS (%)
YEAR

Fig. 2.