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《**Review**》

The Neutron: Prospects After the Golden Anniversary of Its Discovery

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Abstract

About 25 years ago, halfway along the recorded history of the neutron as a separate entity, Korea entered the nuclear age and initiated its own neutron research and development programs. Since that time Korean scientists have taken all possible advantages of the special opportunities offered by the neutron. Scientists the world over, in the Far East, Near East, and the West, have adapted these opportunities to their special needs. These needs are manifested in all phases of modern life, including power generation by nuclear means, food preservation, production of new types of food-bearing plants, commercial uses of activation analysis, irradiations, and isotope production, nuclear medicine, industrial quality control through nuclear measurements, and direct use of neutrons in research in many areas including solid state physics, chemistry, physics, biology, and medicine. Research with neutrons has been successfully conducted using nuclear research reactors of all sizes ranging from the very small (~10 kilowatts) to the very large(50-100 Megawatts). This speaker has been associated with nuclear research since 1945 and directly with neutron research since 1957. From this continuous research and development activity, he will report on some of the prospects in the second 50 years of the neutron.

1. Introduction

The speaker feels greatly honored and privileged to be able to speak on this happy occasion. His relationship with the neutron in Korea extends backward to 1958 when Korea made the decision to acquire a TRIGA reactor[1] as its first nuclear research reactor and to initiate its own neutron research and development programs. At that time, several Koreans were trained in research reactor operations in the speaker's laboratory in San Diego. In 1960, the speaker spent a happy five weeks in Korea as a nuclear consultant to KAERI. In 1962, he returne as the startup scientist for the first nuclear research reactor in Korea. It was indicative of the Korean skills that one of their gifted electronic engineers constructed a pile oscillator, installed it, and made the first prompt neutron lifetime determination in a TRIGA reactor during the one-month startup of this first Korean reactor. Several more visits to Korea were made subsequently to renew scientific ties with San Diego. In 1972, the speaker was the startup scientist for the two-megawatt reserch reactor at KAERI More recently, he has been involved in Korea with the installation of a neutron radiography facility using a Van de Graaff source of neutrons.

Since the speaker's personal experience with neutrons in Korea has continued for more than two decades, he is privileged to give an address before this assembly marking an important anniversary of KAERI. In the following, we will first review the uses and applications of nuclear technology during the first 50 years of the neutron, and then devote attention to the recent uses of neutrons and predictions for the future.

2. Uses of Nuclear Technology

Scientists and research planners all over the world have recognized the opportunities that neutrons and related technology offer mankind.

2.1. Examples of Nuclear Technologies

The generation of electricity by nuclear means has been pursued since the middle 1950s. Examples of nuclear power plants exist in both the developed and less developed nations and greatly relieve the dependence on fossil fuels for producton of electricity. France and Korea are typical examples. Nuclear reactors also make possible a wide variety of activities beneficial to mankind. Gamma rays from isotopes produced in such reactors are used regulary for many aspects of food preservation. In Korea, special attention has been given to preservation of, or delayed spoilage of, fish which is an important component of the diet. Similar applications to fish preservation are made in Pakistan, Bangladesh, and India, to mention a few more examples. Use of gamma rays to control infestation of grain in storage is very important since it is estimated that as must as 15% of the stored grains worldwide is destroyed by infestation by insects and their larvae.

Additional uses of nuclear radiation include the production of several new types of plants. Improved rice is a case in point. Development of grains that are more resistant to rust is particulary important.

Nuclear reactors make possible many commercial applications of nuclear technology. Activation anlysis is available commercially for very sensitive analysis of commercial and industrial products, environmental samples, pharmaceuticals. and forensic samples. The in-core irradiation of high purity silicon for phosphours doping is a significant new application in solid state technology. The production of nuclear isotopes is of great importance to industry (e.g., Co^{60}, Ir^{192}), to the medical industry (e.g., Tc^{99m}, Au^{198}, I), and for quality control through gaging for the metals industry and many other manufacturing activities.

The use of beams of neutrons has been heavily exploited for solid state physics, chemistry, nuclear physics, biology and medical technology. In many of these applications, diffraction technology exploits the elastic, cherent scattering of the neutron. In others, such as small angle scattering, the small angle, incoherent, elastic scattering features of the neutron are used to advantage. With advancing development of techniques, crystallographic studies are now possible with ultra small samples as for instance one cubic millimeter of blood protein. Inelastic scattering of thermal and epithermal neutrons makes possible experimental determination of the atomic binding and dynamics of atoms within a compound. While these latter applications started as pure research of a fundamental nature, the results are so widely useful that many of these applications are now made routinely for commercial benefit.

2.2. Nuclear Technology in Developed and Less Developed Nations

The above brief listing of uses of nuclear technology is far from complete. However, it shows the broad range of applications that are possible. Nations all over the world have made efforts to take advantage of the neutron and nuclear technology. Not long after the first research reactors were brought into use, the International Atomic Energy Agency (IAEA) was created. This Agency has been a unifying force to make available to all member nations the benefits of nuclear technology. Under the auspices of IAEA, examples of the applications discussed briefly in Section 2. 1 have been made available by providing nuclear experts, training of scientists from member nations, and direct grants. As a result, there is a broad, well-formed foundation of nuclear technology and know-how common to both the developed and less developed nations.

3. Review of Recent Advances in The Uses of Neutrons and Predictions for The Future

Let us review together the most advanced applications of neutrons witnessed recently and make an attempt to foresee some future uses. In only the broadest sense can we hope to foresee future uses because competing, and frequently non-nuclear, techniques continue to appear. As a notable example of this competition, we can note the appearance of sonic probes and nuclear magnetic resonance (NMR) as recent noninvasive diagnostic tools for medical technology. Neither of these uses ionizing radiation.

In reviewing recent advanced applications of neutrons, it becomes clear that many of the advances depend on sophisticated approaches or very high intensities of neutrons or both. In the past as expected in the future, a need always exists for even more intense sources of neutrons. Such sources make possible the investigation of ever smaller scales of phenomena.

3. 1. Applications of Advanced Technology

3. 1. 1 *Flectric power production* is a major application of nuclear technology. It will continue in the future as more nations realize that nuclear power is a sensible method to reduce dependence upon expensive fossil fuel. The misguided anti-nuclear effort has been disruptive in the past and will continue for some time in the future. However, reason must prevail ultimately so that the full potential for nuclear power generation can be realized.

Large scal production of isotopes has been practiced in test reactors ($\geqslant$10 MW). More such reactors will be utilized for this purpose in the future. The isotopes will be used commercially for industrial and medical purposes. Large scale use of gamma rays will be devoted to such uses as processing of wood impregnated with epoxy, food preservation, grain deinfestation, and production of new food types with additional desirable features. Finally, we will mention the use of radioisotopes in thermo electric generators that are so useful in making long lived marine beacons, as an example.

Ouality control is an ever growing area that utilizes more and more nuclear tehcniques to improve the buality of industrial and commercial products[2]. Neutron radiography (NR) is an expanding quality control measure in the aircraft industry. Examination of turbine blades is a well known example. Boeing may invoke NR for a number of sophisticated applications for the new 757 and 767 airplanes. The new noise reducing muffler for the 767 is a typical component well suited to NR examination. Additionally, the aircraft industry (especially the military) has recently become well aware of the benefits of NR for assessing airplane wing tank corrosion and debonding of honeycomb components in vital areas. Examination of turbine blades by NR immediately after manufacture will confirm that all casting material has been removed from the cooling lines.

Finally, we note that thickness gaging by means of nuclear radiation from isotopes is a growing application for quality control in industry.

Large scale neutron-induced doping of silicon is a rapidly growing application of nuclear technology to the solid state industry[3]. Very high quality diodes for high power are needed by the electrical industry in Japan and Europe where D.C. transmission of electric power is practiced. Only reactor-produced doped silicon has the required high quality. At the present time, tens of tons of doped silicon are required each year. In the near future, hundreds of tons of doped silicon will be required annually. It is very likely that special test reactors will be built or adapted in the future solely for this use.

The *oil industry* uses a wide variety of isotopes in the cracking plants for monitoring the performance of facility. Additionally, clever use of the radiation from isotopes permits routine investigation of frothing in oil pipe lines. Proper steps can be taken to improve the flow and transport of oil potentially subject to frothing.

Heavy industry and the auto industry have made sophisticated use of nuclear techniques. An example for heavy industry is the use of neutron diffraction analyses of steel alloys to assure proper steps to reduce streas corrosion cracking. A Finnish Research Institute offers this service regularly to the steel industry. In England, the Rolls Royce Company uses real-time cold neutron radiography to investigate the oil flow in operatingautomobile engines[4].

3.1.2. *Medical Applications*-In the past as well as in the future the medical industry's use of isotopes is extensive. The uses of technetium, gold, and iodine for medical diagnosis and therapy are welll known. Less well known and developing rapidly is the use of *cloned bioradiopharmaceuticals.* These cloned molecules can be made to seek directly diseased organs such as those with cancer. By attaching a radiatition emitting isotope to such a cloned molecule, we can be sure to insert the therapeutic radiation directly into the organ of our choice. This high technology use of radiation is growing at a very rapid rate. *Neutron capture therapy* for cancer can be expected to develop in the future, based on the successful work in Japan with brain tumors[5]. The advance to be expected in this area will be the use of epithermal neutrons with special energy selected through the use of specialized neutron filters[6] to provide peak thermal neutrons in the tumor. Such an advance will eliminate the need for surgery to open the cranium as is needed with use of thermal neutrons.

Medical neutron radiography and *computerized axial tomography* using neutrons have been successfully demonstrated during the past 10 years. Scientists at GA in San Diego[7] and at the University of Missouri[8] have published papers on these successful demonstrations. There is every reason to expect future applications of these techniques since the use of neutrons provides the medical doctor with more important information than similar diagnosis using x-rays.

Improved electronic imaging techniques are needed for the widespread utilization of neutrons in medical radiography. At present, the charge coupled device (CCD) which is the heart of the imaging system provides about 250,000 pixels. When this number has been improved by a factor of 10 or more, we can expect that several applications of medical radiography using neutrons will appear.

3.1.3. *Solid State Physics and Biochemistry*— Chemistry, physics, biology and medicine have benefited from the use of beams of neutrons as research tools. We will choose solid state physics and biochemistry as examples. The use of *coherent elastic scattering* of neutrons makes possible the diffraction analyses of samples.

These elastic scattering patterns reveal structure on an atomic level and are useful in solid state and metallurgical studies as well as in structure studies in biochemistry. With the advent of very intense neutron beams[9], it is now possible to study the structure of a minute sample of organic crystal such as a one cubic millimeter sample of blood protein.

Thermal neutron inelastic scattering of neutrons has also been exploited to study the dynamics of atomic motion[10]. These studies have been particularly useful in such diverse areas as moderators in nuclear reactors, fluids and solids at the critical point, the dynamics of metal alloys, and the diffusion of one fluid within another. Neutron radiography has also been used for this latter study.

It may be noted that the above two major types of scattering analyses have been the mainstay of neutron experimental research for the past 30 years, and can be confidently expected to remain so in the future.

3. 1. 4. *Small Angle Scattering*—Although neutron scattering was treated above in Section 3. 1. 3. a special type of neutron scattering has been developed in the last few years. It has become so popular that we treat it separtely. Neutrons have the fortunate characteristic that they undergo small angle scattering in most substances, the size of the angle determined predominantly by the *size* of the scattering molecules or crystal zones. By instrumenting this technique cleverly as has been done at Grenoble, France, NBS in the USA and other places, it is easy to determine sizes of inclusions or density of admixtures from the scattering patterns. Hundreds of measurements are made each year at Grenoble for industrial customers with metallurgical, pharmaceutical and other samples. We can confidently expect this application of neutrron technology to grow enormously in the future.

3. 2. Techniques Available or Needed for Advanced Studies

Many sorts of neutron sources are used for the advanced studies with neutrons. All share one feature: namely, the need for ever higher intensity of neutrons[9]. The largest such test reactor now is the 57 MW Grenoble reactor. The Russians are rumored to be building a 100 MW test reactor in Leningrad. Proton synchrotrons with proton energies in the range of 800 to 1000 MEV are powerful sources of neutrons. Such an energetic proton can be made to groduce more than 20 neutrons per proton. Careful design of the moderator will produce very intense bursts of slow neutrons for neutron scattering experiments. Multiply pulsed reactors can be used to produce many intense bursts of neutrons per second. The multiple pulsed TRIGA reactor can be pulsed to 10 or 20 MW peak powers 50 times per second. The Russians have built a series of large pulsed fast reactors such as the IBR systems[12]. The largest of these produces peak fluences of 1.75×10^{17} nvt fast neutrons at repetition rates of 5 per second.

3. 3. Properties of Nuclear Particles. Especially Neutrons

For the past 50 years very many experiments have been performed to define the parameters and characteristics of nuclear particles. As is well known, high enerhy accelerators have been used to study the proton and the anti-proton. Similar experiments on neutrons have been more difficult but the anti-neutron has been confirmed. The *half life of the proton* is receiving great attention at present. Although this half life is very long (if indeed the proton is unstable), this characteristic of the proton is related to the neutron whose halflife has been measured accurately.

The interaction of basic nuclear particles is of utmost importance to a full understanding of nuclear reactions. It has been relatively easy to use beams of protons or neutrons to study (p, p) scattering and (n, p) scattering. Up until this time it has been impossible to study directly the *(n, n) scattering interaction*, although indirect measurements have been made by comparing (p, p) and (p, d) scattering measurements[13]. A specially designed reactor can be used as a source for the (n, n) scattering mesurement. A pulsed TRIGA can give 10^{15} neutrons per pulse and is sufficient for this measurement if a specially constructed central beam port is available[14].

Many nuclear properties of the neutron have been measured using reactor based techniques. With a larger reactor ($\geqslant$20 MW) ultra-cold neutrons ($\sim 10^{-8}$eV) are proving to be the key to successful measurement of additional fundamental neutron properties[15]. The electric dipole moment has already been investigated for higher energy neutrons and has an upper limit of 3×10^{-24}e centimeter, where e is the elecron charge. A still lower limit may be set with experiments using ultra cold neutrons because their slow motion (meters per second) allows a long observation time and hence a more precise determination of a resonance frequency.

Surface chemistry is a relatively new phemomenon to be studied with ultra-cold neutrons[15]. Since ultra-cold neutrons have very low energy ($\sim 10^{-8}$ eV) it is also easy to see how they can be used as a probe to study the small motion of, and sometimes very small forces between, atoms on the surface of metals. Ultra cold neutrons scatter from the surface and "sample" only the first 5 to 10 atomic layers. These scattered neutorons are sensitive to the nature of the binding of the adsorbed surface layer. In particular, this study may throw light on the reason whey the so-called, "neutron bottle" will not retain a collection of ultra cold neutrons indefinitely[15].

4. Conclusion

Scientists and engineers in 1983 have successfully exploited many phenomena that an understanding of the neutron makes possible. As shown herein, increased understanding may make other beneficial uses avilable to mankind. As new, advanced technology from other areas such as the imaging system from the space program becomes anailable, expanded applications of neutrons in medicine can be exected. Application of nuclear technology based on the neutron will be significantly expanded in the coming years in areas such as food processing, sterilization of commercial produts (especially medical items), production of electricity from nuclear power and industrial application of process heat from high temperature nuclear reactors. Neutron radiography may one day be as important in QA as xradiography is today.

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