D-T Neutron Sources

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An update of the status of D-T neutron sources is given, including some historical background and a review of recent developments in the construction, operation, and planning of D-T sources.

1. INTRODUCTION

In 1979 the present author reviewed D-T neutron sources. This review was published in 1983 as a chapter[1)] in the book "Neutron Sources for Basic Physics and Applications". In 1984 additional information about D-T sources, especially developments in Eastern Europe, was reported at a symposium held in Gaussig (GDR) under the heading "Neutron Generators and Application".[2)]

The present report is an attempt to provide some historical background and to review recent developments in the manufacturing, operation, and planning of D-T neutron sources.

D-T sources have the advantage over other neutron sources that they are relatively compact and intense and do not emit gamma rays. They have the advantage over radioactive sources that they can be turned off or pulsed and that they produce neutrons with a small energy spread. On the other hand, they have the disadvantage that for some applications the source strength cannot readily be made as high as is desirable, that the energy of the neutrons cannot be varied very easily, and that tritium is a hazardous material.

Until the relatively recent past the advantages of D-T neutron sources appeared to outweigh their disadvantages, but more recently the interest in D-T neutron sources has decreased to the extent that many of the commercial suppliers no longer manufacture such sources and many fewer D-T sources are operating now or are being planned for the future than ten years ago.

2. USE OF D-T SOURCES FOR NUCLEAR PHYSICS

Shortly after appreciable amounts of tritium became available, the first D-T neutron source was developed at Los Alamos early in 1948. It was immediately used to measure neutron interaction cross sections at 14 MeV. At the time, very little was known about the interactions of 14 MeV neutrons so that a large body of information could be gathered in a short time. As might be expected, the first experiment we did was to measure the angular distribution of 14 MeV neutrons scattered by protons, and this was published in 1949.3)

Now 14 MeV neutron sources are rarely used for studying the properties of nuclei, but there remains an active interest in measurements of the nuclear interactions of 14 MeV neutrons for applied problems. Even though D-T sources produce large fluxes of neutrons of known energy, the results of measurements are often surprisingly inconsistent. As an example, recent measurements4,5) of the cross section for the reaction $^{12}C(n,\alpha)$ differ by a factor of almost three. This cross section is particularly important for applications. There are other important cross sections for which different measurements do not agree well. One reason for differences in the results of various measurements may be that the effective neutron energy may differ.6) The effective neutron energy depends on the tritium distribution in the target if a solid target is used, and on the beam composition if an unanalyzed deuteron beam is used. The interaction cross section, especially of light target nuclei, may vary rapidly with neutron energy, which may explain some of the inconsistencies. In spite of the importance of some of these cross sections, few such measurements are in progress.

3. ROTATING TARGET NEUTRON SOURCES - A BRIEF HISTORY

In 1969 the head of our radiotherapy department visited me to tell me about recent successes in the use of fast neutrons in the treatment of malignant disease. He had just returned from London, England, where a cyclotron was used as a neutron source, and he was wondering whether a D-T neutron source might be preferable.

I expressed doubt that a solid target could provide enough intensity, but mentioned the possibility of using a gas target. To my surprise I found out that this casual remark led to the construction of a gas target source at our university. This source is still in active use for radiobiological experiments, but it has never been used for therapy.

When I looked through the literature, I found a 1967 abstract7) that described what was by far the most intense D-T source. It had been built by Rex Booth at Livermore and produced close to 2×10^{12} neutrons/sec. I visited Rex Booth and was impressed by the clever design of the rotating target that made the high source strength possible. Rex Booth was enthusiastic about working with me on trying to increase the source strength. One of the first experiments we tried was to see whether we could increase the source strength by using simultaneously atomic and molecular deuterium ions; only atomic ions were in use at the time. To our surprise, we found that even a small admixture of molecular ions resulted in a rapid decrease in source strength. We quickly realized that the molecular ions displace tritium in the target at a depth where the atomic ions produce the highest neutron yield. This explained why the Livermore target lasted so much longer than targets at generators which used an unanalyzed deuteron beam. Although we published this observation8) in 1972, it was not generally accepted. For example, the D-T generator built by Radiation Dynamics for the Eppendorf hospital in Hamburg used an unanalyzed beam in spite of the fact that I had tried to persuade them of the problems this would cause. More recently a small separation of the atomic and molecular beam on the target resulted in a six-fold increase in target life time.9)

To increase the output of the Livermore source we acquired a larger high voltage power supply which permitted the beam current to be increased from 8 to 25 mA. To maintain a good target life time the diameter of the rotating target was increased from 15 cm to 22 cm. With these changes a neutron source strength of 6×10^{12}/sec was attained in 1975. This source strength should have been adequate for the use of this source for radiotherapy, but by that time the National Cancer Institute had been persuaded that the Cyclotron Corporation could manufacture a closed tube D-T source for therapy, and there was no interest in developing the Livermore design for hospital use.

When it became known that there was an intense D-T source available, material scientists interested in the fusion program began to use the source for studies of radiation damage produced by 14 MeV neutrons, but the available intensity was only marginally useful. We decided that a new facility built on the rotating target design could achieve an increase in source strength by a factor of five, and possibly even by a factor of ten. Even that was less than what was needed to learn what would happen in a fusion reactor, but the cost of building a larger rotating target source was by one or two orders of magnitude less than the cost of building other facilities that were being proposed for materials test facilities for fusion reactors. In 1976 the U.S. Department of Energy authorized the construction of a new facility containing two high-intensity rotating target D-T sources at a cost of five million dollars. The first source became operational in 1978, the second in 1982 following an agreement with the Japanese government providing for joint funding of the operation of the source.

After this brief review of my own involvement in the use of D-T sources let me return to an overview of the applications of such sources.

4. APPLICATIONS OF D-T SOURCES

I have mentioned the use of D-T sources for obtaining nuclear data for pure and applied nuclear physics. A second area of application of D-T sources is in activation analysis to detect elements that do not readily produce observable activities with slow neutron irradiation, and for the detection of fissionable materials for safeguards applications. Although this is in principle a useful method, it does not appear to have wide uses. Whenever there are threats of explosives on airplanes, the discussion of the use of D-T sources for the detection of explosives in baggage resumes. The idea is to look for objects which have a high nitrogen content, but so far no such detection devices are in use.

A third area of applications of D-T sources is for geophysical exploration. Small diameter sealed tubes are widely used in boreholes, but probably this is of limited interest to nuclear physicists. Details about geophysical applications are often considered proprietary by exploration corporations and few details about this application are available in the scientific literature.

Ten years ago a promising application of D-T neutron generators appeared to be in radiotherapy. A compact neutron source that could be moved around the patient would have great advantages over a cyclotron which has a fixed beam. 14 MeV neutrons are more penetrating than the neutrons from 16 MeV deuterons on Be which had been used in England,10) so that such neutrons could be used for treating more deep seated tumors. As a consequence, several manufacturers developed D-T neutron generators for radiotherapy which were installed in hospitals. All but one of these generators used sealed tubes to avoid the problem of having to handle tritium in a hospital. While it is relatively easy to build sealed-tube generators for low intensity applications, the problems with trying to get high intensity turned out to be much greater than the manufacturers had expected. In order to keep treatment times down to the order of 10 minutes, source strengths of the order of $5 \times 10^{12} s^{-1}$ are needed, and none of the D-T generators achieved such an intensity. At the same time radiotherapists became more interested in using neutrons of higher energy than 14 MeV in order to get even better penetration into tissue. The use of small superconducting cyclotrons appears to be a much more promising approach to obtaining high intensity and high-energy neutron sources than D-T generators.

The early successes of neutron therapy could not be reproduced at other hospitals, and the question what caused the difference has not yet been resolved. While the present evidence does not indicate that neutrons have advantages over photons in treating all malignant diseases, there is good evidence that neutrons do have advantages in the treatment of some diseases, especially in cancers which grow slowly.11) There are several hospitals that will continue to use neutron radiotherapy, but only two or three centers, all in Germany, continue to use D-T neutrons.

Related to the interest in neutron therapy is a continuing effort to understand better the radiobiology that is basic to neutron therapy. For example, there is some evidence that combinations of neutron and photon treatment have advantages over either radiation alone, and there is a continuing effort to study the radiobiology of this effect. For such studies D-T sources could be used.

I have mentioned another application for which high-intensity D-T sources were desired, i.e., for the study of radiation damage caused by 14 MeV neutrons. This information is needed for the design of fusion reactors, since the first wall of a fusion reactor is bombarded by a very high flux of 14 MeV neutrons. How long the first wall of a reactor can be subjected to such a bombardment determines how long the reactor can operate without a major overhaul. The effect of 14 MeV neutrons is sufficiently different from that of fission neutrons that it appeared necessary to build intense sources that could produce neutrons of at least 14 MeV energy. Ten years ago there were several proposals to build intense neutron sources for fusion technology, and the construction of three of these was authorized in the U.S.: INS at Los Alamos, FMIT at Hanford, and RTNS II at Livermore. INS was cancelled several years ago, FMIT was cancelled more recently, and only RTNS II, the least ambitious of the three was completed. Although the RTNS II sources worked well and were used in many radiation damage experiments, primarily carried out by Japanese scientists, the sources will be turned off shortly after the end of the current year. There are several reasons for this decision. The most important is probably that funding for fusion technology has been contracting in the U.S., largely because the energy problem appears less worrisome and because fusion reactors do not appear a likely solution to the energy problem in the near future. In addition, many material scientists believe that they can obtain the needed information in other ways.

Nevertheless the Japanese scientists who have used RTNS II so successfully plan to build a similar source in Japan and to continue research with an intense source of D-T neutrons.

5. COMMERCIALLY PRODUCED D-T GENERATORS

5.1 Deuteron Accelerators

Ten years ago there were several manufacturers who supplied accelerators in which several milliamperes of deuterons bombarded tritium, usually absorbed in titanium. These generators produced typically 10^{11} neutrons/sec although higher source strengths could be produced with a fresh target. Hundreds of such generators were sold for teaching, research, and applications. While I have no statistics, my impression is that not very many of them are now in operation, and no new generators are being manufactured as far as I have been able to learn. There is, however, a small company (Potentials Inc.) that buys used generators that were originally manufactured by Texas Nuclear. This company restores the machines to their original state and sells them as equivalent to new machines. Apparently several generators are bought and sold by this company every year.

5.2 Sealed Tube Generators

Two types of sealed tube generators have been available commercially: Tubes intended for high intensities and continuous operation, and low-intensity sources intended primarily for pulsed operation.

Tubes for high-intensity ($\geq 10^{12} s^{-1}$) operation have been manufactured in the U.K., Holland, Switzerland, and the U.S. Of these only the Swiss manufacturer may still offer such a system. All the units manufactured by the other companies have been shut down.

Kaman manufactures a sealed tube generator that produces up to 10^{11} D-T neutrons/sec. This tube is advertised to have more than 50% of its initial yield after 100 hours of operation, but the cost of replacing the tube is over $15,000.

There are several manufacturers who sell closed tubes for pulsed operation, typically delivering 10^8 neutrons per pulse. Such tubes are manufactured by Sodern in France, GEC Avionics in England, and Kaman in the USA. These systems are intended primarily for geophysical and safeguards applications. In addition, several geophysical corporations, such as Schlumberger, Haliburton, Dresser, and Gearhart manufacture such tubes, but they have not been described in the literature and are not for sale.

6. EXAMPLES OF OPERATING D-T GENERATORS

6.1 RTNS II

The most intense operating D-T sources are the RTNS II sources at

Livermore.[12] They use typically 125 mA of atomic deuterium ions at 370 keV to bombard a rotating target that contains tritium in Ti. The target is 50 cm in diameter and rotates at 5000 r.p.m. A fresh target contains about 5000 Ci of tritium and produces about 3×10^{13} neutrons/sec. The source strength gradually decreases at a rate that varies from target to target. For an average target the source strength drops to half its original value after bombardment by 15 A hr. Some targets have substantially better life times, some considerably worse. The reason for the variations is not known. Targets are usually replaced after they have produced more than 10^{19} neutrons. This means that 4000 tritium atoms are lost from the target for every neutron that is produced.

During 1985 RTNS II was operated around the clock five days per week. During the year it produced 2.9×10^{20} neutrons and the availability of the sources averaged 84%.

6.2 Oktavian

Oktavian[13] is an intense D-T source at Osaka University similar to RTNS I at Livermore. It uses 20 mA of analyzed D^+ at 300 keV on a rotating TiT target. Its output is 3×10^{12}/sec in steady operation. It can be operated in a pulsed mode with bursts 1.5 to 3 ns long and at a 1 kHz to 2 MHz repitition rate with 10^4 neutrons per pulse.

There is a program to build an upgraded facility in which the deuteron current will be increased to 200 mA and the energy to 400 keV. The expected output is 5×10^{13} neutrons/sec in steady operation. In the pulsed mode an increase by a factor of fifty in the number of neutrons per pulse is expected.

6.3 Dynagen

The facility[9)] at Eppendorf Hospital in Hamburg, Germany, is used for radiation therapy. The accelerator built by Radiation Dynamics produces 12 mA of unanalyzed 500 keV deuterium ions. Originally it had a conventional rotating target, but, since an unanalyzed beam was used, the target life was very short. More recently the atomic and molecular beams were separated by about one cm by a small magnet, and the target now consists of a rotating cylinder. Both target spots serve as neutron sources. The total output is 3.5×10^{12}/sec. The active total target area is 300 cm^2. Each target produces about 4×10^{17} neutrons before it is replaced.

6.4 University of Wisconsin Gas Target Source

The only high intensity source with a differentially pumped gas target is at the University of Wisconsin-Madison.[14)] It is used for radiobiological studies. Typically 12 mA of 210 keV unanalyzed deuterium ions are accelerated; about half the beam actually gets into the tritium target. Typical output is 1.4×10^{12}/sec, but occasionally up to 4×10^{12}/sec have been produced. The tritium use per neutron produced is considerably higher than for a solid target. The large physical size of the gas target is a disadvantage for experiments that require a high neutron flux density.

6.5 Karin

About 12 years ago a closed high-intensity tube was developed at Karlsruhe by K.A. Schmidt.[15)] Generators using these tubes were manufactured by Haefely in Basel, Switzerland. Inquiries to Haefely about the status and availability of these generators have remained unanswered.

These tubes use 150 mA of mixed deuterium and tritium beams accelerated by 200 kV. The beam impinges on a scandium target. The tube contains 500 Ci of tritium and is rated to produce 6.5×10^{12} neutrons/sec. The life expectancy of the tube is several hundred hours.

Five such generators have been purchased, three for radiation therapy, one for activation analysis, and one for a fusion-fission test facility. The therapy units are isocentrically mounted to allow the source to be moved around the patient.

7. PULSED SOURCES

Neutron spectra are most readily measured by the time-of-flight method, and for this purpose sources that produce nanosecond bursts are needed. RTNS I is an early example of such a source. It uses bunched deuterons that produce neutron pulses of 2 ns width with repitition rates of the order of a MHz.16)

A more recent example is the PNG-300 pulsed neutron generator at Debrecen.17) It produces pulses 1 ns long with repitition rates of several MHz. The average neutron output is 10^9/sec with intensities as high as 4×10^{10}/sec in the pulses. This is achieved with an average deuteron beam current of 10-20 μA.

8. PLANNED INTENSE SOURCES

Oktavian II mentioned earlier, with a deuteron beam current of

200 mA would be the most intense D-T source both for continuous and pulsed operation. Its output would be 5 × 10^{13}/sec continuous, and 5 × 10^{5}/sec in a 2 ns pulse.

Other intense sources, which are similar to RTNS I, are under construction in various laboratories. They include INGE-1 at Dresden, Intense NG at Bratislava, and similar sources at Debrecen and at Lanzhou University in China. All these sources use rotating targets and are expected to produce 1-2 × 10^{12} neutrons/sec.

9. RADIATION HAZARDS

The use of D-T sources exposes the operators to radiation produced by radioactivities induced by the neutrons, and to the tritium in the target.

The experience with RTNS II, which is the most intense operating source may be of interest. The original design included a plan to change targets and experiments remotely by using a cart that traveled on rails to the target position. When this system was first installed, it did not work satisfactorily, and it turned out to not be necessary. The activities are allowed to decay over a weekend before a target change. The operators who change targets get an annual exposure of about 3 mSv from induced radioactivity.

Tritium contamination turned out to be a more serious problem not so much because of high exposure to personnel, but because unexpected contamination was occasionally found outside the accelerator area in spite of regular surveys. The explanation appears to be that specks of Ti containing tritium come off used targets but are missed by the swipes which appear to show no contamination. These specks migrated in uncontrolled ways and occasionally found their way into the office areas. Until these occurrences were explained and preventive measures were instituted two years ago, there were extended shut downs of the facility to track down tritium contamination. Last year the annual average exposure to tritium was 0.6 mSv for the operating personnel.

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