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Miniature neutron sources:
thermal neutron sources and their uses in the academic field

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ABSTRACT

The three levels of thermal neutron sources are introduced - University laboratory sources, infrastructure sources and world-class sources - and the needs for each kind and their inter-dependence will be emphasized. A description of the possibilities for University sources based on α-Be reactions or spontaneous fission emission is given, and current experience with them is described. A new generation of infrastructure sources is needed to continue the regional programs based on small reactors. Some possibilities for accelerator sources that could meet this need are considered.

I. INTRODUCTION

From the time of the discovery of the neutron until the advent of nuclear reactors, research with thermal neutrons was conducted using either radioactive sources or low powered accelerators. In subsequent years as the field developed rapidly and the sources grew more powerful, the experimental techniques and instruments became more sophisticated. These developments have been described in various reviews and conferences (for example Bacon[1] or Birgeneau et al[2]). At first the personnel training, the technical development and the front line research modes of work were interleaved at the same source (usually a reactor, but sometimes an electron or proton accelerator). Often any given scientist would be active in all three modes. But as the field expanded over a period of the order of 50 years these three different modes have slowly separated, sometimes to the disadvantage of the field. To handle the problems that this has created we shall argue that a range of neutron sources, with differing capabilities, are needed and that they should be distributed among a variety of locations.

There are interdependent roles for the radioactive sources at University training laboratories, for the medium output sources at the infrastructure or regional laboratories and for the high flux world class source as a tool for front line research. We shall discuss the former two kinds of sources in this paper, and we shall conclude that the future success of thermal neutron research will depend on the development and wide-spread use of these sources just as much as it will depend on the development of world class sources.

II. THE NEED FOR A RANGE OF NEUTRON SOURCE TYPES

Thermal neutron sources are used for a variety of purposes, for example the production of radioisotopes, for neutron radiography and for pure and applied research on materials using neutronbeams. The radioisotopes may be exploited in a variety of ways, in radio-chemical analysis, in tracer based research, etc. Neutron radiography had advantages in the penetrability of neutrons, in the high contrast for hydrogenous materials and in the special properties of cold neutrons. Neutron beam research includes neutron diffraction and SANS experiments using crystalline, amorphous and liquid samples, neutron inelastic scattering studies of time-dependent phenomena over wide time ranges and neutron reflectivity research into the properties of surface, films and other samples. In all of these fields there are interesting topics for academic, industrial and government laboratory research programs. A major limitation to the techniques employed, has been the relatively low levels of the thermal neutron fluxes relative to (say) those used in light or X-ray scattering. Moreover development programs to improve the flux levels are expensive and time consuming, as shown by the current examples of the Advanced Neutron Source (West and Hayter[3]) and the European Spallation Source (Taylor et al[4]). It is possible that the need to concentrate on advanced sources, has resulted in the neglect of the other two types of source - the laboratory source and the infrastructure source.

In order to understand the needs in one field a study of the structure of complementary fields may be of interest. For example we may look at the range of source types and source strengths available to scientists whose research involves either light scattering or X-ray scattering. In these cases a wide range of source strengths are in use, moreover are used profitably by those involved. A concentrated effort to produce a world-class source (e.g., the ESRF at Grenoble or the APS at Argonne) does not obviate the need for sources at all other levels. Instead there is a general strengthening of the total field, and research and development on weaker sources continues and is perhaps enlarged while world-class sources are used. A multi-faceted relationship develops between sources of various types, involving training, technical development and research. It is possible to pose the question "Can the case for a world-class source in these be maintained, without the widespread existence and use of sources of radiation at other levels?" Certainly, in whatever way this question is answered, it is clear that there is a significant interplay between the users and sources of the several kinds, which enhances the whole field and especially the usefulness of the major sources.

This simple observation and resulting effects must apply in the thermal neutron case. Indeed such beneficial effects occurred naturally in the early development of the subject, and were pointed out above. In the remainder of this paper we shall list several kinds of small neutron source and indicate some of the academic or developmental work that may be done with them. These sections of our paper should be regarded as an indication of what may be done today only. The current development of sophisticated neutron beam techniques that can be employed at reasonable prices, has led to the possibility of exploiting small sources in many new and profitable ways. Therefore the lists given here should be looked on as preliminary because it is possible that they will be extended greatly in the future.

III. RADIOACTIVE SOURCES AND THEIR USES

These sources are the most useful for University laboratory settings or for in-field measurements such as radiographic work. Their advantages are their relatively low cost, their small size (including shielding), and their portability. It is worth listing some of the most widely used kinds in Table I.

TABLE I

List of Radio-Neutron Sources for Laboratory Use

1. α-Radioactive Isotope Sources

α-Beryllium sources are the most popular, and use the reaction:-

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n + 5.7\ \mathrm{MeV}.$$

Sources of α particles include the following naturally radioactive isotopes:

^{238}Pu, ^{239}Pu, ^{210}Po, ^{241}Am, ^{226}Ra, ^{222}Rn, ^{242}Cm, ^{244}Cm.

In these cases yields are approximately 5×10^{6} neutrons/sec-Ci, and the neutrons have energies about 5 MeV. These yields vary from cases to case.

Other α,n sources are used sometimes, and the reaction is:-

$$\alpha + X \rightarrow Y + n + Q;$$

where X may be ^{10}B, ^{11}B, ^{19}F, ^{13}C, or ^{7}Li.

In these cases yields are approximately 5×10^{5} neutrons/sec-Ci, and the emitted neutrons have energies around 2 MeV.

2. Spontaneous Fission Sources

Any spontaneously fissile isotope is a potential source, but for a high yield a short half-life is needed. Possible candidates are ^{250}Cf and ^{252}Cf, and the latter is available commercially. For such reasons ^{252}Cf, half-life 2.6 years is the most advantageous and its yield is 2.3×10^{6} n/sec/microgram. The neutrons have a fission spectrum, with a mean energy of about 1 MeV.

3. Photoneutron Sources

A variety of (γ,n) reactions have been used for neutron production, for example:-

$$\gamma + {}^{9}\mathrm{Be} \rightarrow {}^{8}\mathrm{Be} + n \quad (Q = -1.666\ \mathrm{MeV}),$$

$$\gamma + {}^{2}\mathrm{D} \rightarrow \mathrm{H} + n \quad (Q = -2.226\ \mathrm{MeV}).$$

In these cases the neutrons are nearly monoenergetic, with energy determined by kinematics and the sum of the gamma energy and the (negative) Q value. A number of γ sources are available, for example if ^{124}Sb is used (half-life 60 days, gamma energy 1.691 MeV) the yield will be about 5×10^{4} neutrons/sec-Ci, and the neutrons have energies around 24 keV. Further details may be found in Knoll or Beckurts and Wirtz[5].

It is useful to note that neutrons from all these sources are accompanied by equal or greater numbers of gamma rays.

It is useful to compare the α-radioactive and the spontaneous fission sources. A 2-Ci ^{241}Am-Be source has a yield of about 5×10^{6} neutrons/sec at energies of about 5 MeV. This is a modest yield, and the size of the hydrogenous moderator to produce thermal neutrons and the necessary shielding, occupies a cube of about 1.5 m per side. The cost would be with the budgets of most university departments, and, the half-life of ^{241}Am being 432 years, the maintenance free life is essentially infinite. On the other hand, a 40 µgram ^{252}Cf source has a yield of about 10^{8} neutrons /sec with a fission spectrum, for which a hydrogen or deuterium containing moderator is relatively efficient. Therefore it has a higher flux, lower background and can be slightly more compact than the Am-Be source. Unfortunately it has a short half-life (2.6 years) and so needs to be replaced (say) every 5 years. The cost would be substantial unless the Californium-252 University Loan Program of the Oak Ridge National Laboratory can be used.

At figure 1 we give a sketch of a possible arrangement of four 10 µgram ^{252}Cf sources in heavy water, installed in a geometry such that the thermal neutron flux in a double beam tube is a maximum. Heavy water is used because the low neutron absorption leads to higher fluxes. For most university laboratory teaching or testing environments one or two beam tubes is sufficient. The thermal neutron flux from this tube is 10-100 times greater than that for the Am-Be source geometry described below, and so offers a corresponding wider range of experiments or a more rapid turn-around.

However in many cases the only practical sources are the α-Be ones, and we shall describe briefly the thermal neutron source and experiments used in laboratory courses for students at the University of Guelph. Figure 2 is a diagram of the thermal neutron beam source and neutron diffractometer. A 2-Ci Am-Be source is surrounded by a cylinder of paraffin wax 30 cm in diameter which in turn is imbedded in a neutron absorbing shield (1.5 m per side). The beam hole is a 7 cm diameter aluminum tube which penetrates the wax, so that there is 1 cm of wax between the end of the hole and the source. A neutron beam defining slit (not shown on the diagram) can be mounted at the surface of the shield. The thermal neutron beam, so defined, falls on a pyrolytic graphite crystal (7 cm x 10 cm long) mounted on an angular table which is set by hand. A bank of three 2.5 cm diameter x 12 cm long ^{3}He neutron detectors is located as shown on the figure. The detector housing is attached to an arm which is pivoted on the crystal mount, and may be rotated by the student's hand pressing against the friction built into the wheels. A scale marked on the floor shows the student the angular setting. Thus the construction costs are low and the operation is simple. The detector is connected to a standard amplifier, discriminator and timing scaler available commercially. Students using this apparatus are provided with a description of it and the method of use and an experimental outline, in a similar way as for the other physics experiments in the laboratory. Table II is a list of the experiments that are available; they are of varying difficulty and duration.

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TABLE II

List of Student Experiments for the apparatus in Figure 2

1. Demonstration of the relative thermal neutron transmission through Lead, Cadmium and polyethylene (where an X-ray set is available this may be compared to the transmission for X-rays).

2. Demonstration of the Bragg reflection of neutrons, and evaluation of the line shape.

3. Measurement of the neutron energy distribution from a moderator and comparison to theoretical prediction.

4. Simple demonstration of the influence of neutron filters on the neutron energy distribution.

5. Measurement of the 1st and 2nd order content of a Bragg reflected beam, by comparing measured and calculated transmissions through Indium foils. Comparison with predicted ratio of 1st to 2nd order intensities.

6. Experimental test of the De Broglie relationship and the measurement of Planck's constant h.

Notes: The counting rate (minus background) when the crystal and detector are set for 1.4 Å neutrons, is about 500 counts in 4 minutes. Backgrounds are determined by mis-setting the crystal by 6°.

If the ^{252}Cf source in heavy water arrangement is used, having thermal neutron fluxes 10-100 times larger it becomes possible to enlarge the range of experiments considerably. For example a simple neutron chopper may be installed which will improve and extend some of the experiments listed in Table II. This source could be used also for some tests related to experimental programs on more advanced sources.

A number of classroom experiments based on the use of small neutron generators have been developed at the University of Michigan in the Nuclear Engineering program. These include measuring the space-and time-dependent response of a 2 m^3 graphite "Sigma Pile" and a subcritical natural Uranium assembly driven by a sealed tube pulsed neutron generator (see below) and by isotope neutron sources.

IV. INFRASTRUCTURE SOURCES

Three kinds of sources were discussed in section 2. They were the university laboratory source (section 3), the infrastructure or regional source and the world-class source. For a number of years nuclear reactors (such as the pool type reactors) with an isotropic thermal neutron flux of 10^{12} -10^{13} neutrons/cm^2-sec at the beam source served this purpose. Their essential role was clearly demonstrated during the buildup of the neutron scattering program in Europe in the 1970s. The ILL reactor program had links and interactions with perhaps 12 small reactor laboratories in different European countries. New ideas for experiments and instruments could be tested in these laboratories, technical and scientific personnel could be trained, and a two way profitable interaction developed between the central world-class source in Grenoble and a ring of infrastructure sources. This made a significant contribution to the success of the ILL reactor. Unfortunately in the USA these sources were generally older and were progressively shut down, and therefore a system of relationships of a similar magnitude did not develop. Nevertheless there were and still are some relationships of this general kind between the different sources in the USA. Today the small neutron sources in Europe and the USA are nearing then ends of their lives, and because of their importance in the chain of scientific work, a modern replacement is needed. It is possible that new designs for small reactors (e.g., the Slowpoke reactor[7]) will be suitable for this field. In any case the utility of small reactors in a university environment has been demonstrated at MIT by C. G. Shull[8], for example.

The 2-MW pool reactor at The University of Michigan is used in a wide range of reactor physics training exercises, including activation analysis, flux distribution measurements in the reactor and in the pool, control rod, void, thermal feedback and Xenon transient reactivity measurements, and startup and shutdown transients. The reactor produces Sb-124 used in an Sb-Be neutron source for flux distribution experiments. Thermal neutron beams have been used for a small triple axis spectrometer, a two axis diffractometer, a multirotor time-of-flight spectrometer, a time-of-flight diffractometer, interferometry experiments, for neutron radiography, neutron capture surface profiling, detector development and testing and for time-of-flight and crystal reflection measurements of moderator spectra.

Small accelerator sources may become a viable alternative for some of these purposes and some possibilities are listed below. The overriding requirements are that the operation of the accelerator be made as simple as operating an automobile, and that the price be reduced to that appropriate for widespread university and industrial use. A discussion of the feasibility of these requirements is beyond the scope of this paper. However the experimental work conducted on them would be a natural extension of the work done with regional reactors as mentioned above.

1. D-D and D-T Sources

The reactions used are:-

$$D + T \rightarrow {}^{4}He + n \; (Q = 17.6 \text{ MeV}) \text{ and}$$

$$D + D \rightarrow {}^{3}He + n \; (Q = 3.26 \text{ MeV}).$$

The emitted neutrons have energies that depend on the distribution of energies of the reacting particles (they slow down in the target), and the kinematically-adjusted Q value (which depends on the angle of emission relative to the direction of the incoming charged particle beam). The energy of D-D neutrons is about 2. MeV, and for D-T neutrons about 14. MeV. A number of accelerator types might be used, and we list several below.

A. Sealed-Tube Generators

These are available in pulsed and steady source versions, operating with a sealed cell containing mixed Deuterium and Tritium. The sources are compact and portable and various models produce 10^{8} to 10^{11} n/sec (time average), principally of 14 MeV neutrons, but mixed with 2 MeV D-D neutrons. Pulsed types provide up to 10^{8} n/pulse at frequencies up to 100 Hz. A line of sealed tube neutron generators is offered by MF Physics, Inc. of Colorado Springs.

B. Dense Plasma Focus Devices

These operate on the principle of electromagnetic acceleration and compression of a deuterium or deuterium-tritium plasma, in a special geometry. Recent work has been reported in a review of developments by Nardi and Brzosko[6].

With a pure deuterium plasma, the yield so far demonstrated is 4×10^{9} neutrons per shot; with a 50-50 deuterium-tritium, 4×10^{11} per shot. The pulse is about 50 nanoseconds long. The yield scales as the square of the energy delivered to the system. Only low frequency operation has been demonstrated, but the system shows promise for further development.

2. Accelerator Sources

We confine attention to low energy accelerators relevant to the University laboratory and small infrastructure applications. Reactions that have been used are:-

$$p + {}^{7}Li \rightarrow {}^{7}Be + n \quad (Q = -1.640 \text{ MeV}) \text{ and}$$

$$p + {}^{3}H \rightarrow {}^{3}He + n \quad (Q = -0.746 \text{ MeV}),$$

but the neutron yields are not as large as for the D-D and D,T reactions. Figures 3 and 4 display global, thick-target (stopping length) neutron yields for various (d,n) and (p,n) reactions.

A. Cockroft-Walton Generators

These are small, low-voltage, inductively charged DC accelerators which can be operated in steady beam mode or in pulsed mode with either steady or pulsed proton or deuteron ion source of a few milliamperes current. For example, with a solid target of tritium-loaded Titanium, a 300 keV column produces 14 MeV neutrons at a peak rate of about 10^{11} n/sec; with a (self-replenishing) deuterium-loaded Titanium target, 2 MeV neutrons at about 10^{9} n/sec. These are fairly common laboratory-scale neutron sources, once offered by Texas Nuclear Corporation and by Kaman Nuclear Corporation, now available in modern versions by MF Physics Corporation.

Table III shows the parameters of Cockroft-Walton accelerators offered by Science Research Laboratory of Sommerville, Massachusetts for use as neutron generators.

Table III[9]

COCKROFT-WALTON NEUTRON GENERATORS

Accelerator Characteristics	Single-ended Cascade Type	Tandem Cascade Type
Beam Energy	100-600 keV	2.5 MeV
Maximum Continuous Current	500 µA	4. mA
Maximum Neutron Production Rate	1×10^{10} n/sec D-Be 4×10^{9} n/sec D-D 1×10^{11} n/sec D-T	4×10^{12} n/sec p-Li
Length	1. meter	2.6 meters
Diameter	0.5 meters	0.8 meters
Pulsed beam options	10 µsec @ 10 kHz 1 ns @ 5 MHz	1 ns @ 5 MHz

The Cockroft-Walton sources are available at prices that make them appropriate for University laboratory and special purpose infrastructure installations. Their modest size allows portable application.

B. Van de Graaf Accelerators

These are DC accelerators charged by various methods and referred to by correspondingly different names ("Pelletron", ...). For example a 1 MeV van de Graaf could provide up to 4 mA proton or deuteron beams, in some cases yielding more neutrons as the Cockroft-Walton systems of A. above.

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C. Cyclotrons

On a somewhat larger scale, cyclotrons offer higher particle energies and a variety of particles for neutron production, production of radionuclides and radiation therapy. Cyclotrons are available commercially, one supplier offering a variety of machines producing up to 120 MeV protons. For example, Table IV shows the characteristics of a 17 MeV proton cyclotron, which can be operated with different particles. Cyclotrons typically operate in steady beam mode, but can be pulsed at the ion source with consequent reduction in time average current.

Table IV[10]

A CYCLOTRON NEUTRON SOURCE

Particle	Energy	Extracted Current
Protons	17 MeV	50 μA
Deuterons	8.5 MeV	50 μA
Helium-3	13. MeV	30 μA
Helium-4	17 MeV	30 μA

Such an installation costs on the order of $2 M. Larger cyclotrons providing higher particle energies are also available commercially.

D. Synchrotrons

For completeness, we mention synchrotrons. These are generally one-of-a-kind, central installations providing high energy particles and very intense neutron fields. As such they are beyond the scope of this paper.

3. Electron Bremsstrahlung Photoneutron Sources

Relativistic electron beams produce bremsstrahlung radiation, gamma rays, upon stopping in solid targets. The energetic photons subsequently produce photoneutrons through the giant resonance interaction with nuclei, either in the stopping target or in a separate target. Figure 6 shows the global neutron yields for various combined-target materials as a function of electron energy. Clearly, the neutron yields are greatest at energies above about 20 MeV and for the heaviest target elements. These general truths notwithstanding, Bowman[11] has worked out the design of an electron-beam-driven neutron source based on a low energy (12 MeV) electron linac and using light element target materials, which would provide and effective source for an infrastructure-scale installation.

Electron linear accelerators are commercially available, which provide currents suitable for University installations and up to energy and current levels suitable for infrastructure installations and even for central research facilities of moderate size. The accelerators typically operate in a pulsed mode with pulse lengths up to a few microseconds and frequencies of a few hundred Hz, with time average beam power up to some tens of kilowatts. Smaller, compact electron "microtrons" are also available which provide lower energy electrons and lower currents than the linacs.

It must be borne in mind that the neutrons from bremsstrahlung sources are accompanied by a large flux of gamma rays.

IV. MODERATORS AND NEUTRON THERMALIZATION

In all these instances the primary sources produce neutrons of roughly 1 MeV energy. It is necessary to provide moderators to slow these down to thermal energies, where they have roughly a Maxwellian distribution with a temperature close to the temperature of the moderating medium. These look in general like the arrangements of Figures 1 and 2, in that the sources are all rather small. More elaborately, they may consist of a multilayered arrangement in which the thermal neutron source, i. e., the moderator, is surrounded by a fast neutron reflector. A very rough estimate of the isotropic thermal neutron flux averaged over a 100 cm^2 viewed surface is

$$\frac{\phi_{Th}}{S_{Fast}} = 5 \times 10^{-4}\ n_{Th}/cm^2/n_{Fast}$$

for a dense, hydrogenous moderating medium.

The moderator may be of water, wax or polyethylene (all having about the same proton density) at room temperature. To provide more low energy (long wavelength) neutrons the spectrum can be shifted with about the same total flux but with a lower temperature if the moderator is cooled to cryogenic temperatures. The best material for this purpose is solid Methane, although liquid Hydrogen is a useful possibility. A volume of about one-half liter is sufficient, and can be cooled to temperatures of 20 K or less by a closed cycle Helium refrigerator of nominal 10 W cooling capacity. A low temperature moderator is relatively inexpensive to install and operate on any of the sources listed in section III above, because the access is good and the heat loads are small. The original techniques described by Butterworth et al[15] would be satisfactory in many cases.

VI. CONCLUSIONS

The thesis presented here is that for the health and success of a technique, such as the scattering of electromagnetic radiation or of neutrons, it is essential that viable sources of radiation exist at various power levels. These levels would fit the needs for training, development and research in an interlinked way. For electromagnetic radiation (X-rays) this situation has occurred naturally in the course of development of the field. However over the past 20 or 30 years the fields related to neutron sources have begun to slip away from this ideal situation. We argue that technical possibilities and uses exist for all types of neutron sources and interesting, profitable work with them is waiting to be done.

We also argue that there are numerous prospects and existing possibilities for different types of neutron sources to fill these needs and the needs for portable installations such as are required for in-field neutron imaging (aircraft inspection, components production control, baggage inspection, ...) or for neutron capture gamma ray interrogation.

Small neutron sources at the laboratory and infrastructure levels not only provide directly for these and other applications, but also enable development of all the relevant methods in university settings appropriate to innovation and training.

Acknowledgement

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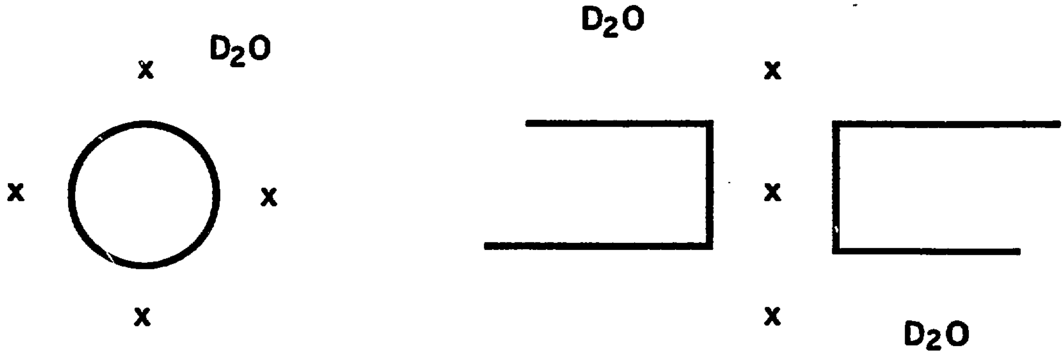
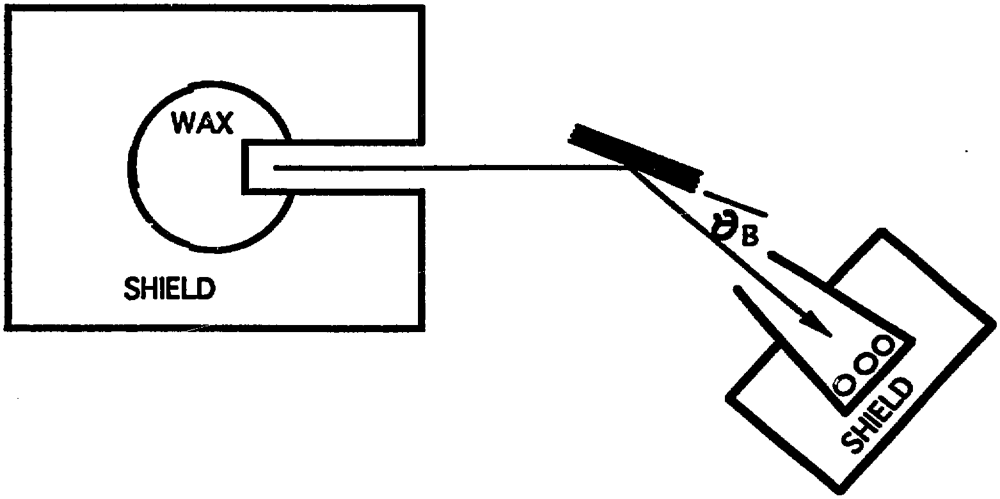
FIGURES



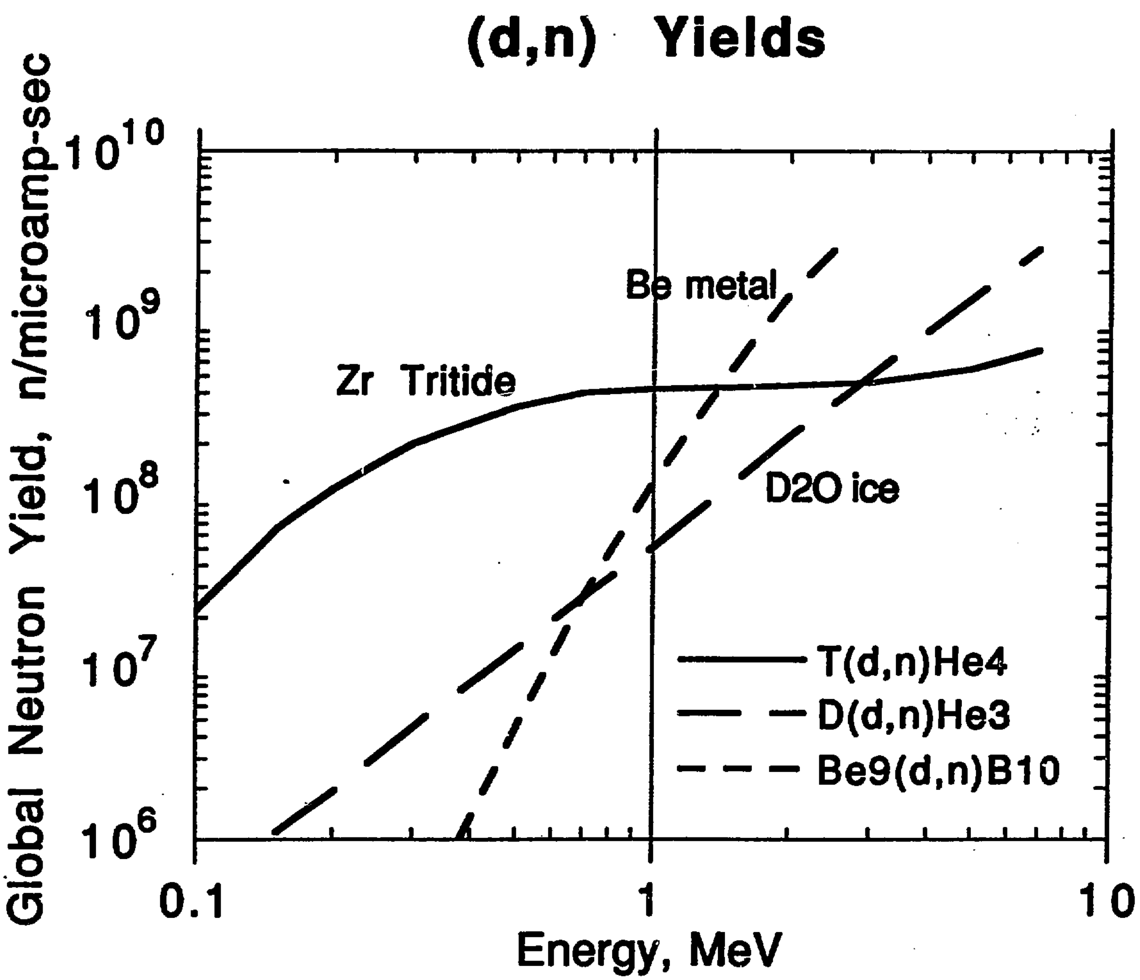
1. A sketch showing a useful geometry for the production of two thermal neutron beams, using four 10 μgram ^{252}Cf sources in a heavy water moderator. Two beams are sufficient in many applications.

   (a) End view of holes: circle (8 cm diameter) is end view of beam tube and crosses are the four 10 μgram ^{252}Cf sources each, 7 cm from beam centre line.

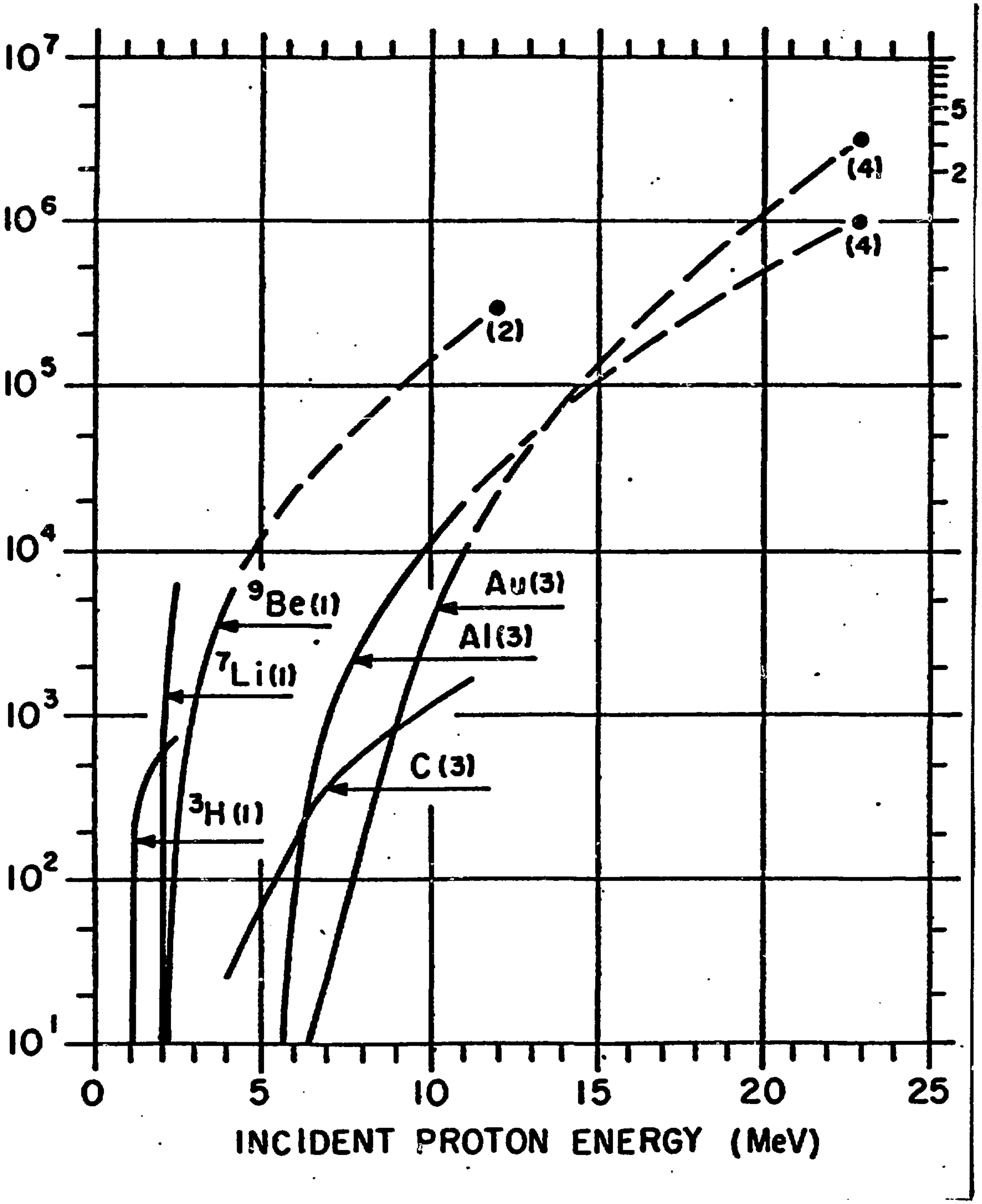
   (b) Side view of holes: crosses are location of sources and line drawing indicates cross sections of the two beam tubes which are 7 cm apart.



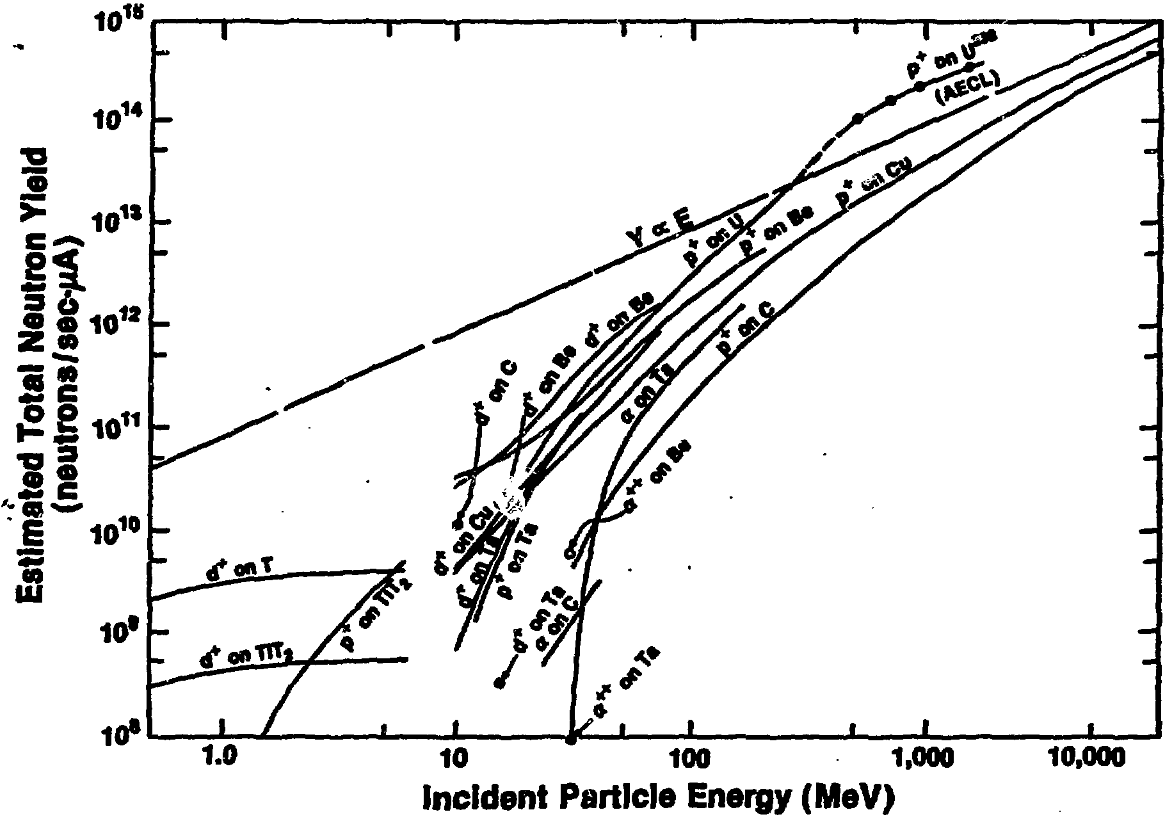
2. A diagram of the thermal neutron beam and diffractometer used for student laboratory work at the University of Guelph. ϑ_B is the Bragg angle and neutrons are detected through the reaction $n + {}^3He \rightarrow p + {}^3H$. This view is a central cross section; the arrow shows the centre line of the neutron beam.



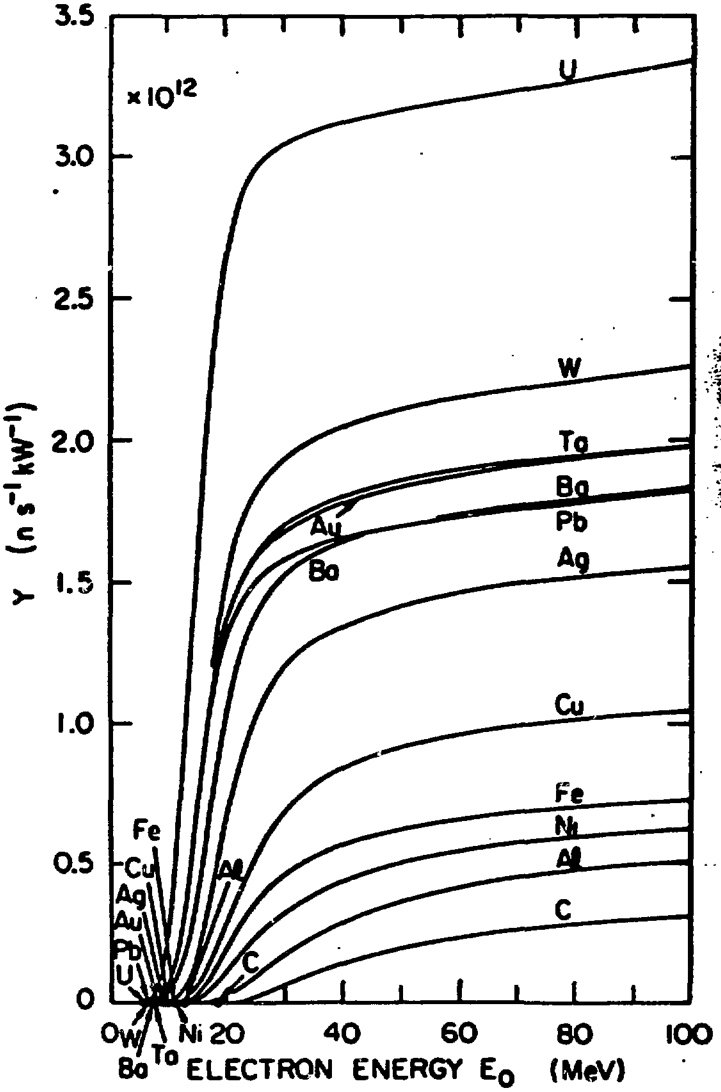
3. Global neutron yields for (d,n) reactions as a function of deuteron kinetic energy[12].



4. Global neutron yields for (p,n) reactions as a function of proton energy[10]. To obtain the yield, multiply the ordinate by $4\pi \times 10^4$.



5. Global neutron yields for various charged particle reactions[13].



6. Global neutron yield as a function of electron energy for various target materials[14].