A practical target system for accelerator-based BNCT which may effectively double the dose rate

G. Randers-Pehrson[a)] and D. J. Brenner
Center for Radiological Research, Radiological Research Accelerator Facility, Columbia University, Irvington, New York 10533

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A dose-limiting component of a proton accelerator-based source of epithermal neutrons is the neutron production target. Possible targets are lithium, producing high yield but having low melting point and thermal conductivity, and beryllium, presenting less engineering problems but a much smaller neutron yield. We propose that a hybrid Be-Li target would provide the best of both worlds, with the upstream beryllium component producing neutrons and providing containment to the lithium, and the downstream liquid lithium in turn producing further neutrons as well as cooling the beryllium. The engineering considerations associated with such a target system are within the range of current technology. Calculations suggest a yield of such a practical target that is at least double that from pure beryllium.
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If boron neutron capture therapy (BNCT) is to become a practical option, accelerator-based sources of high fluxes of epithermal neutrons are essential.[1–4] Much work has been performed on development of high-flux compact proton accelerators,[5–7] but a dose-limiting component remains design of the neutron production target.[8]

Engineering considerations apart, it is clear that the best low-energy neutron production target for a proton accelerator would be pure lithium.[9] Figure 1 shows that the neutrons yields are high and, additionally, the kinetics are such that the secondary neutron spectrum is relatively low energy. Because of these advantages, early designs for accelerator-based BNCT systems focused on lithium targets.[3,4,10,11] However, when such systems began to be built, the engineering problems of using a pure lithium target proved difficult to overcome. Specifically, lithium has a low melting point (180 °C) and low thermal conductivity (44 W/m °C), and is also chemically reactive with air.

Because of these difficulties, several groups chose instead to use beryllium as the neutron production target.[8,12] Whilst the yield at a given proton energy is much lower (see Fig. 1), beryllium has a much higher melting point and thermal conductivity, and is less reactive with air. Thus it has been reasoned that by increasing the proton energy to around 4 MeV (compared to $\sim$2.5 MeV which had been proposed for lithium targets), a comparable neutron yield could be obtained, but with a much simpler target configuration.[8] The disadvantage of such a scenario relate to the increased cost and complexity of a $\sim$4-MeV vs a 2.5-MeV accelerator. Although the kinematics for the $p+$Be reaction are less favorable in terms of the highest energy neutrons emitted, seeming to require a larger and more expensive moderator, Wang and Moore[8] suggest, and Howard *et al.*[12] confirm, that the main bulk of the neutrons are produced through multiparticle reactions that result in softer spectrum.

In this note, we propose that a hybrid target of beryllium plus lithium could provide the best of both worlds. Specifically, we propose (Fig. 2) a 3 to 4 MeV proton beam incident on a thin beryllium target which is cooled on the downstream side by a moving pool of liquid lithium, which would itself act as a second neutron production target. Lithium is, of course, an extremely efficient coolant.[13] In turn, the beryllium acts as a containment device for the lithium on the upstream side, providing a barrier between the lithium and the accelerator beam tube.

Depending on the beam current, and thus the target cooling requirements, the liquid lithium would either be in the form of a stirred pool or a flowing lithium jet. Lithium jets have been under development for some years[14,15] as targets for the d-Li reaction in fusion research systems, though this latter requires far larger beam currents and cooling capabilities than the current application. Static liquid metal targets have also been used.[16,17]

Figure 3 shows calculated yields (integrated over angle and energy) of neutrons produced by 4.1-MeV protons incident on such a hybrid Be-Li target, as a function of the thickness of the beryllium component; the lithium component is sufficiently thick as to degrade the incident protons at least to the neutron production threshold. Comparison with Fig. 1 shows that, for example, 4.1-MeV protons incident on a 50-μm beryllium target cooled by lithium would produce a neutron yield about twice that of a pure beryllium thick target.

Figure 4 shows calculated yields for different combinations of incident proton energy and beryllium target thickness. Overall, from the neutronics standpoint, it would be advantageous to use the thinnest practical beryllium component within the overall hybrid target. With a 50-μm beryllium component, the hybrid Be-Li target would probably be advantageous (considering only neutron yield) for proton energies above about 3.5 MeV; with a 25-μm beryllium component, the hybrid target would be advantageous for proton

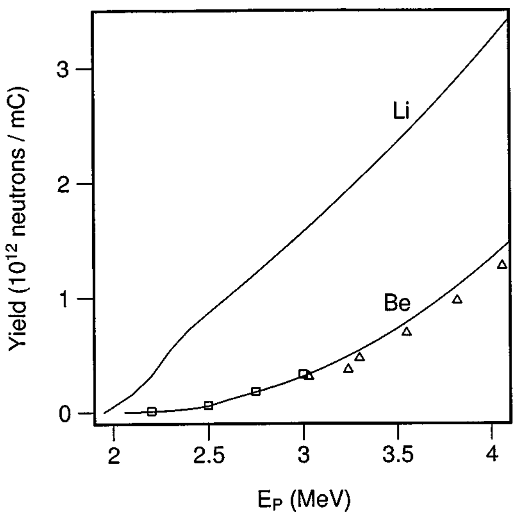

FIG. 1. Thick target total neutron yields after proton bombardment of thick lithium and beryllium targets, as a function of incident proton energy. Curves were calculated based on cross sections from Liskien and Paulsen (Ref. 21) for lithium, and Gibbons and Macklin (Ref. 22) for beryllium. Direct measurements of total neutrons yields from thick beryllium targets, by Cambell and Scott (Ref. 23) (squares) and Porges *et al.* (Ref. 24) (triangles) are also shown.

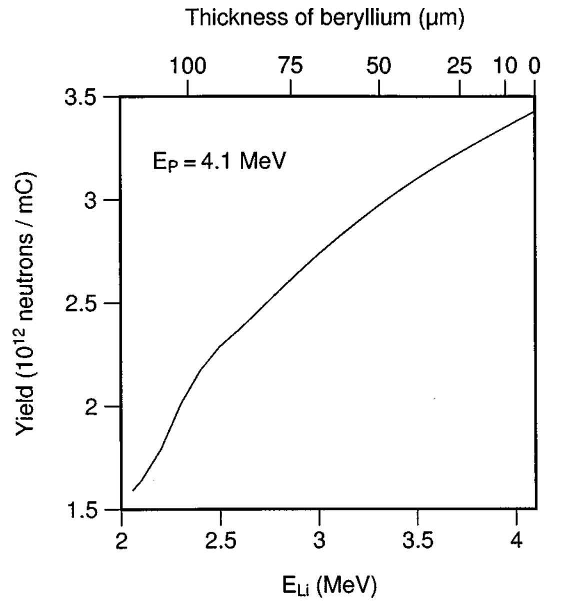

FIG. 3. Calculated total neutron yield after 4.1-MeV proton bombardment of hybrid Be-Li targets, as a function of thickness of the beryllium component. E_{Li} refers to the energy of the proton beam as it exits the beryllium component, and enters the lithium part of the target.

beams above about 3 MeV. Selection of the optimum design will follow from Monte Carlo modeling of moderator assemblies for each possible beam energy and beryllium thickness combination, along with consideration of the cost and reliability of the accelerator.

The engineering considerations associated with such a target system are within the range of current technology. Liquid lithium cooling systems have been used in a variety of applications, particularly in fusion reactor research where, like the current system, the cooling must take place *in vacuo*,[18] as well as in power generation systems for space travel;[19] a variety of different types of pumps have been assessed in these applications.[18,19] These reactor-related liquid lithium cooling and heat-exchange systems are used to cool considerably larger power loads than in the current proposed application.

Because of the good thermal conductivity of beryllium, the temperature differential through the target in the direction of the proton beam will be small. The heat transfer through the boundary layer of the flowing lithium will, however, require careful analysis, as a suboptimal configuration at the Be-Li interface could lead to substantial local temperature differentials. In the direction of the lithium flow, there

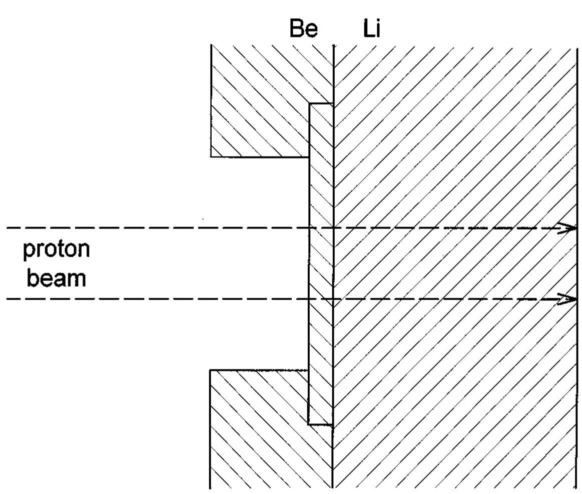

FIG. 2. Schematic of proposed Be-Li hybrid neutron production target (for clarity the horizontal and vertical scales are different). The beryllium component consists of a thin beryllium film attached to a beryllium support structure; the lithium component, which serves both as coolant and as a further source of neutrons, consists of either a jet or a stirred pool of liquid lithium. The two sides of the target are in vacuum systems which are coupled to one another.

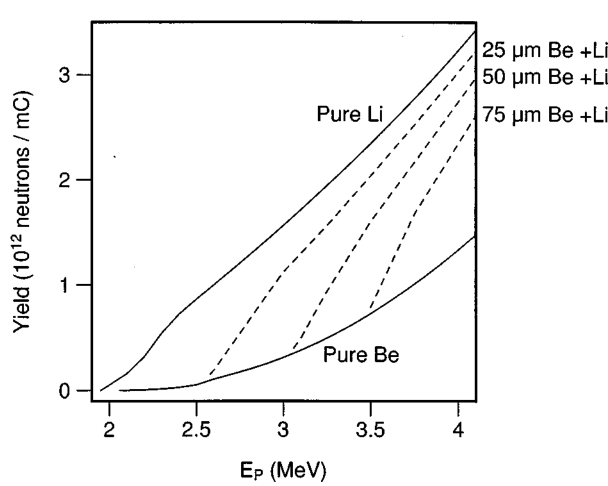

FIG. 4. Calculated total neutron yield after proton bombardment of hybrid Be-Li targets, as a function of incident proton energy (E_p), for three different thicknesses of the beryllium part of the target. Corresponding yields for thick lithium-only and beryllium-only targets are also shown.

could also be a significant temperature differential across the beryllium target, and so a target which is narrow in this direction (and broader in the perpendicular direction) would be appropriate.

The design issues for the proposed target system relate to the mechanical stresses on the thin beryllium target, due both to the temperature gradients and the lithium flow. The construction of the thin beryllium target (see Fig. 2) would be relatively straightforward, consisting of a thin beryllium foil mounted on a thicker beryllium support structure. The beryllium target would not be subject to differential pressure, having coupled vacuum systems on either side, and would have a temperature differential of only a few degrees from front to back.[20] If a lithium jet system were used, the jet nozzle would be directed at the thicker part of the beryllium structure above the beam (see Fig. 2), minimizing the mechanical stress on the thin target region. The laminar flow of liquid lithium across the thin beryllium foil would still, however, necessitate careful mechanical and thermal optimization of this thin beryllium target, in order to ensure its integrity.

In conclusion, the proposed Be-Li hybrid target is, from an engineering standpoint, within the range of current technology; it should allow increased neutron yields by at least a factor of 2 compared with pure beryllium targets, and would not be subject to most of the practical problems that had resulted in the abandonment by most groups of pure lithium targets.

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[a]Electronic mail: gr6@columbia.edu

[1]C. K. Wang and T. E. Blue, ''An accelerator neutron source for boron neutron capture therapy,'' Trans. Am. Nucl. Soc. **54**, 302–304 (1987).

[2]R. E. Shefer, R. E. Klinkowstein, J. C. Yanch, and G. L. Brownell, ''A versatile new accelerator design for boron neutron capture therapy: Accelerator design and neutron energy considerations,'' in *Neutron Beam Design Development and Performance for Neutron Capture Therapy*, edited by O. K. Harling, J. A. Bernard, and R. G. Zamenhof (Plenum, New York, 1990), pp. 259–270.

[3]N. Gupta, J. Niemkiewicz, T. E. Blue, R. Gahbauer, and T. X. Qu, ''Effect of head phantom size on ^{10}B and ^{1}H$(n,\gamma)^{2}$H dose distributions for a broad field accelerator epithermal neutron source for BNCT,'' Med. Phys. **20**, 395–404 (1993).

[4]D. A. Allen and T. D. Beynon, ''A design study for an accelerator-based epithermal neutron beam for BNCT,'' Phys. Med. Biol. **40**, 807–821 (1995).

[5]T. P. Wangler, J. E. Stovall, T. S. Bhatia, C. K. Wang, T. E. Blue, and R. A. Gahbauer, ''Conceptual design of a RFQ accelerator-based neutron source for boron neutron-capture therapy,'' in *Proceedings of the 1989 IEEE Particle Accelerator Conference, Accelerator Science and Technology*, edited by F. Bennett and J. Kopta (IEEE, New York 1989), Vol. 1, pp. 678–680.

[6]R. E. Shefer, R. E. Klinkowstein, J. C. Yanch, and W. B. Howard, ''Tandem electrostatic accelerators for BNCT,'' in Proceedings of the 1st International Workshop on Accelerator-Based Neutron Sources for Boron Neutron Capture Therapy (Idaho National Engineering Lab Report CONF-940976), edited by D. W. Nigg (INEL, Idaho Falls, ID, 1994), pp. 89–97.

[7]J. W. Kwan, O A. Anderson, L L. Reginato, M. C. Vella, and S. S. Tu, ''A 2.5 MeV electrostatic quadrupole dc accelerator for BNCT application,'' Nucl. Instrum. Methods Phys. Res. B **99**, 710–712 (1995).

[8]C-K. C. Wang and B. R. Moore, ''Thick beryllium target as an epithermal neutron source for neutron capture therapy,'' Med. Phys. **21**, 1633–1638 (1994).

[9]H. H. Barschall, G. A. Bartholomew, C. B. Bigham, R. C. Block, R. M. Brugger, R. E. Chrien, S. Cierjacks, H. Conrads, J. S. Fraser, G. F. Knoll, M. A. Lone, C. A. Uttley, L. Walter, G. B. West, and W. L. Whittemore, *Neutron Sources: For Basic Physics and Applications* (Pergamon, Oxford, UK, 1983).

[10]C. K. Wang, T. E. Blue, and R. Gahbauer, ''A neutronic study of an accelerator-based neutron irradiation facility for boron neutron capture therapy,'' Nucl. Technol. **84**, 93–107 (1989).

[11]J. C. Yanch, X-I. Zhou, R. E. Shefer, and R. E. Klinkowstein, ''Accelerator-based epithermal neutron beam design for neutron capture therapy,'' Med. Phys. **19**, 709–721 (1992).

[12]W. B. Howard, J. C. Yanch, S. M. Grimes, T. N. Massey, S. I. Al-Quraishi, D. K. Jacobs, and C. E. Brient, ''Measurement of the ^{9}Be(p,n) thick target spectrum for use in accelerator-based Boron Neutron Capture Therapy,'' Med. Phys. **23**, 1233–1235 (1996).

[13]R. J. Holroyd and J. T. D. Mitchell, ''Liquid lithium as a coolant for TOKAMAK fusion reactors,'' Nucl. Eng. Des./Fusion **1**, 17–38 (1984).

[14]C. E. Annese and K. E. Schwartz, ''Experimental results from a flowing lithium target,'' Trans. Am. Nucl. Soc. **43**, 195–196 (1982).

[15]T. Hua, D. Smith, A. Hassanein, and I. Gomes, ''Design and analysis of the lithium target system for the International Fusion Materials Irradiation Facility (IFMIF),'' in *16th IEEE/NPSS Symposium Fusion Engineering, SOFE '95. Seeking a New Energy Era* (IEEE, New York, 1995), Vol. 2, pp. 1242–1246.

[16]H. L. Ravn, S. Sundell, and L. Westgaard, ''Target techniques for the ISOLDE on-line isotope separator,'' Nucl. Instrum. Methods **123**, 131–144 (1975).

[17]H. Hoffmann, ''Prospects of a liquid metal target system for a spallation neutron source,'' in Meeting on targets for neutron beam spallation sources (JUL-Conf-34), edited by G. S. Bauer (Kernforchungsanlage Julich GmbH, Julich, West Germany, 1997), pp. 127–153.

[18]R. Kolowith, K. E. Schwartz, G. E. Meadows, and J. D. Berg, ''Development of a large lithium coolant system for coolant under vacuum,'' in *10th Symposium on Fusion Engineering Proceedings* (IEEE, New York, 1983), Vol. 2, pp. 1002–1007.

[19]T. T. Fallas, G. B. Kruger, F. R. Wiltshire, G. C. Jensen, H. Clay, H. A. Upton, R. E. Gamble, C. Kjaer-Olsen, and K. Lee, ''SP-100 liquid metal test loop design,'' in *Ninth Symposium on Space Nuclear Power Systems*, AIP Conference Proceedings Vol. 246 (1992), Part 1, pp. 298–303.

[20]B. R. Moore, ''A neutronic study of an intense neutron source based on the ^{9}Be$(p,n)^{9}$B reaction for neutron capture therapy,'' M.S. Thesis, Georgia Institute of Technology (1992).

[21]H. Liskien and A. Paulson, ''Neutron production cross-sections and energies for the reactions ^{7}Li$(p,n)^{7}$Be and ^{7}Li$(p,n)^{7}$Be*(431 keV),'' At. Data Nucl. Data Tables **15**, 57–84 (1975).

[22]J. H. Gibbons and R. L. Macklin, ''Total neutron yields from light elements under proton and alpha bombardment,'' Phys. Rev. **114**, 571–575 (1959).

[23]J. Campbell and M. C. Scott, ''Absolute neutron yield measurements for protons on Li, Cu, Co, and Be from threshold to 3 MeV,'' in *Proceedings of the 4th Conference on the Scientific and Industrial Applications of Small Accelerators* (IEEE, New York, 1977), pp. 517–521.

[24]K. Porges, J. L. Snelgrove, R. Gold, A. DeVolpi, R. J. Armani, and C. E. Cohn, ''Thick target neutron yields of lithium and beryllium targets bombarded with protons and deuterons,'' Argonne National Laboratory Report ANL -7910 (Argonne National Laboratory, Argonne, IL, 1972), pp. 361–362.