PRODUCTION OF ^{7}Be FROM A HEAVY ION CYCLOTRON: A NEW TOOL FOR WEAR STUDIES*

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ABSTRACT

Wear studies using a cyclotron to activate the surface layers (SLA) of a test sample were first reported at the 7th International Cyclotron Conference in 1975. There studies involved the bombardment of test samples with a p, d, or He beam and are applicable for test samples with atomic mass >40, where appropriate radioactive isotopes can be made. These SLA samples are now being actively embraced by industry in a variety of wear measurements; for example, piston ring wear in a diesel engine.

At MSU, we have developed a radioactive ^{7}Be ion beam and have implanted it into a ceramic disk. The ^{7}Be beam can be implanted into any test sample, thus opening up the possibility of tribology studies for ceramics, plastics, aluminum, and other light materials. The radioactive ^{7}Be beam at MSU is produced in the fragmentation of a high-energy (≈17 MeV/A) nitrogen ion that is accelerated by the K500 superconducting cyclotron. Design studies for an optimized cyclotron to make ^{7}Be for implantation have been started. We foresee a large request for ^{7}Be implantation for tribology studies and thus another application of the cyclotron to applied research problems.

INTRODUCTION

The beginning of research into the use of the ^{7}Be radioisotope for wear analysis at the NSCL K500 heavy ion cyclotron was initiated in October 1986 at the Eleventh International Conference on Cyclotrons and Their Applications. At this conference, the acceleration of radioactive ion beams from cyclotrons[1)] was discussed. H. Schweikert from KFK had inquired that if it was possible to make ^{7}Be at high intensity by fragmentation of heavy ions from the K500 these fragments could be used for wear studies by implanting them into wear test samples. Since that time, a series of studies have been completed at the NSCL on ^{7}Be production and in the following sections these results are reported.

*This material is based upon work supported by the National Science Foundation under Grant No. PHY-8519653.

WEAR STUDIES ISOTOPES

The requirements for an isotope to be used for wear studies are that it has a reasonably long half-life and that it decays by an energetic γ-ray. Figure 1 shows the radioactive isotopes that meet this requirement for atomic mass less than 70 and for half-lives greater than 20 days.[2)] Above mass 43, the possibilities for making such isotopes proliferate. For example, iron, which is the dominant metal now studied for wear, can be transmuted into a cobalt isotope by light-ion beam bombardment. This reaction is the major tool for research for wear studies by surface layer activation.[3,4)] Below mass 43, only two isotopes meet the requirements for wear studies, ^{22}Na and ^{7}Be, and thus a large class of materials cannot be studied by surface layer activation.

The ^{22}Na isotope has a 2.6 year half-life and a 1275 keV γ-ray. The ^{7}Be isotope has a 53.6 day half-life and and a 10% branch via a 478 keV γ-ray. These isotopes lead to the consideration of radioactive tagging of surfaces for wear studies in light-mass materials. Our studies at NSCL have focussed on the implantation of ^{7}Be produced by heavy ion fragmention.[5)]

PRODUCTION OF ^{7}Be BY HEAVY ION FRAGMENTATION

One of the significant findings of recent heavy ion research is that the fragmentation cross-section of heavy-ion projectile beams is large.[6,7)] Studies on the fragmentation mass production versus projectile, target, and beam energy have been completed for a limited number of parameters. Figure 2 shows the fragment mass distribution for a Nb beam on a carbon target. The produced fragments peak at light masses and around the projectile mass. (For our studies, ^{7}Be is considered a light mass.) Figure 2 also gives an indication of the production cross section versus energy/nucleon of the projectile beam. The data for the fragmentation cross section for particles of Z<5 (Be has a Z=4) are lower at 11.4 MeV/A than at 14.7 and 18 MeV/A. These data then indicates that the best energy for the production of ^{7}Be lies near 15 MeV/A.

For practical reasons, our studies have used a nitrogen ion as the projectile beam since it is easy to produce in high intensity from the cyclotron. A carbon target was used to fragment the beam because it can withstand large beam power. Additional studies on other beam-target combinations are planned.

IMPLANTATION OF ^{7}Be INTO TEST SAMPLE

An advantage of using the fragmentation of heavy ions is that the fragments are produced near the projectile velocity. This means that the fragments can escape from the fragmenting target in the beam forward direction and allows sample implantation at 0°, where the cross-section is largest. The target should be designed to stop the primary beam completely before implanting into the test sample. Figure 3 shows the difference in stopping distance between a nitrogen beam and the ^{7}Be fragments produced in a carbon target as a function of the primary beam energy. Energies of 15 MeV/A for the nitrogen beam provide separation distances that allow construction of a practical target and vacuum window, with the test sample in air.

The above target design also allows the separation of the radiation damage and thermal heating effects from the test sample, where these factors are attributed to the primary beam.

The test sample will be implanted with all other light particle fragments, but the only fragment that has a long lifetime and a detectable γ-ray is ^{7}Be. Thus, waiting 2-3 days after the implantation bombardment allows only ^{7}Be to be detected. Figure 4 shows the experimentally detected γ-ray spectrum of the nitrogen beam fragments from an Al foil stack. The nitrogen beam energy for this particular foil stack was above 15 MeV/A. In this case the N beam was not stopped by the C target. ^{7}Be fragments were easily detected, but also ^{22}Na, where it is believed that the ^{22}Na is produced by some kind of nuclear reaction with the Al target and the still energetic nitrogen beam. The ^{22}Na is expected to be absent from a nitrogen stopping target design.

^{7}Be DOSE-DEPTH MEASUREMENTS

In order to quantitatively measure the wear rate of a test sample, the ^{7}Be dose-depth must be known. Figures 5,6 and 7 show experimental data obtained for ^{7}Be distributions in Al foil stacks for three nitrogen bombardment energies. Each Al foil is .001" thick. The nitrogen beam energy was reduced to 10 MeV/A by the carbon target before entering the Al foil stack. This distribution can be analytically derived from fragment spectra results obtained from nitrogen beam studies[8] on thin carbon targets. An analytical spectrum shape that has a Gaussian distribution for the high-momentum fragments (and an exponential shape for the lower energy fragments) fits those data. Using appropriate range curves and assumption on the energy variation of fragment cross section, Fig. 8 was calculated using Gaussian part of the distribution. This calculated result can be compared with the Al foil stack data and is promising. Thus, we are beginning to develop an analytical method for predicting the ^{7}Be dose-depth distribution into any test material.

^{7}Be SAMPLE IMPLANTATION

Figure 9 shows a photograph of a Si_3N_4 implanted disk. A carbon target in front of the disk was bombarded for 24 hours with a 17 MeV/A nitrogen beam. The disk had an implanted dose of 3.7×10^{11} ^{7}Be ions. This disk is now being used in a wear study program. The beam current of the K500 cyclotron was limited by the power dumped onto the electrostatic deflector. This deflector is uncooled, and it is expected that a cooled deflector would allow beam intensities greater than 1×10^{13} pps. The cyclotron beam current upper limit is unknown, but beam power limits, ion source output and space charge limitations are all starting to be areas of concern and are of interest to accelerator design. Experiments at increasing the nitrogen beam limits from 10^{11} pps to 10^{13} pps are underway on the K500 cyclotron.

CONCLUSION

In summary, ^{7}Be implantation into light materials has been demonstrated at the K500 cyclotron. Additional cyclotron development and material property studies are needed before this technique will be easily available. Pilot studies with the present K500 beam intensity are planned. Studies of a dedicated ^{7}Be cyclotron are being undertaken. Such a dedicated machine appears to be able to make economical ^{7}Be implanted wear samples.

ACKNOWLEDGEMENT

We acknowledge the contributions of Y.X. Dardenne of the NSCL and H.J. Schock of the MSU Engineering College in these initial ^{7}Be studies.

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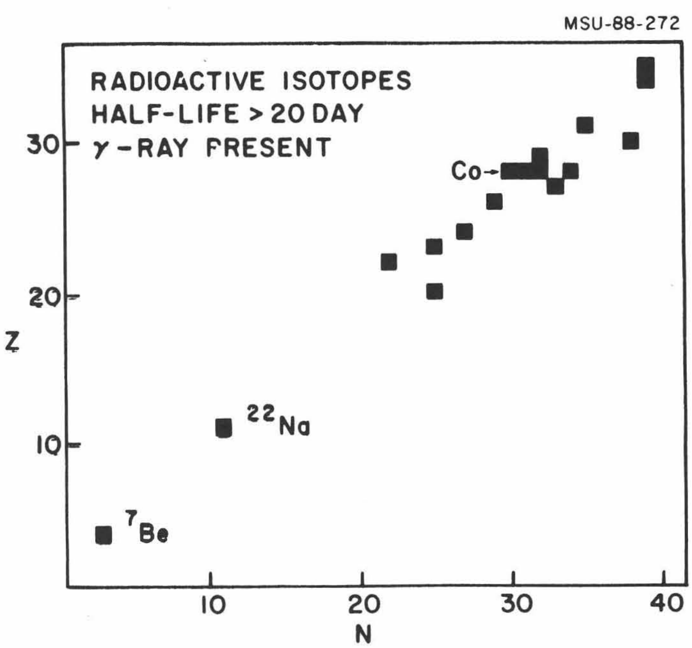

Fig. 1 -- The radioactive isotopes with half-lives >20 days and having a γ-ray in their decay are plotted in a nuclide chart format, i.e. the atomic charge (Z) vs the neutron number (N). Below <40, only ^{7}Be and ^{22}Na meet the criteria for wear studies.

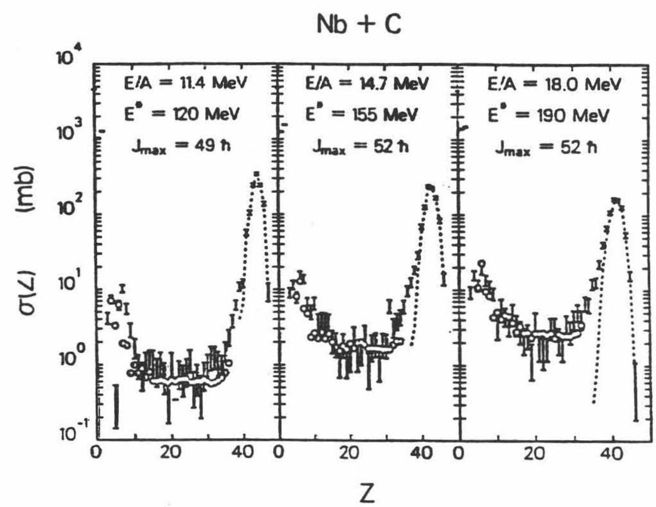

Fig. 2 -- The total cross section for Nb fragmenting on a carbon target is shown for three energies as a function of the fragment atomic number. The bars are experimental data points. The cross-section peaks near the projectile atomic number and for the very light isotopes.

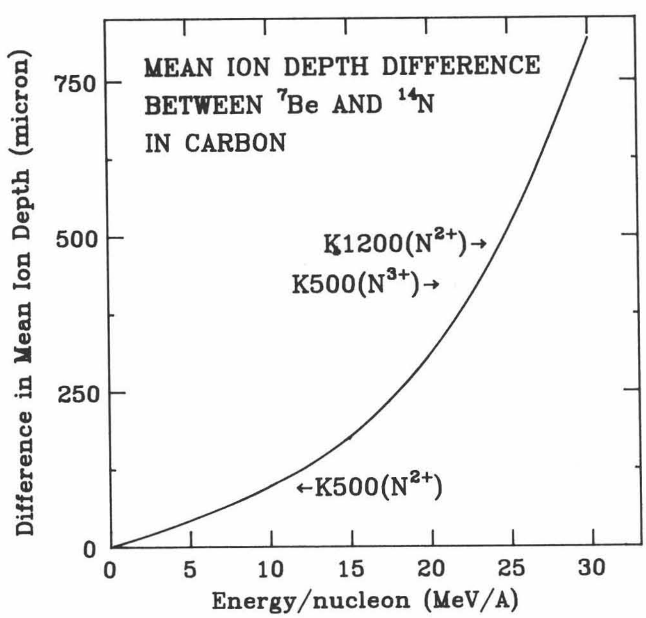

Fig. 3 -- The stopping difference between ^{7}Be and ^{14}N as a function of energy per nucleon is shown for a carbon target. ^{7}Be requires more carbon to stop it, hence the distance between the ^{7}Be and ^{14}N curve is a window in which the technique for separating the primary beam and secondary beam using the target thickness works. At lower energy this window becomes smaller. These data support the ^{7}Be implant cyclotron to have energies of 15 MeV/A or higher for a nitrogen beam.

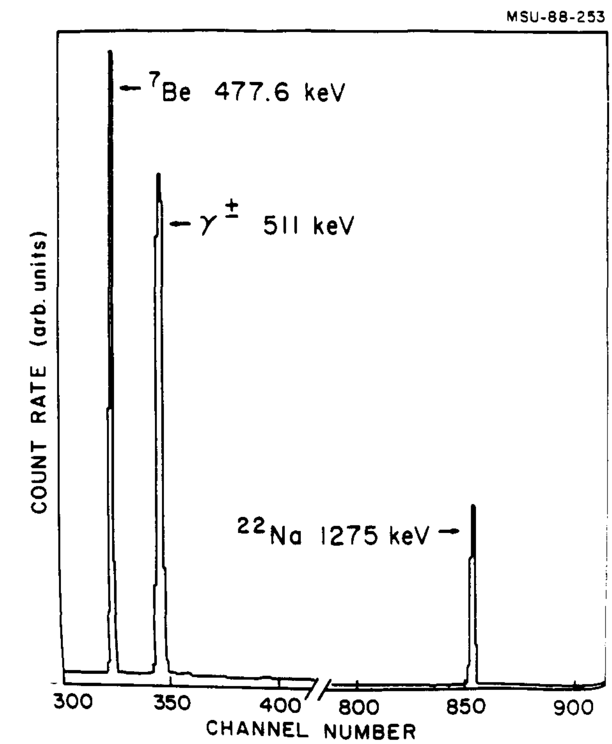

Fig. 4 -- The γ-ray spectrum from an Al foil placed behind the C target bombarded with a 35 MeV/A ^{14}N beam. This spectrum was taken with a 35% efficient Ge detector. Only γ-rays from ^{7}Be and ^{22}Na are detected.

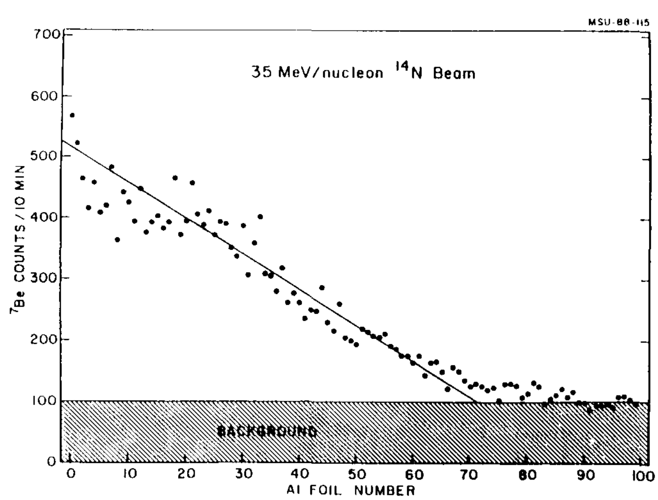

Fig. 5 -- The dose-depth relationship is shown for ^{7}Be ions implanted in stacked 0.0025-cm thick Al foils for primary ^{14}N beam energies of 35 MeV/A.

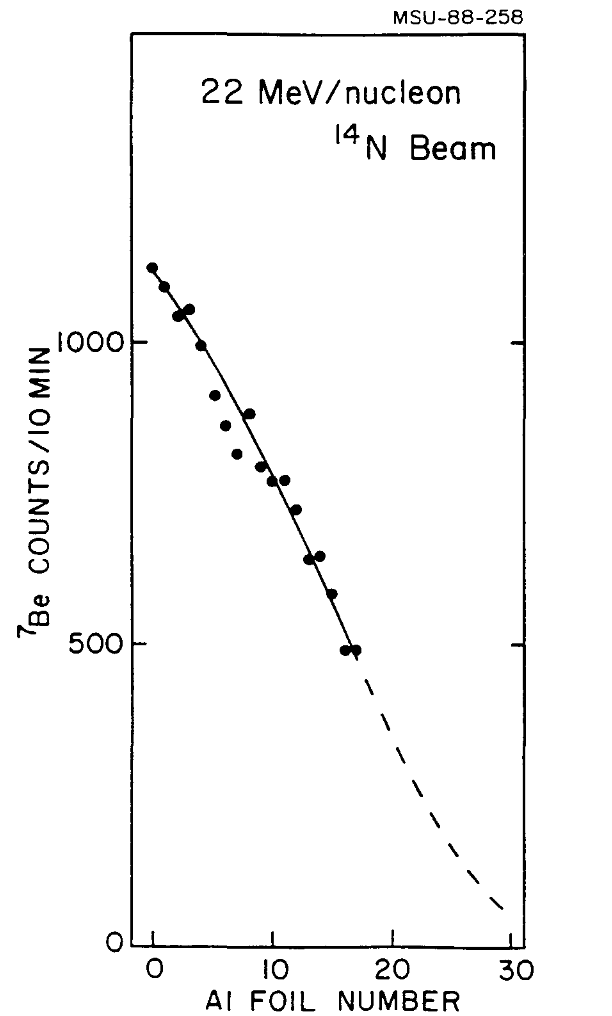

Fig. 6 -- Same as Fig. 5, except the nitrogen beam energy is 22 MeV/A.

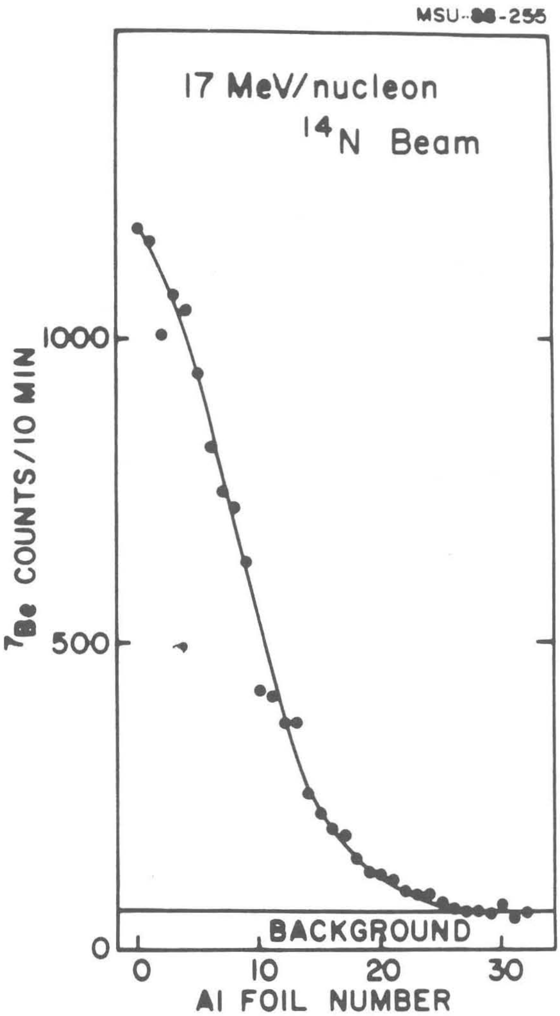

Fig. 7 -- Same as Fig. 5, except the nitrogen beam energy is 17 MeV/A.

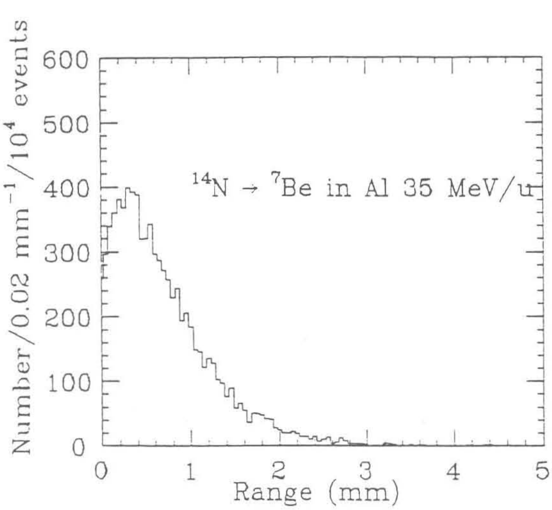

Fig. 8 -- A theoretical simulation of the dose-depth distribution of ^7Be in Al at 35 MeV/A is shown. Additional nuclear research data will make it possible to compute the dose-depth of ^7Be in any material.

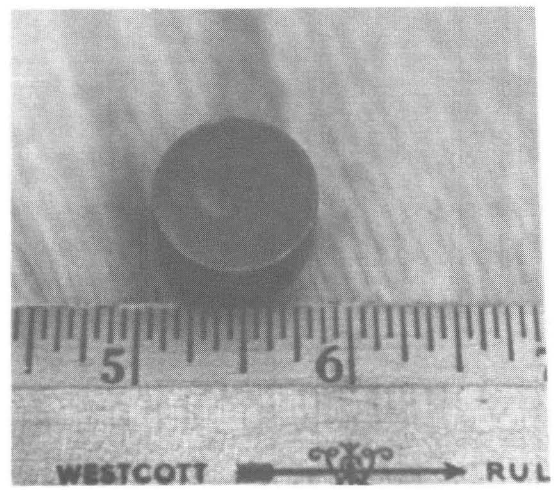

Fig. 9 -- Photograph of the Si_3N_4 ceramic disk after implantation of a dose of 3.7×10^{11} ^7Be ions. The disk is 1.91 cm in diameter by 1.27 cm thick. The integrated nitrogen beam current was 4.2×10^{16} particles.