Distribution of the isotopes produced in the YBa$_2$Cu$_3$O$_{7-x}$ superconductor and PbZr$_{0.54}$Ti$_{0.46}$O$_3$ ferroelectric by energetic charged particles

V. A. Didik, R. Sh. Malkovich, and E. A. Skoryatina

A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

V. V. Kozlovskii

St. Petersburg State Technical University, 195251 St. Petersburg, Russia

(Submitted May 26, 1998)

Fiz. Tverd. Tela (St. Petersburg) 40, 2189–2192 (December 1998)

A study has been made of the concentration profiles of radioactive isotopes produced by transmutation in the YBa$_2$Cu$_3$O$_{7-x}$ superconductor and PbZr$_{0.54}$Ti$_{0.46}$O$_3$ ferroelectric by energetic protons (10 and 15 MeV), deuterons (4 MeV), and $^3$He and $^4$He nuclei (20 MeV). Profiles of two types have been observed: monotonic and with a maximum. It is shown that the type of isotope concentration profile is determined by the nature of the cross-section energy dependence of the nuclear reaction producing a given isotope. © 1998 American Institute of Physics.

2. RESULTS AND THEIR DISCUSSION

We measured in the YBCO superconductor the profiles of the radioactive isotopes $^{65}$Zn, $^{90}$Zr, $^{90}$Nb, $^{66}$Ga, $^{92m}$Nb, $^{138}$Ce, and $^{141}$Ce produced by reactions $^6$Cu ($p$, $n$) $^{65}$Zn, $^{89}$Y ($p$, $n$) $^{90}$Zr, $^{63}$Cu ($d$, $p$) $^{64}$Cu, $^{89}$Y ($^3$He, $2p$) $^{90}$Nb, $^{67}$Cu ($^3$He, $n$) $^{66}$Ga, $^{89}$Y ($^3$He, $n$) $^{92m}$Nb, $^{136}$Ba ($^3$He, $n$) $^{139}$Ce, and $^{138}$Ba ($^3$He, $n$) $^{141}$Ce. As seen from Fig. 1a–1d, the concentration of various isotopes reaches $10^{13}$–$10^{14}$ cm$^{-3}$ in irradiation by protons, deuterons, and $^4$He nuclei, and is slightly in excess of $10^{12}$ cm$^{-3}$ in the case of $^3$He nuclei (the quoted concentrations relate to the end of the irradiation). The profile depth varies from 60 to 170 $\mu$m. When irradiated by $^4$He nuclei, the profile depth is the largest for the $^{66}$Ga isotope, and the smallest for $^{138}$Ce. All profiles fall off monotonically away from the surface, with the exception of the $^{92m}$Nb isotope profile, which exhibits a fairly flat maximum. Note that irradiation by protons was carried out under oblique incidence (18° beam angle to the surface).

In the PZT ferroelectric, we measured the profiles of the radioactive isotopes $^{48}$V, $^{90}$Nb, $^{92m}$Nb, $^{206}$Bi, $^{51}$Cr, $^{93m}$Mo, and $^{99}$Mo produced by the reactions (Ref. 6) $^{48}$Ti ($p$, $n$) $^{48}$V, $^{90}$Zr ($p$, $n$) $^{90}$Nb, $^{92}$Zr ($p$, $n$) $^{92m}$Nb, $^{208}$Pb ($p$, $n$) $^{208}$Bi, $^{48}$Ti ($^3$He, $n$) $^{51}$Cr, $^{90}$Zr ($^3$He, $n$) $^{93m}$Mo, and $^{96}$Zr ($^3$He, $n$) $^{99}$Mo. The concentration of various isotopes reaches $4 \times 10^{12}$–$10^{13}$ cm$^{-3}$ in irradiation by protons, and $10^{13}$–$10^{14}$ cm$^{-3}$ when irradiated by $^4$He nuclei (Fig. 2a and 2b). The profile depth is 70–150 $\mu$m for $^4$He nuclei, and 420–650 $\mu$m for protons. The profiles of the $^{90}$Nb, $^{206}$Bi, and $^{93m}$Mo isotopes are monotonic, whereas those of $^{48}$V, $^{92m}$Nb, $^{51}$Cr, and $^{99}$Mo pass through a maximum. The PZT was irradiated by protons under continuous variation of the beam incidence angle.

As follows from the measurements, the concentration profiles obtained in the above experimental conditions are of two types, namely, monotonic and with a maximum. Profiles with a maximum are observed for the $^{92m}$Nb, $^{99}$Mo, and $^{51}$Cr...
isotopes produced by $^4$He nuclei in the $(^4$He,$n)$ reaction, as well as for $^{92m}$Nb and $^{48}$V obtained by the $(p,n)$ reaction.

To find an interpretation for the isotope profile pattern, consider the expression relating the concentration of the transmutation-produced radioactive isotope $c(x)$ to the parameters of the material and irradiation

$$c(x) = N \Phi \sigma(x) \lambda^{-1} [1 - \exp(-\lambda t)],$$

(1)

FIG. 1. Depth profiles of radioactive transmutation isotopes produced in irradiation of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ by (a) protons, (b) deuterons, (c) $^3$He, and (d) $^4$He. (a) 1 — $^{65}$Zn, 2 — $^{89}$Zr; (b) $^{64}$Cu; (c) $^{90}$Nb; (d) 1 — $^{66}$Ga, 2 — $^{92m}$Nb, 3 — $^{141}$Ce, 4 — $^{139}$Ce.