SELECTION OF THE SIZE OF A CYCLOTRON FOR MEDICAL APPLICATIONS

M. ANWAR CHAUDHRI
University of Islamabad, Islamabad, Pakistan

AKHTAR J. CHAUDHRI and QAISER J. CHAUDHRI
Lahore College for Women, Lahore, Pakistan

ABSTRACT

The cost and usefulness relationship of cyclotrons has been studied from the points of view isotope production, charged-particle activation analysis and production of neutrons for therapy. Thick-target yields of the isotopes produced by proton, deuteron and alpha bombardment of all the elements with Z=20 to Z=83 have been presented as a function of the cyclotron-size and its cost. The size of a cyclotron is represented by the maximum attainable energy E, and its cost is assumed to vary as E to the power of 3/2. The mean-energies and the dose-rates, at 100 cm from the target, of neutrons beams produced by the interaction of deuterons of upto 20 MeV with beryllium, deuterium and heavy-water targets have also been investigated as functions of the cyclotron-size and its cost. It is suggested that a cyclotron big enough to accelerate deuterons to upto 12-14 MeV is of the "Optimum-size" regarding its cost and usefulness. With such a cyclotron enough quantities of isotopes can be produced through one and two-particles-emission reactions while the undesirable contribution from the three-particles-emission reactions would be zero or negligible Such a machine would also produce a useful neutron beam for therapy from a beryllium target while a neutron beam as good as having 10 MeV average energy and imparting upto 100 rads/min would be produced from a suitable deuterium target.

INTRODUCTION

Interest in the use of cyclotrons in bio-medical fields has been increasing steadily over the past few years and at present medical cyclotrons are operating or being installed in various institutions around the world. The size of a cyclotron for medical applications is probably the most important parameter because it not only determines the cost of the machine but also its usefulness. Therefore, proper attention to this point must be given when choosing a cyclotron for installation in a medical institution.

Medical Cyclotrons have so far been used mainly in the production of short-lived isotopes and, to some lesser extent, in the fields of neutron therapy and total-body activation analysis. There are other fields like in-vitro and in-vivo activation analysis with fast and slow neutrons, charged-particle activation analysis, reaction analysis by charged-particles and neutrons and radio-biological studies with neutrons and other particles of higher LET, which are now getting more attention and where such cyclotrons have great potential. All these fields must, therefore, be given due consideration when selecting the size of a cyclotron.

When the medical cyclotrons (also known as compact cyclotrons due to the compactness in their size) were first introduced in the mid-sixties their maximum size (about 7.5 MeV deuterons, 15 MeV protons and alphas and 20 MeV He-3 particles) was fixed mainly on the financial grounds and no consideration was given to the extent of their usefulness. A couple of unfortunate institutions who ordered such machines are, perhaps, regretting now at the limitations and incapabilities of their expensive tools. Had the relevant data about the usefulness of the cyclotrons in medical fields been available to them and properly considered along with the costs such catastrophic mistakes could have been avoided. A small extra money spent on increasing the size of these machines would have increased their usefulness tremendously. A couple of years later the size of such commercially available machines was slightly increased (again arbitrarily without considering the physical data) and now cyclotrons are available in the market which can accelerate deuterons to upto 14-15 MeV (corresponding proton, alpha and He-3 energies being about 30,30 and 40 MeV respectively). Generally speaking the bigger a cyclotron the better would it be for obtaining higher isotopic yields, more detection sensitivity in charged particle activation analysis and more intense and penetrating neutron beams for therapy. But, of course, the higher would also be the cost of such a machine. As often the money available for such projects is always unfortunately limited, one is forced to search for an optimum between the size (and hence the price) of the cyclotron and its usefulness. Making use of the available experimental data and of our extensive calculations we have studied the cost and usefulness relationship of a cyclotron from the points of view of isotope production, and the production of neutrons for therapy. Other cyclotron applications, mentioned earlier on, either follow the same "size-usefulness" pattern or they donot demand such stringent conditions on the maximum attainable energy.

METHOD

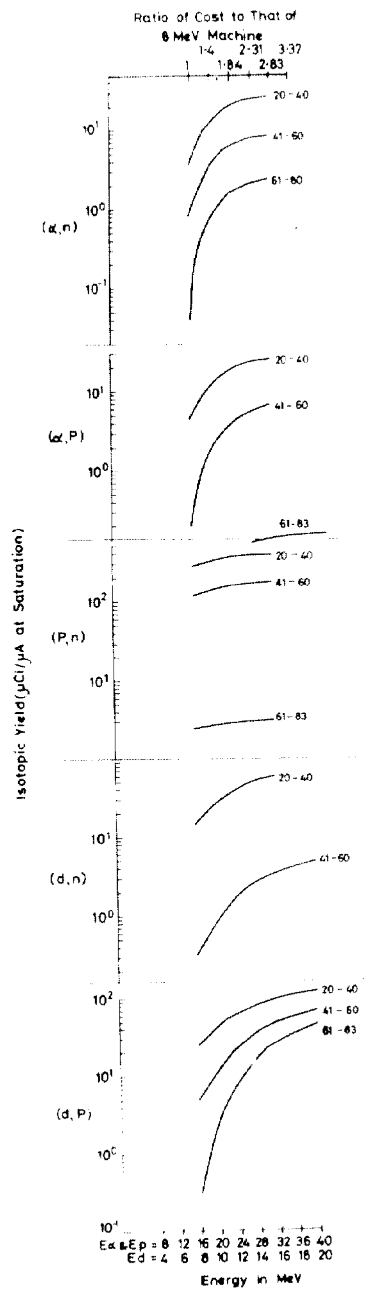
Using the method given by Chaudhri (1) and the empirically constructed excitation functions (2) thick target yields of the isotopes which are produced by proton, deuteron and alpha bombardment of all the elements with Z = 20 to Z = 83 have been calculated. These yields at saturation (when the rate of production is the same as the rate of decay) have been plotted as a function of the energy of the incident projectile verying from 4to20 MeV for deuterons and from 8 to 40 for protons and alphas. The relative cost of cyclotrons of different sizes (classified by the maximum projectile energy provided by them), expressed as a ratio to the cost of the 8 MeV-cyclotron, has also been calculated and indicated on the yield curves. It is assumed that the cost of a cyclotron vary as E to the power of 3/2 where E is the maximum attainable energy and, as mentioned above, determines the size of the machine. This seems to be a reasonable assumption and many scientists and manufacturers agree upon it,though some suggest that the cost should go up as E square. As the sensitivity obtained in charged-particle activation analysis is directly proportional to the corresponding isotopic yield, the same yield-curves are suitable for examining the cost and sensitivity relationship too.

In neutron production for bio-medical applications it is not only the flux that counts but also the mean energy of neutrons which plays an important role. Both the flux and the mean energy depend upon the target material being used and the energy of the incident particles. Using the available experimental data for the (d.n) reactions on Be(3-6) and on heavy water (3) and calculations of Chaudhri and Batra for deuterium (7) the dose rates of neutrons at 100 cm from the target have been calculated and plotted as a function of the incident deuteron energy. Similarly the mean energies of neutrons produced by the deuteron bombardment of the above mentioned targets at different energies have been plotted. The relative cost of the various sizes of cyclotrons is indicated on both the curves.

RESULTS AND DISCUSSION

Figure 1 shows the yield curves of the isotopes which are produced by p,d, and alpha bombardment of elements with Z=20 to Z=83 through one particle-emission reactions. The maximum attainable deuteron energies (specifying the size of a cyclotron) from 4 to 20 MeV along with the corresponding proton and alpha energies are given on the curve. Also shown on the curves is the ratio of the cost of a particular-sized cyclotron to that of the 8 MeV one.

It can be seen from these curves that, though, the yield goes on increasing with energy, the rate of increase drops off at higher energies. However, the price of the cyclotron goes on increasing continuously as E to the power of 3/2 . This indicates that there may be an optimum energy (or the size of the cyclotron) byond which a slight increase in the yields may not be justified by a much higher increase in the cost of the corresponding machine. This "optimum



energy" seems to be around 12-14 MeV for deuterons. The corresponding maximum energies for protons, alphas and He-3 particles would be 24-28, 24-28 and 32-37 MeV respectively.

Now let us examine how this "Optimum energy" would fare in the case of isotope production through two and three particles-emission reactions. The yield-curves corresponding to these reactions are shown in figures 2 and 3 respectively. It can be seen from fig.2 that though the yield of the isotopes from two particles-emission reactions at about 12-14 MeV deuteron energy (and corresponding protons and alphas energies) is not quite maximum but it is sufficient. But for three particles-emission reactions the yield at this "optimum-energy" is quite small or none at all. This, however, is advantageous in most cases as no unwanted and troublesome long-lived activities would be produced through three particles-emission reactions when isotopes are being produced (or activation analysis being carried out) through reactions emitting one or two particles.

Figure 4 shows the dose rates of neutrons obtained by the (d.n) reaction on Be,deuterium and heavy water targets as a function of the deuteron energy (the cyclotron size) and the relative cost As mentioned in the diagram part of this data is experimentally

Figure 1: Thick-Target yields of isotopes, produced by p,d and alpha bombardment of all the elements with Z=20 to Z=83 through one particle-emission reactions, as a function of the cyclotron size and the corresponding cost.

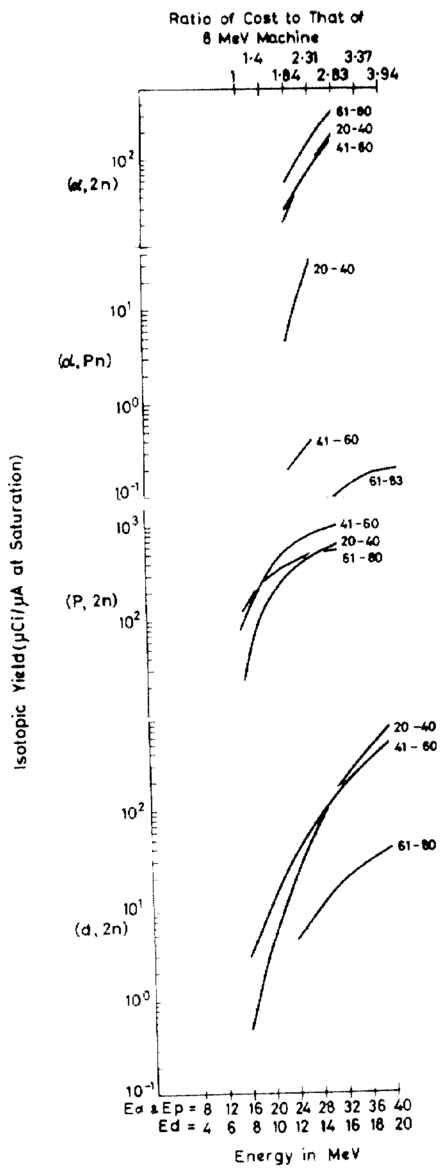


Figure 2: Thick-target yields of isotopes,produced by p,d and alpha bombardment of all the elements with Z=20 to Z=83 through two particles-emission reactions, as a function of the cyclotron size and the corresponding cost.

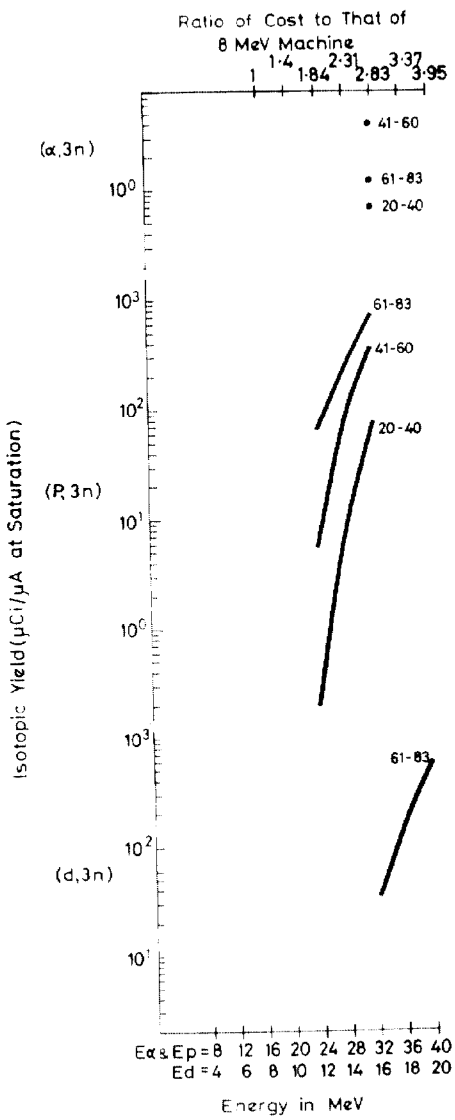


Figure 3: Thick-target yields of isotopes produced by p,d and alpha bombardment of all the elements with Z=20 to Z=83 through reactions where three particles are emitted, as a function of the cyclotron size and the corresponding cost.

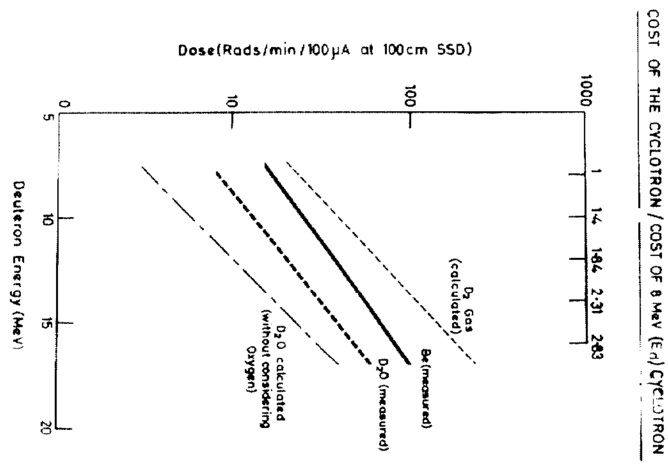


Figure 4: The Dose rate of neutrons produced through (d,n) reactions on Be, heavy water and deuterium, at a distance of 100 cm from the target, as a function of the cyclotron size and its cost.

measured while the rest is calculated. The difference between the calculated and the measured dose rates is due to the fact that in calculations the contribution of oxygen to neutron production is neglected. However, it is taken into account for degrading the incoming deuteron beam.

For neutron therapy the minimum accepted dose rate at a distance of 100 cm from the target is about 10 rads/min(8). Of course, higher figures would be an advantage. It can be seen from fig.4 that a 12-14 MeV cyclotron would produce an acceptable dose rate from all the targets with as much as 100 rads/min with a deuterium target.

Average energy of neutrons produced by (d.n) reactions on thick Be and deuterium targets as a function of the incident deuteron energy (the size of the cyclotron) and the corresponding cost is shown in fig.5. Again the data for Be is experimental while that for deuterium calculated. It can be seen that just like the yield curves the average energy increases with the incident energy but the rate of increase starts decreasing at higher bombarding energies. This means that byond a certain limit a slight increase in the everage neutron energy would be unjustified on the basis high accompanying cost.

The minimum acceptable average energy of a neutron beam for therapy is around 6-7 MeV. Such a neutron beam, which is slightly inferior to the neutron beam produced by the Hammersmith Cyclotron (ave-

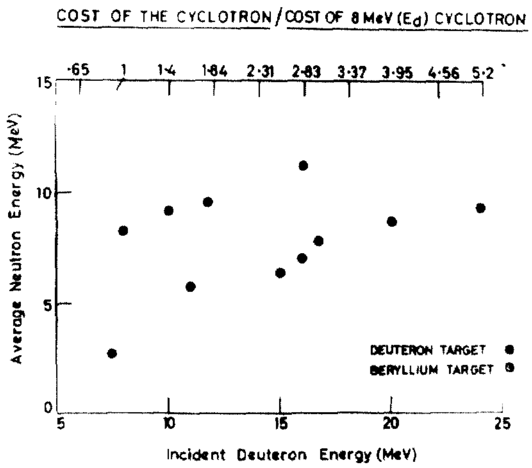


Figure 5 : The mean energy of neutrons produced through (d,n) reactions on Be and deuterium as a function of the cyclotron size and its cost

rage energy 7.5 MeV), could be produced by the 12-14 MeV cyclotron with a Be target and would be good for treating superficial tumors only. However, the same cyclotron could produce a neutron beam having an average energy of around 10 MeV with a deuterium target. Such a neutron beam would have almost the same depth-dose characteristics as the Cobalt-60 and thus could be acceptable for treating a wide variety of tumors. To obtain this sort of mean energy with a Be target one would have to go for a machine nearly five times more expensive.

This finding that a deuterium target can produce a much better neutron beam for therapy than a Be target under similar bombarding conditions is very significant. Uptil now scientists have been thinking of going to bigger and expensive cyclotrons in order to obtain a more peneterant neutron beam which, as mentioned above, can easily be obtained even from a smaller and much cheaper cyclotron if a proper deuterium target is used.

In conclusion it can be mentioned that here we have provided most of the relevant data which one requires to be able to select the "optimum" size of a cyclotron (from the cost and usefulness points of view) for medical applications. Full consideration has been given to isotope production and to the production of neutrons for therapy. A proper use of this data should enable the scientists to avoid making mistakes in going for smaller and slightly cheaper (and hence with limited applications) or a much bigger and more expensive cyclotrons for medical applications. It is suggested that a cyclotron big enough to be able to produce a deuteron beam of about 12-14 MeV would be of "optimum" size from the cost as well as usefulness points of view.

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