CONF-9509230--5

SELECTION OF RIB TARGETS USING ION IMPLANTATION AT THE HOLIFIELD RADIOACTIVE ION BEAM FACILITY*

G. D. Alton and J. Dellwo[1]
Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, Tennessee 37831-6368

ABSTRACT

Among several major challenges posed by generating and accelerating adequate intensities of RIBs, selection of the most appropriate target material is perhaps the most difficult because of the requisite fast and selective thermal release of minute amounts of the short-lived product atoms from the ISOL target in the presence of bulk amounts of target material. Experimental studies are under way at the Oak Ridge National Laboratory (ORNL) which are designed to measure the time evolution of implanted elements diffused from refractory target materials which are candidates for forming radioactive ion beams (RIBs) at the Holifield Radioactive Ion Beam Facility (HRIBF). The diffusion coefficients are derived by comparing experimental data with numerical solutions to a one-dimensional form of Fick's second law for ion implanted distributions. In this report, we describe the experimental arrangement, experimental procedures, and provide time release data and diffusion coefficients for releasing ion implanted ^{37}Cl from Zr_5Si_3 and ^{75}As, ^{79}Br, and ^{78}Se from Zr_5Ge_3 and estimates of the diffusion coefficients for ^{35}Cl, ^{63}Cu, ^{65}Cu, ^{69}Ga and ^{71}Ga diffused from BN; ^{35}Cl, ^{63}Cu, ^{65}Cu, ^{69}Ga, ^{75}As, and ^{78}Se diffused from C; ^{35}Cl, ^{68}Cu, ^{69}Ga, ^{75}As, and ^{78}Se diffused from Ta.

* Research sponsored by the U.S. Department of Energy under contract No. DE-AC05-84OR21400 with Lockheed Martin Energy Systems.
[1] Former post-doctorial student, present address: Eaton Corporation, Austin, TX 78758.

1 INTRODUCTION

Ion implantation offers a cost effective and powerful technique for predetermining the time-release behavior of stable complements of interesting radioactive species from target materials which are candidates for RIB generation in facilities such as the HRIBF now under construction at ORNL [1]. The method can also be used, as well, for determining diffusion coefficients for many element/target combinations which are fundamentally important toward the understanding of the kinetics and chemistry of the diffusion process. Experiments [4, 5] are underway at the HRIBF which utilize the 25 MV tandem accelerator to implant stable complements of interesting radioactive atoms into refractory targets mounted in the UNISOR [2] version of the FEBIAD ion source [3]. The objective of these studies is to select the refractory target material most appropriate for swift release of the element of interest, as well as to make realistic estimates of the efficiency of ion sources prior to actual radioactive ion beam (RIB) generation. In this report, we describe experimental equipment and procedures, and present results from these experiments including diffusion coefficients for Cl implanted into Zr_5Si_3 and As, Br, and Se implanted into Zr_5Ge_3, as well as estimates of the diffusion coefficients for Cl, Cu, and Ga implanted into and diffused from BN; Cl, Cu, As, Ga, Se, and Br diffused from C; and Cl, Cu, Ga, As, and Se implanted into and diffused from Ta. The diffusion coefficients, derived from the experimental data, are then used to model the release of radioactive ion beams from homogeneously distributed planar and spherical geometry targets which represent the actual distributions and target geometries that will be used for RIB generation. Examples of the experimental and predicted data behavior for selected species/target combinations are presented in this report.

2. DIFFUSION AND ADSORPTION PROCESSES

The principal means whereby short half-life radioactive species are lost between initial formation and utilization are associated with diffusion and surface adsorption processes where the release times are long with respect to the life-time of the species in question for forming RIBs. The ionization efficiency of the source is also important and should be competitively high. The diffusion and surface adsorption processes are briefly described below.

2.1 Diffusion Theory

The time and temperature-dependent release of a nuclear reaction product species, embedded in a chemically dissimilar target material, implies the presence of a binary diffusion mechanism which underlies the release process. Whenever there is a concentration gradient of impurity atoms or vacancies in a solid material, the atoms or vacancies will move through the solid until equilibrium is reached [6]. The net flux, J, of either the atoms or the vacancies is related to the gradient of concentration, ∇n, by Fick's first equation given by:

$$J = -D\nabla n, \tag{1}$$

where D is the diffusion coefficient.

A generalized time dependent form of Fick's second equation which allows for the creation of particles S(x,y,z,t) as well as the loss of particles E(x,y,z,t) is given by

$$\frac{\partial n}{\partial t} = D\left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} + \frac{\partial^2 n}{\partial z^2}\right) + S(x,y,z,t) - E(x,y,z,t)\ . \tag{2}$$

The S term is a creation term appropriate for the case where the targets are being irradiated with primary projectile beams for the production of radioactive species and the E term accounts for losses of the species as would be the case when the species are radioactive.

The target geometries that will be used or are envisioned for use at the HRIBF include: planar, cylindrical and spherical target geometries. The time-dependent form of Fick's second equation appropriate for planar targets, used in the subject ion implantation experiments, can be expressed as

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} + S(x,t) - E(x,t). \tag{3}$$

For the more general case the distribution function S must be chosen to represent the actual distribution of the radioactive species within the target material. However, we assume that the particles are either uniformly distributed during production of the radioactive species or in the case of ion implantation, the particles have a sharply Gaussian profile as represented below. For a uniform distribution of particles such as assumed in the production of radioactive species

$$S(x,t) = \sigma N \ell I/Ze \tag{4}$$

with a primary ion beam of intensity I and charge Z where e is the charge on the electron, N the number of interaction nuclei per unit volume ℓ, is the length of the target material, and σ the cross section for production of the species of interest.

For the case where the distribution function S(x,t) is Gaussian, as would be the case for an ion implanted distribution, the function S is given by

$$S = \frac{I\sigma N\ell}{aeZ\sqrt{2\pi}} \exp\left[-\frac{1}{2}\{(x - < x >)/a\}^2\right] \quad (5)$$

where **a** is the standard deviation of the distribution and **<x>** is the depth of the distribution from the surface. For the ion implantation experiments, $\sigma N \ell = 1$. For the case where **a** is small, the particles are very localized beneath the target surface as is the case for ion implanted distributions. For stable ion implantation, the E term is usually zero; however, for production of radioactive species with half-life $\tau_{1/2}$, E is given by

$$E(x,t) = n\lambda \text{ where } \lambda = 0.693/\tau_{1/2}. \quad (6)$$

The diffusion process for solids is also dependent on the activation energy H_A required to move the atoms or vacancies from site to site. The diffusion coefficient is dependent upon H_A, and the temperature T according to:

$$D = D_0 \exp(-H_A/kT) \quad (7)$$

where D_0 is the intrinsic diffusion coefficient of the atom within the particular crystal matrix. D is related to the vibrational frequency and lattice parameters of the particular atom and crystal and k is Boltzmann's constant. H_A can be extricated from experimental data by measuring the dependence of D on target temperature T. As noted from Eq. 7, higher temperatures significantly affect the release times of particles from the solid. Thus, in order to maximize the release of radioactive atoms from a target material, it is desirable to operate the target material to the limits set by the vapor pressure of the target material which does not compromise the ion source efficiency. The limiting vapor pressure P_l of the high temperature sources presently used at the HRIBF [7, 8] is $P_l \leq 2 \times 10^{-4}$ Torr [9].

2.2 Theory of Adsorption

Any time delays that are excessively long in relation to the life-time of the radioactive species can result in significant losses of beam intensity in an ISOL facility. The residence time of a particle on a surface is given by the Frenkel equation:

$$\tau = \tau_0 \exp[H_{ad}/kT], \tag{8}$$

where H_{ad} is the heat of adsorption or enthalpy required to evaporate the atom or molecule from the surface, k is Boltzmann's constant, T is the absolute temperature, and τ_0 is the time required for a single lattice vibration (~10^{-13} s). The heat of adsorption increases with increasing bonding between the adsorbed atom and the surface where the adsorption takes place. This value varies widely depending upon the adsorbent/adsorbate combination. From Eq. 8 it is apparent that the choice of the materials of construction of the vapor transport system for the source is important. Refractory noble metals have low enthalpies of adsorption and have been suggested for use as coating materials for the interior surfaces of target ion sources [4, 5].

3 EXPERIMENTAL APPARATUS AND PROCEDURES

The 25-MV tandem accelerator, which will serve as the primary accelerator for RIBs at the HRIBF, is presently being utilized to implant stable complements of interesting radioactive atoms into refractory targets maintained in the on-line FEBIAD [3] ion source which is the standard source used at the UNISOR facility [2]. The final energy of the implanted species, after passing through a thin Ta entrance window, is chosen so that the ions penetrate to a depth of 2 to 35 μm in a thin circular disk (~ 9 mm in diameter and ~ 1.5 mm in thickness) of the material of interest. The simulation program,

TRIM [10], is used to numerically determine the position and distribution of the implanted species within the target material.

The target temperature, prior to ion implantation, is typically 1645°C; beam heating effects raise the target temperature in proportion to the beam power; this effect has been measured; typically a 10-Watt beam raises the temperature by an additional 50°C. The target, thus, resides at ~1700°C during the implantation. Particles diffuse out of the face of the entry side of the target, and effuse into the anode region of the ion source where they are bombarded with an electron beam accelerated from a hot cathode. A fraction of the particles are ionized, accelerated from the ion source, and mass analyzed. The intensity versus time spectra for each implanted species is monitored and recorded for both the "beam-on" and "beam-off" regions of the spectra. Typically, the intensity with beam-on-target increases until "saturation" is reached, at which point in time the beam is turned off. The time required to release 50% of the saturation value is defined as the release time for the particular species/target combination. A simulation program called DIFFUSE [11] is used to solve Fick's second equation (Eq. 3) and to determine diffusion coefficients D for the implanted species by fitting to experimental, diffusion release data. The input parameters required by DIFFUSE include the particle distribution function as calculated by the use of TRIM, the depth of implantation, and the diffusion coefficient D. Initial estimates of D are determined by fits to the intensity versus time release curve and then iteratively altered until an acceptable fit is found.

4 RESULTS

The time-release information derived from ion implanted samples which have sharply Gaussian distributions is only of qualitative value for estimating release of radioactive species from actual RIB target materials which are more or less uniformly distributed within the sample. The release times from implanted targets are dependent on the sample temperature T, the initial distribution, as well as the

depth of the implanted material. Therefore, information derived from such experiments cannot be directly used to predict release times of the complementary, short-lived, homogeneously distributed, radioactive species from the same target material. However, diffusion coefficients D can be derived by fitting solutions to Fick's second equation to experimental release data; the diffusion coefficients can then be used to predict release times of short-lived radioactive complements of the implanted species from homogeneously distributed, planar- or spherical-geometry samples operated at the same temperature T which are the principal target geometries that will be used for actual RIB generation.

Figure 1 compares the experimentally measured time-release profiles of ^{37}Cl implanted to a depth of 2.6 μm in CeS (target temperature: 1690°C) with fits to the data derived by use of DIFFUSE. The dashed line superposed on the experimental data represents a computational fit to the data from which the diffusion coefficient D was determined. As noted, the fits to the release profile are exceptionally good. Figure 2 displays theoretical "beam-on-target" and "beam-off-target" time-release spectra for ^{37}Cl and ^{33}Cl diffusing from homogeneously distributed, 5-μm-diameter spherical-geometry macro-particles of CeS at 1690°C and 1990°C. as predicted. The predictions made for the diffusion release at a target temperature of 1990°C were estimated by assuming an activation energy of 1.0 eV which correlates with an intrinsic diffusion coefficient, $D_0 = 10^{-7}$ cm^2/s. The diffusion coefficient D at the temperature for which the release measurements were made is $D = 4.4 \times 10^{-10}$ cm^2/s. We have assumed an activation energy of H_A of $H_A = 1.0$ eV for purposes of illustrating the behavior of the release of Cl from CeS at higher temperatures than those which were used in the ion implantation experiments. This value may be too low, but is reasonable in relation to measured values commonly found in the literature (see, e.g., Ref. 6).

The time-release behaviors of Cl implanted into Zr_5Si_3 and As, Se, and Br implanted into Zr_5Ge_3 targets have also been measured using the apparatus and procedures discussed previously. These target materials are very refractory, having melting points from 2100°C to 2300°C and are candidates

for use in generating the radioactive complements of these species. These data were also analyzed and diffusion coefficients extracted. Figures 3, 5, 7, and 9 display, respectively, the experimentally measured time-release profiles for these projectiles/target material combinations; the solid lines in each of these figures represent fits to the corresponding experimental data. As noted, the fits provide good to excellent agreement with the corresponding experimental data.

The results of several ion implantation experiments including the results derived from Figs. 1 and 3, 5, 7, and 9 and for Cl, Cu, and Ga implanted into and diffused from BN; Cl, Cu, Ga, As, Se, and Br implanted into and diffused from C; and Cl, Cu, Ga, As, and Se implanted into and diffused from Ta are summarized in Table 1.

During operation of the HRIBF, the radioactive species will be uniformly distributed within either planar or spherical targets. The release times for uniformly distributed species will differ from those obtained from the Gaussian distributions characteristic of ion implanted samples and, therefore, the release time information derived from ion implanted samples is only of qualitative value for use in predicting release times from actual RIB target materials. However, diffusion coefficients can be extricated from such data and used to predict release times for other target geometries and at different target temperatures. In order to use solutions to Fick's second equation (Eqs. 3) for making predictions at temperatures other than those used in the ion implantation experiments, the activation energy must be known.

From fits to the $^{35}Cl/Zr_5Ge_3$; $^{75}As/Zr_5Ge_3$; $^{79}Br/Zr_5Ge_3$; and $^{78}Se/Zr_5Ge_3$ data displayed in Figs. 3, 5, 7, and 9 diffusion coefficients D were derived and then used to predict the time release profiles at the same element/target combination, homogeneously distributed in 20 and 200 μm diameter macro-spherical and 20 and 200 μm thickness planar geometry targets maintained at the same temperature. Examples of the predicted releases of stable and selectively chosen complementary radioactive

species homogeneously distributed in these materials in both spherical or planar target forms are shown in Figs. 4, 6, 8, and 10. The target material for Cl is assumed to be Zr_5Si_3, while that for Br, As, and Se is assumed to be Zr_5Ge_3. The release profiles for the 20-μm-thickness planar-disk target displayed in Figs. 4, 6, 8, and 10, which are, in fact, too thin to fabricate in practice, serve only as a means of comparison of the planar disk targets with the practically sized, 20-μm spherical-geometry targets. It is obvious that spherical macro-particle target materials are always desirable if one can avoid sintering the materials during the release process. The actual release times for radioactive particles which have been released by diffusion from spherical particles will be moderated by the hold-up times associated with the times required to migrate through the distribution of materials. These times may be long enough to offset any advantage gained by using spherical particles coupled with the fact that the target must be operated at temperatures below the sintering temperature (~ 80% of the melting point of the particular material).

6 CONCLUSIONS

The results of the present experiments clearly demonstrate that the ion implantation technique can be utilized as a practical and cost-effective means for evaluating candidate refractory targets for releasing specific elemental materials prior to their actual use in generating radioactive ion beams. Release time and efficiency information derived from such experiments can be used to realistically estimate beam intensities which could be generated in a particular ISOL ion source during RIB beam generation. Diffusion coefficients extracted from this data can also be used to optimize the target particle size and geometry in order to minimize the release time of the element of interest from the candidate target material. Diffusion coefficients are fundamentally important in many areas of solid-state physics, solid-state chemistry, and metallurgy. The method also offers a fast, simple, and cost-effective means for determining diffusion coefficients for element/solid target material combinations which are often time consuming, expensive and tedious to derive experimentally by other means. The method is only valid

whenever the diffusion time τ_d is much longer than the effusion delay time τ_e and the transit time τ_t from the ion source to the detection system or τ_e and τ_c are known. For the species/target combinations considered in this report, this argument is valid.

8 Acknowledgements

The authors are indebted to H. K. Carter, J. Breitenbach, S. Ichikawa, and J. Kormicki of the UNISOR for assistance during the ion implantation experiments.

Table I. Summary of release times $\tau 1/2$ and diffusion coeffcients D from HRIBF ion implantation studies.

Projectile	D(measured) (cm^2/s	D_e(estimated)[1] (cm^2/s)	Target[3] material	Range, <x> (μm)	τ (s)
^{35}Cl	1.2×10^{-6}	1.1×10^{-6}	Zr_5Si_3	31.3	8.8
^{37}Cl	4.9×10^{-10}	4.1×10^{-10}	CeS	2.6	164
^{75}As	5.1×10^{-8}	9.8×10^{-8}	Zr_5Ge_3	18.3	34
^{78}Se	5.1×10^{-8}	6.8×10^{-8}	Zr_5Ge_3	17.9	51
^{78}Se	–	7×10^{-8}	Zr_5Ge_3	15.0	32
^{79}Br	5.2×10^{-7}	3.6×10^{-7}	Zr_5Ge_3	15.9	7.9
^{35}Cl	–	8.1×10^{-9}	C	6.9	59
^{63}Cu	–	7.1×10^{-7}	C	7.0	0.7
^{65}Cu	–	6.5×10^{-7}	C	7.0	0.75
^{69}Ga	–	2.2×10^{-7}	C	6.8	2.1
^{75}As	–	6.6×10^{-9}	C	6.7	68
^{78}Se	–	–	C	6.0	No release
^{79}Br	–	5.4×10^{-9}	C	6.6	80
^{35}Cl	–	2.4×10^{-9}	BN	5.0	103
^{63}Cu	–	5×10^{-8}	BN	6.5	8.5
^{65}Cu	–	4.2×10^{-8}	BN	6.5	10.5
^{69}Ga	–	1.9×10^{-8}	BN	5.9	18
^{71}Ga	–	2.5×10^{-8}	BN	5.9	14
^{35}Cl	–	9.8×10^{-11}, (4.9×10^{-11})[2]	Ta	0.9	83 (166)[2]
^{63}Cu	–	1.5×10^{-10}, (7.8×10^{-11})[2]	Ta	0.7	51 (104)[2]
^{69}Ga	–	1.2×10^{-10}, (6×10^{-11})[2]	Ta	0.7	68 (136)[2]
^{75}As	–	1.9×10^{-11}, (9.6×10^{-12})[2]	Ta	0.9	420 (840)[2]
^{78}Se	–	2.2×10^{-11}, (1.1×10^{-11})[2]	Ta	0.9	363 (726)[2]

[1] Diffusion coefficient D_e estimated from $D_e \simeq \langle x \rangle^2/\tau$.

[2] Full thickness of Ta foil: 1.8 μm; release times (parentheses) assumed to be one-half those from semi-infinite foil. Diffusion coefficients in parentheses are calculated by use of the release times in parentheses.

[3] All target temperatures during ion implantation 1650-1700°C.

9 REFERENCES

1. A Proposal for Physics with Exotic Beams at the Holifield Heavy Ion Research Facility, eds. J. D. Garrett and D. K. Olsen, Physics Division, ORNL, March 1991, unpublished.
2. UNISOR, Oak Ridge Associated Universities, Oak Ridge, TN, 37831, USA.
3. R. Kirchner, D. Marx, O. Klepper, V. T. Koslowsky, T. Kühl, P. O. Larsson, E. Roeckl, K. Rykaczewski, D. Schardt, J. Eberz, G. Huber, H. Lochmann, R. Menges, and G. Ulm, Nucl. Instr. and Meth. A234, 224 (1985).
4. G. D. Alton, H. K. Carter, I. Y. Lee, C. M. Jones, J. Kormicki, and D. K. Olsen, Nucl. Instr. and Meth. B66, 492 (1992).
5. G. D. Alton, J. Dellwo, H. K. Carter, J. Kormicki, G. di Bartolo, J. C. Batchelder, J. Breitenbach, J. A. Chediak, K. Jintoff-Nilsen, and S. Ichikawa, Proc. of the International Conference on Neutrons and their Applications, eds. G. Vourvopoulos and J. Paradellis, SPIE Vol. 2339, p. 335.
6. See, for example, *Diffusion in the Condensed State*, J. S. Kirkaldy and D. J. Young (The Institute of Metals, London, 1987), Ch. 1.
7. G. D. Alton, D. C. Haynes, G. D. Mills, and D. K. Olsen, Nucl Instr. and Meth., A328 (1993) 325.
8. G. D. Alton, Particle Accelerators, 47 (1994) 133.
9. R. Kirchner and E. Roeckl, Nucl. Instr. and Meth. 133, 187 (1976).
10. TRIM - the Transport of Ions in Matter, J. F. Ziegler, IBM Research, Yorktown Heights, New York 10598, USA.
11. DIFFUSE is a program that solves one- and three-dimensional forms of Fick's second equation. The code was written by G. D. Alton, J. Dellwo, and I. Y. Lee.

FIGURE CAPTIONS

Fig. 1. ORNL-DWG 95M-9957. Typical "beam-on-target" and "beam-off-target" time-release spectra for ^{37}Cl implanted into and released from planar geometry CeS targets. The dashed line represents a fit to the experimental data, derived by iteratively solving Fick's second equation (Eq. 3) by the use of the computer code, DIFFUSE (Ref. 11). Target temperature; 1690°C; Implantation depth: 2.6μm; Diffusion coefficient: $D = 4.4 \times 10^{-10}$ cm²/s.

Fig. 2. ORNL-DWG 95M-9699. Theoretical "beam-on-target" and "beam-off-target" time-release spectra for ^{37}Cl and ^{33}Cl diffusing from homogeneously distributed, 5-μm-diameter spherical-geometry macro-particles of CeS at 1690°C and 1990°C as predicted by use of the computer code DIFFUSE (Ref. 11). The code was utilized to determine the diffusion coefficient D by iteratively fitting solutions to Fick's second equation (Eq. 3) to the experimental data taken at 1690°C displayed in Fig. 1. The predictions, made for the diffusion release at a target temperature of 1990°C, were estimated by assuming an activation energy of 1.0 eV which correlates with an intrinsic diffusion coefficient, $D_o = 1.6 \times 10^{-7}$ cm²/s. Diffusion coefficient at a target temperature of T = 1690°C: $D = 4.4 \times 10^{-10}$ cm²/s.

Fig. 3. ORNL-DWG 95M-9694. Typical "beam-on-target" and "beam-off-target" time-release spectra for ^{35}Cl implanted into and diffused from Zr_5Si_3 planar geometry targets. The solid line represents a fit to the experimental data derived by iteratively solving Fick's second equation (Eq. 2) by use of the computer program DIFFUSE (Ref. 11). Target temperature 1695°C; Diffusion coefficient: $D = 1.2 \times 10^{-5}$ cm²/s.

Fig. 4. ORNL-DWG 95M-9701. Theoretical "beam-on-target" time-release spectra for homogeneously distributed ^{35}Cl and ^{33}Cl diffusing from 20-μm and 200-μm-diameter spherical-geometry and 20-μm and 200-μm-thick planar-geometry Zr_5Si_3 targets as predicted by use of the computer program DIFFUSE (Ref. 11). Target temperature: 1695°C; Diffusion coefficient: $D = 1.2 \times 10^{-6}$ cm²/s.

Fig. 5. ORNL-DWG 95M-9693. Typical "beam-on-target" and "beam-off-target" time-release spectra for ^{75}As implanted into and diffused from Zr_5Ge_3 planar geometry targets. The solid line represents a fit to the experimental data derived by iteratively solving Fick's second equation (Eq. 3) with the computer program, DIFFUSE (Ref. 11). Target temperature: 1670°C; Diffusion coefficient: $D = 5.1 \times 10^{-8}$ cm²/s.

Fig. 6. ORNL-DWG 95M-9697. Theoretical "beam-on-target" time-release spectra for homogeneously distributed ^{79}As and ^{69}As diffusing from 20-μm and 200-μm-diameter spherical-geometry and 20-μm and 200-μm-thick planar-geometry Zr_5Ge_3 targets as predicted by the use of the computer program DIFFUSE (Ref. 11). Target temperature: 1670°C; Diffusion coefficient: $D = 5.1 \times 10^{-8} cm^2/s$.

Fig. 7. ORNL-DWG 95M-9702. Typical "beam-on-target" and "beam-off-target" time-release spectra for ^{79}Br implanted into and diffused from planar geometry Zr_5Ge_3 targets. The solid line represents a fit to the experimental data, derived by iteratively Fick's second equation (Eq. 3) by use of the computer program, DIFFUSE (Ref. 11). Diffusion coefficient: $D = 5.2 \times 10^{-7}$ cm^2/s; Target temperature: 1675°C.

Fig. 8. ORNL-DWG 95M-9696. Theoretical "beam-on-target" time-release spectra for homogeneously distributed ^{79}Br and ^{73}Br diffusing from 20-μm and 200-μm-diameter spherical-geometry and 20-μm and 200-μm-thick planar-geometry Zr_5Ge_3 targets as predicted by the use of the computer program DIFFUSE (Ref. 16). Target temperature: 1675°C; Diffusion coefficient: $D = 5.2 \times 10^{-7} cm^2/s$.

Fig. 9. ORNL-DWG 95M-9698. Typical "beam-on-target" and "beam-off-target" time-release spectra for ^{78}Se implanted into and diffusing from planar geometry Zr_5Ge_3 targets. The solid line represents a fit to the experimental data, derived by iteratively solving Fick's second equation (Eq. 3) by use of the computer program DIFFUSE (Ref. 11). Target temperature: 1670°C; Diffusion coefficient: $D = 5.1 \times 10^{-8}$ cm^2/s.

Fig. 10. ORNL-DWG 95M-9696. Theoretical "beam-on-target" time-release spectra for homogeneously distributed ^{78}Se and ^{71}Se diffusing from 20-μm and 200-μm-diameter spherical-geometry and 20-μm and 200-μm-thick planar-geometry Zr_5Ge_3 targets as predicted by the use of the computer program DIFFUSE (Ref. 11). Target temperature: 1670°C; diffusion coefficient: $D = 5.2 \times 10^{-8}$ cm^2/s.

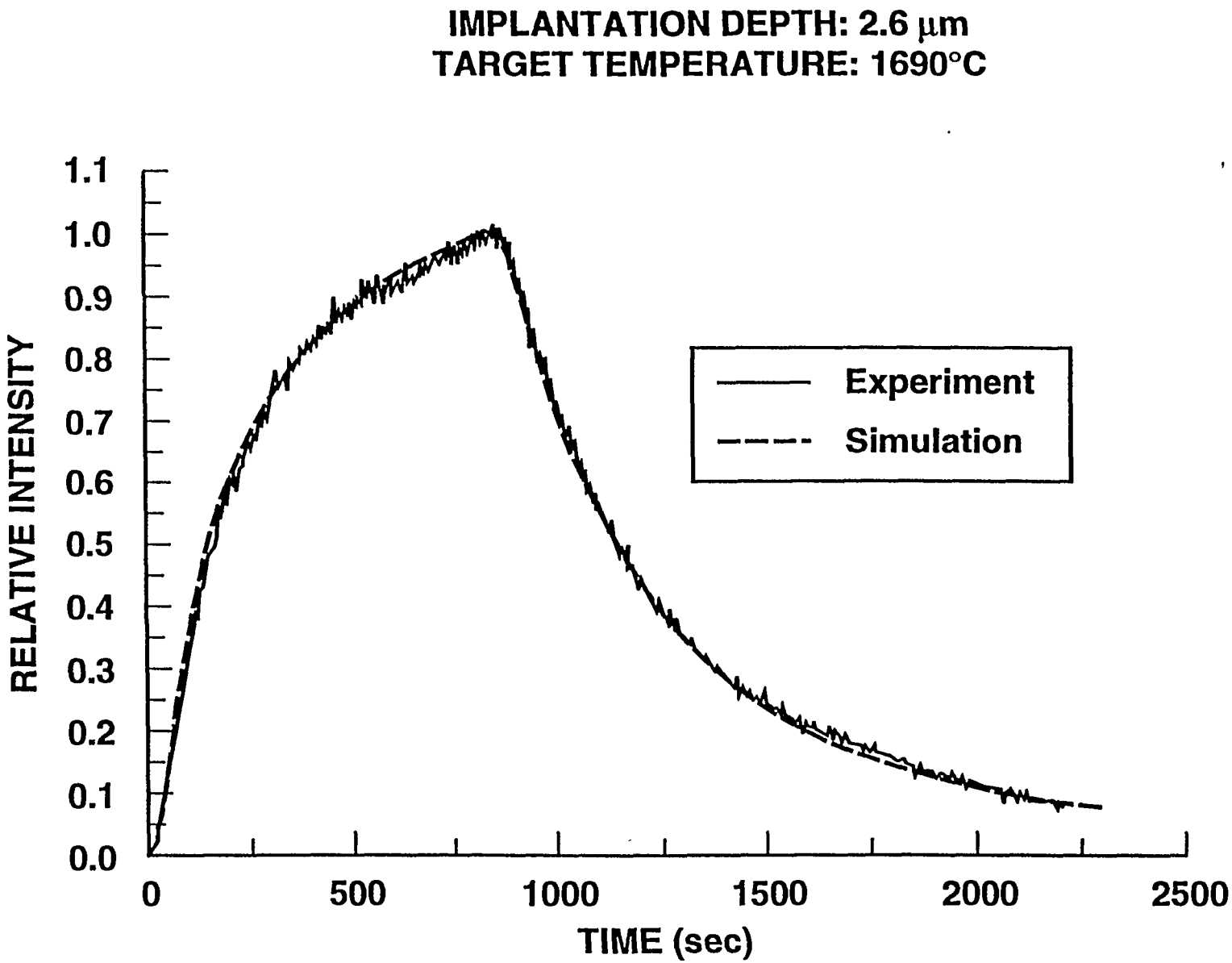
IMPLANTATION DEPTH: 2.6 μm
TARGET TEMPERATURE: 1690°C
RELATIVE INTENSITY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
500
1000
1500
2000
2500
TIME (sec)
Experiment
Simulation

Fig.1

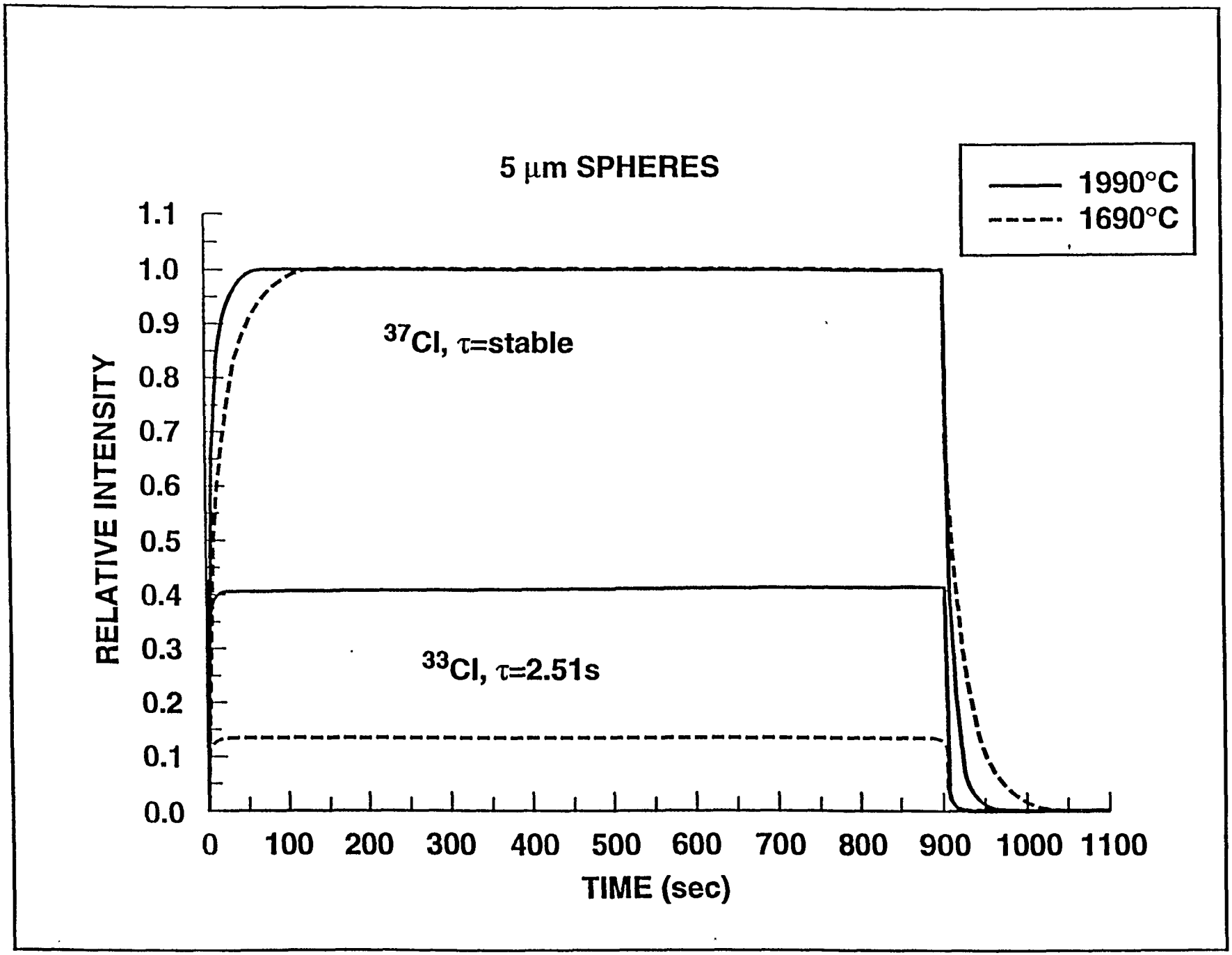
5 μm SPHERES
1990°C
1690°C
RELATIVE INTENSITY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
37Cl, τ=stable
33Cl, τ=2.51s
0
100
200
300
400
500
600
700
800
900
1000
1100
TIME (sec)

Fig. 2

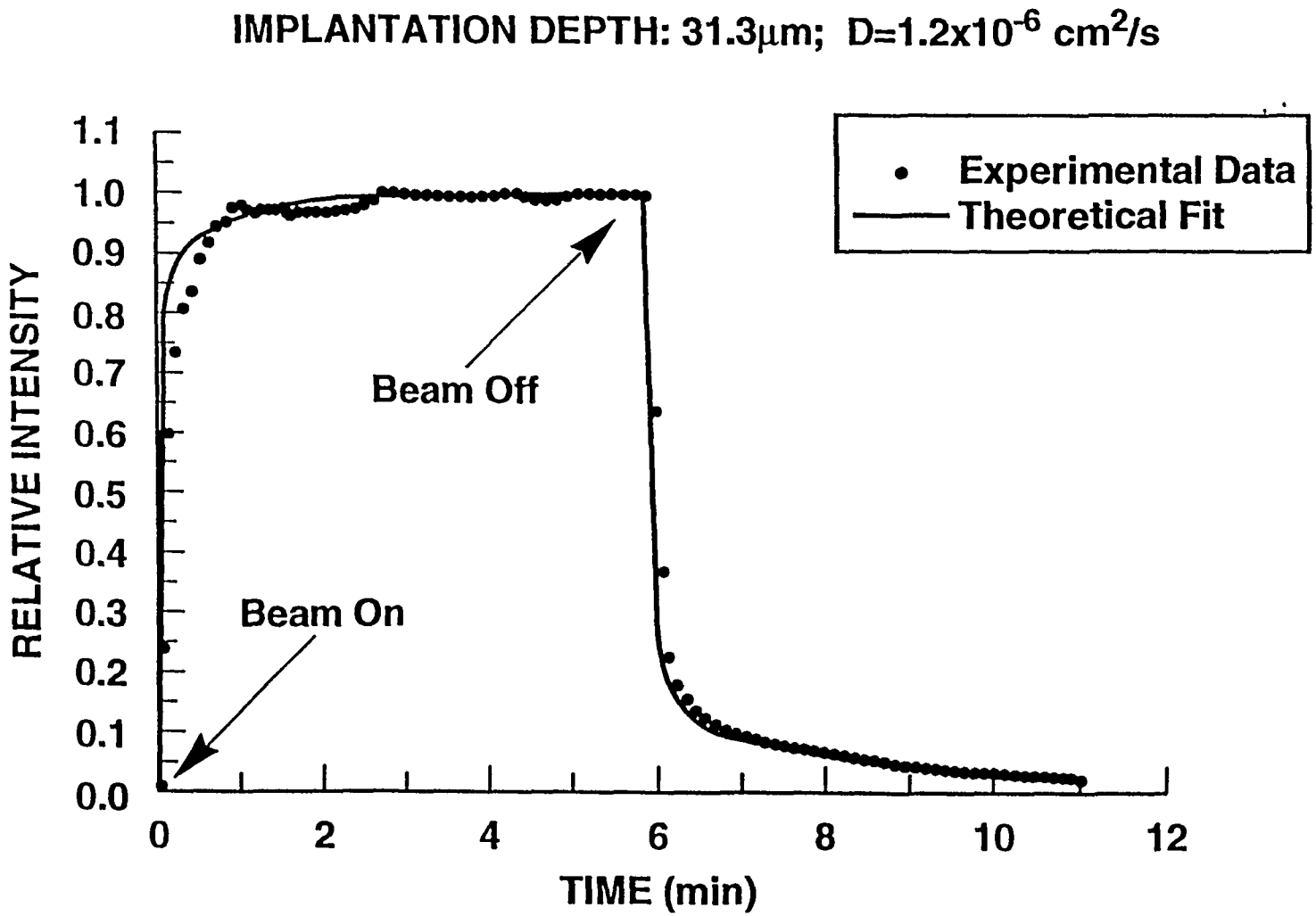
IMPLANTATION DEPTH: 31.3μm; D=1.2x10-6 cm2/s
Experimental Data
Theoretical Fit
Beam Off
Beam On
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
2
4
6
8
10
12

Fig. 3

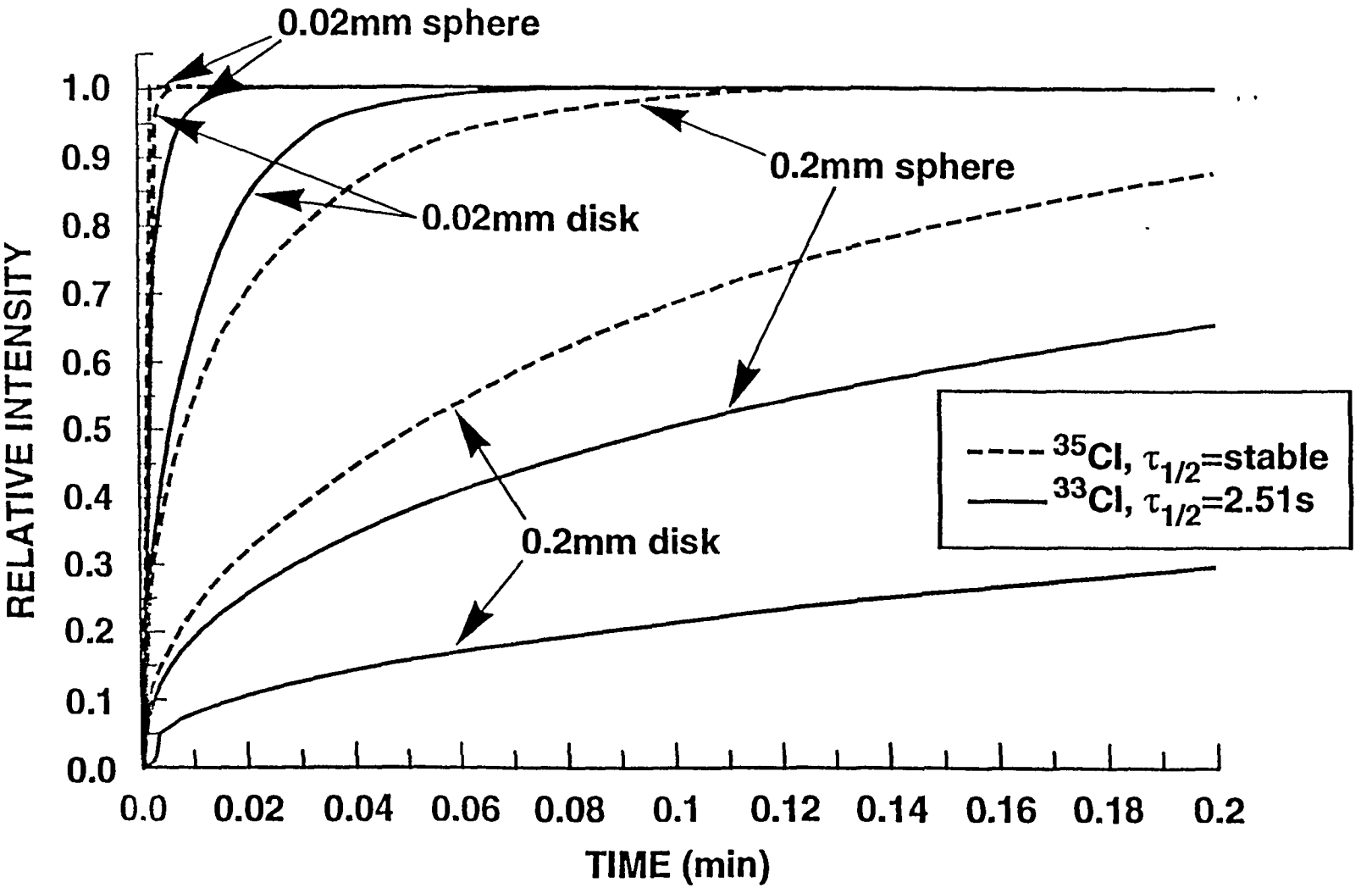
0.02mm sphere
0.2mm sphere
0.02mm disk
0.2mm disk
RELATIVE INTENSITY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
TIME (min)
^{35}Cl, $\tau_{1/2}$=stable
^{33}Cl, $\tau_{1/2}$=2.51s

Fig. 4

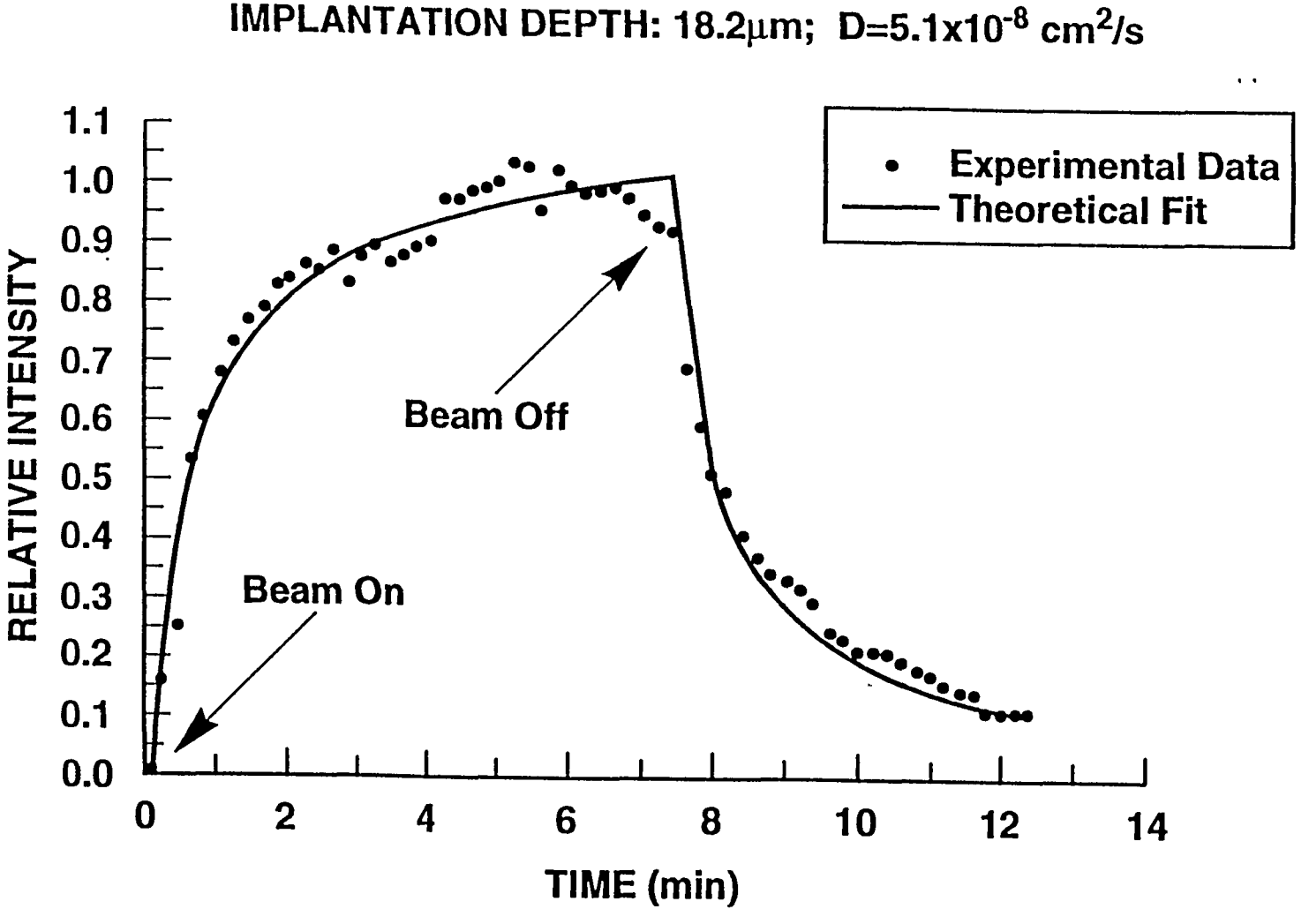
IMPLANTATION DEPTH: 18.2μm; D=5.1x10-8 cm2/s
RELATIVE INTENSITY
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
12
14
TIME (min)
Experimental Data
Theoretical Fit
Beam Off
Beam On

Fig. 5

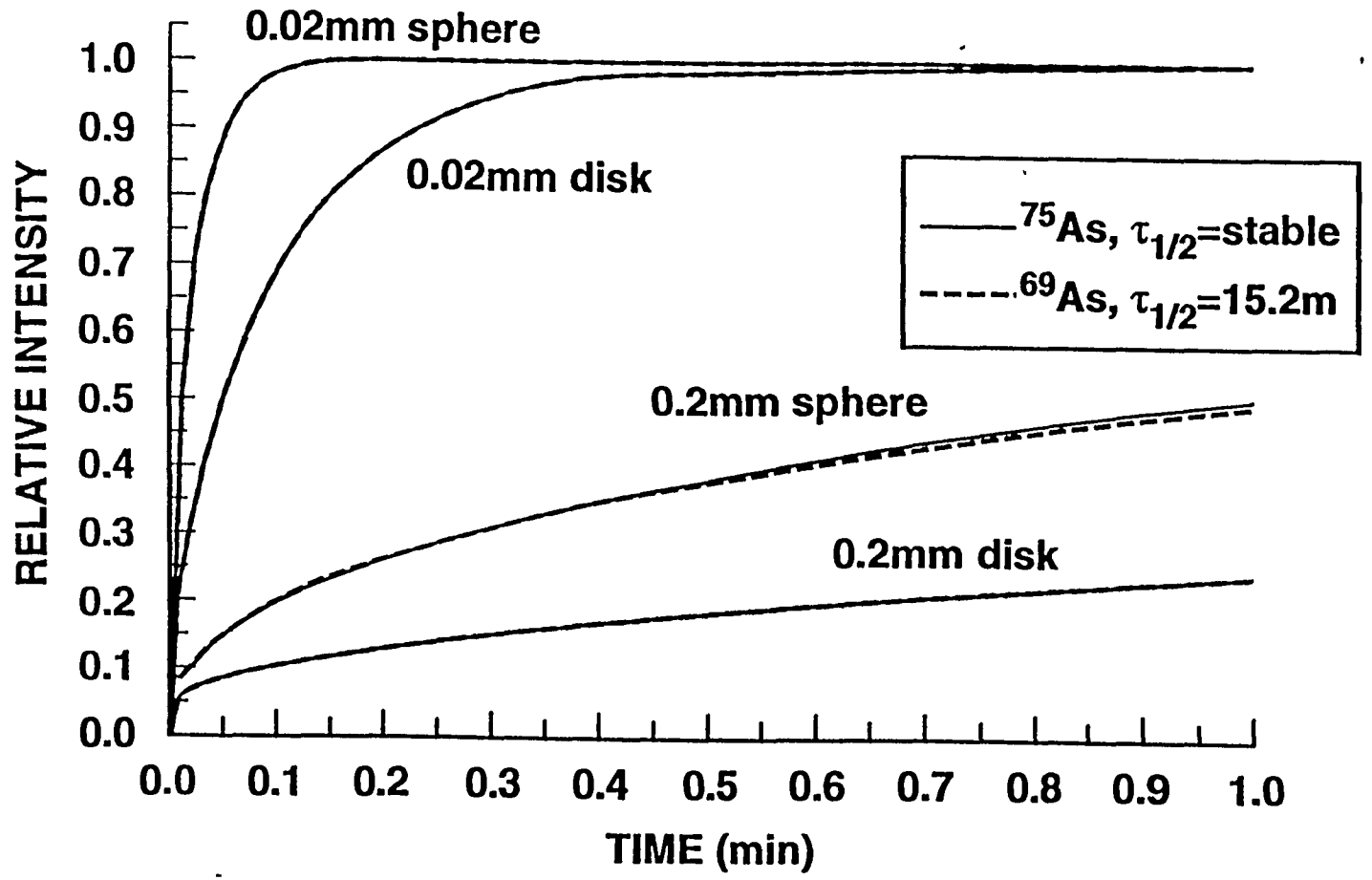
0.02mm sphere
0.02mm disk
0.2mm sphere
0.2mm disk
^{75}As, $\tau_{1/2}$=stable
^{69}As, $\tau_{1/2}$=15.2m
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig. 6

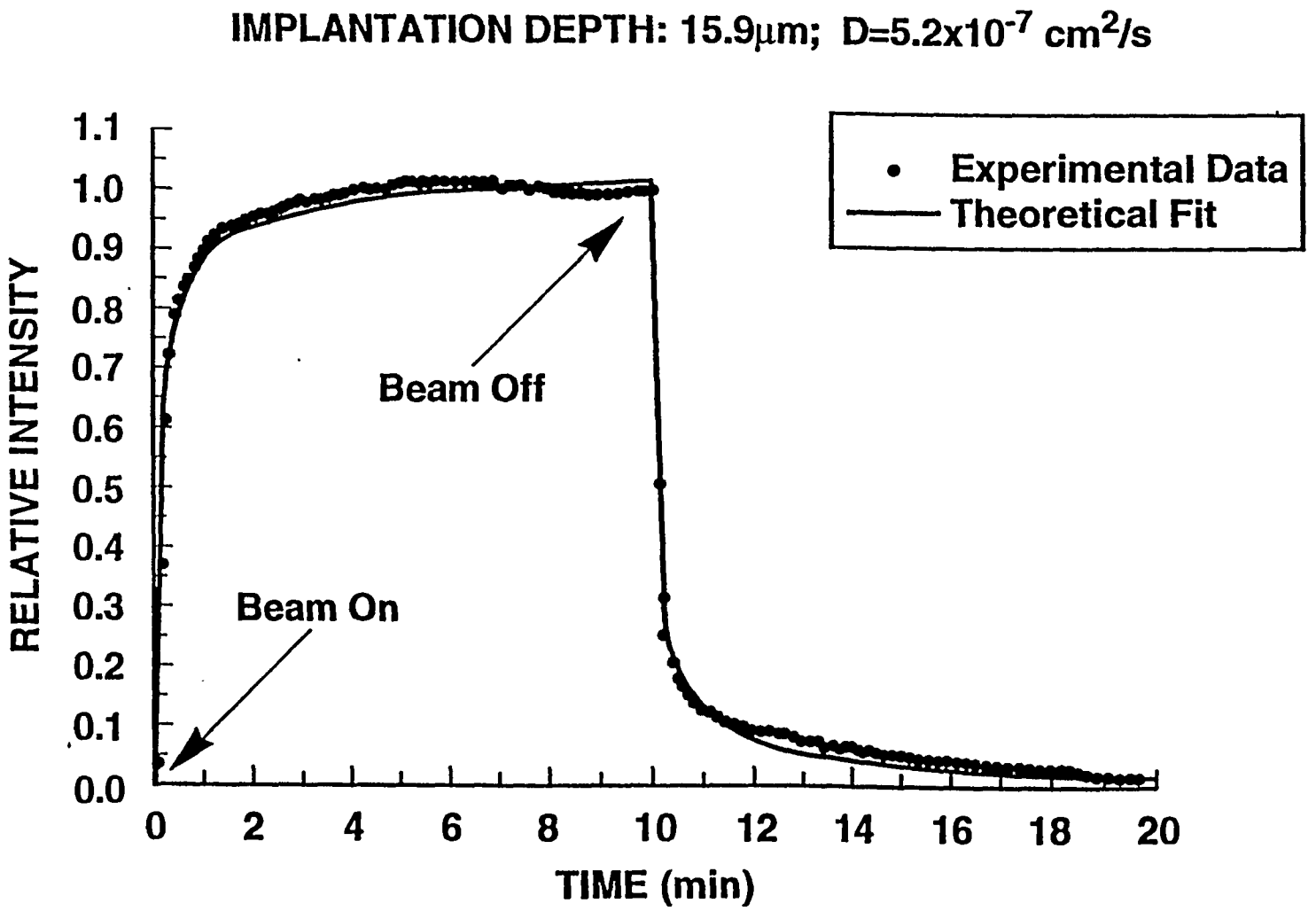
IMPLANTATION DEPTH: 15.9μm; D=5.2x10-7 cm2/s
Experimental Data
Theoretical Fit
Beam Off
Beam On
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
2
4
6
8
10
12
14
16
18
20

Fig. 7

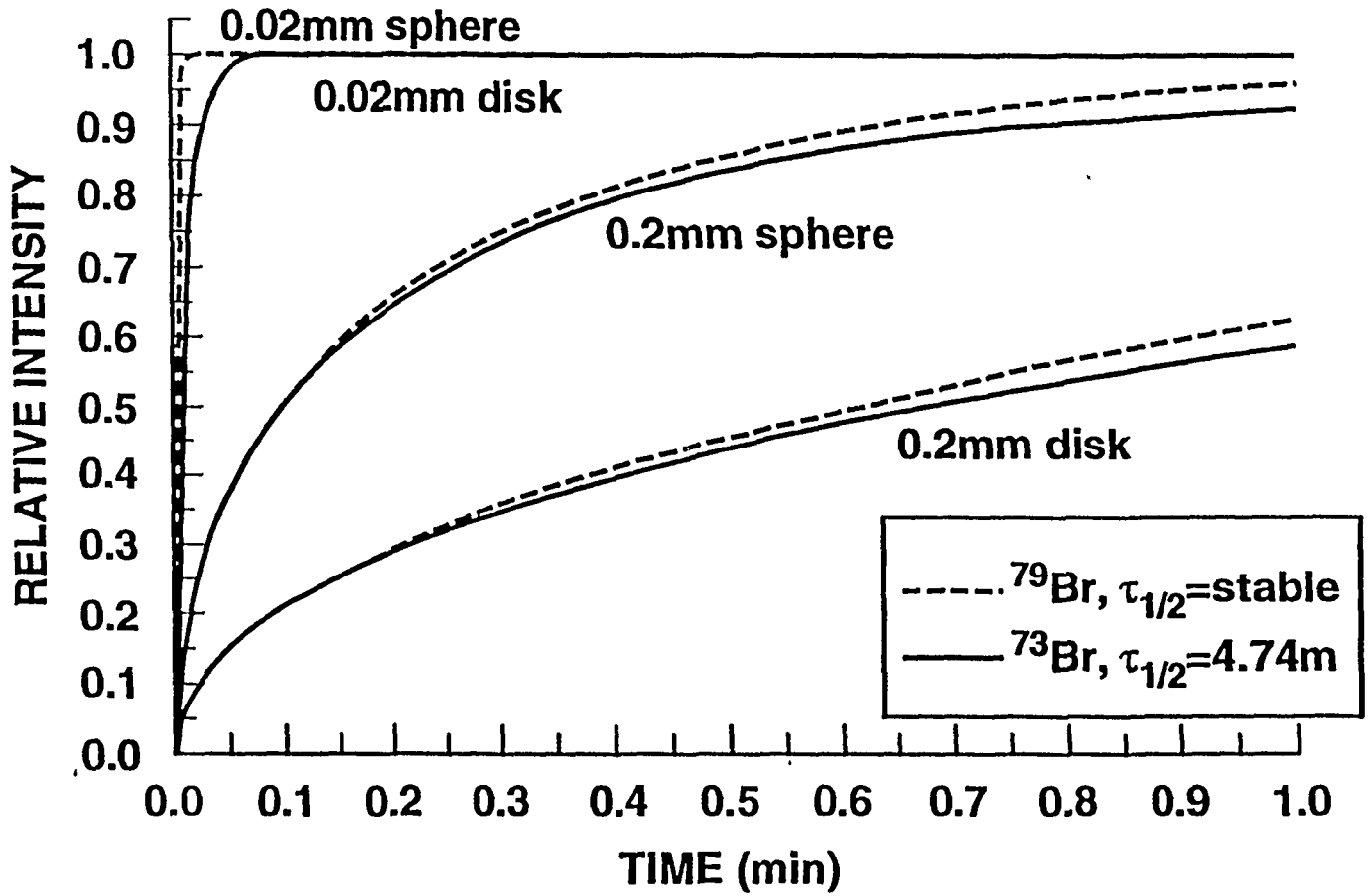
0.02mm sphere
0.02mm disk
0.2mm sphere
0.2mm disk
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
^{79}Br, $\tau_{1/2}$=stable
^{73}Br, $\tau_{1/2}$=4.74m

Fig. 8

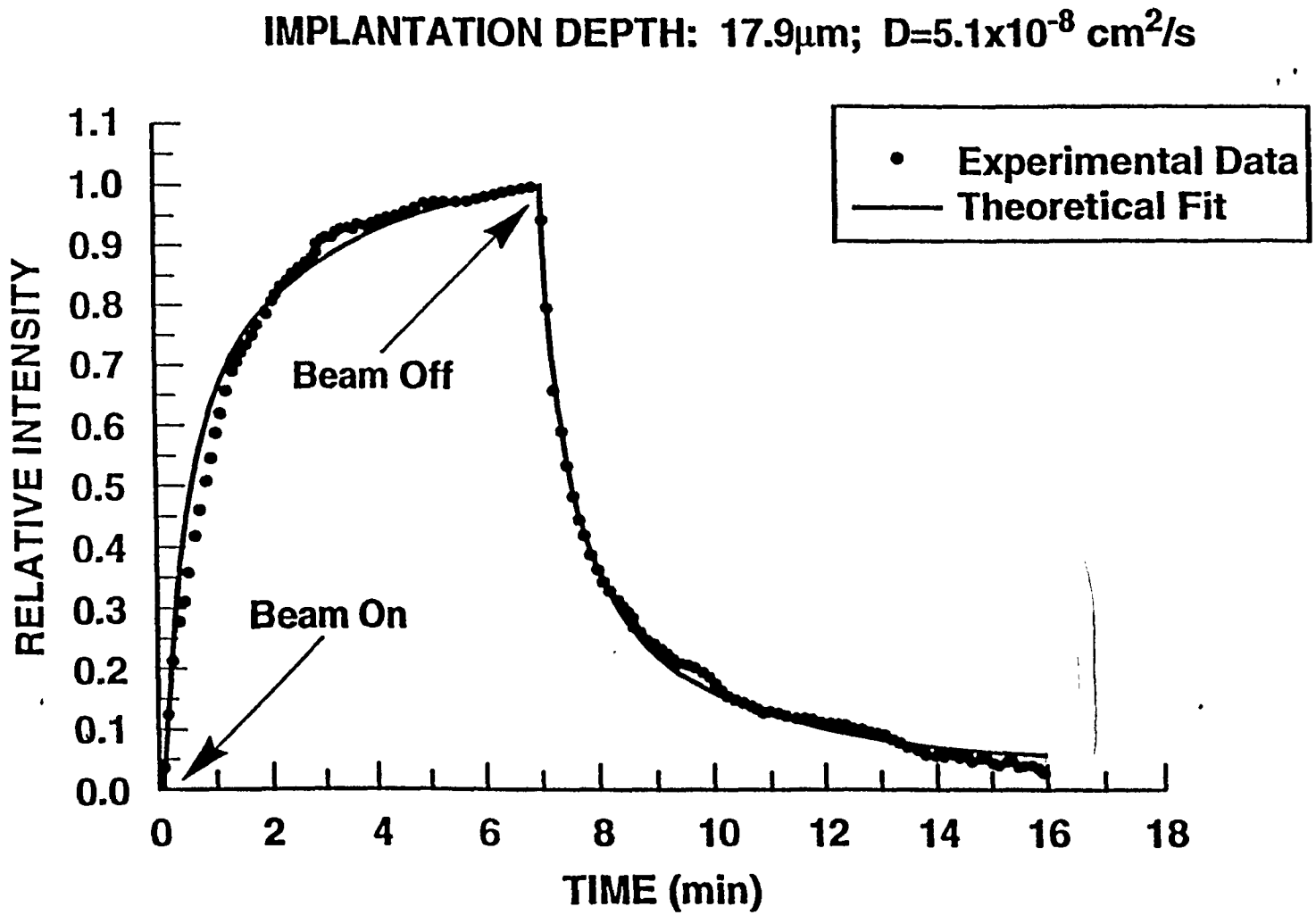
IMPLANTATION DEPTH: 17.9μm; D=5.1x10-8 cm2/s
Experimental Data
Theoretical Fit
Beam Off
Beam On
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
0
2
4
6
8
10
12
14
16
18

Fig. 9

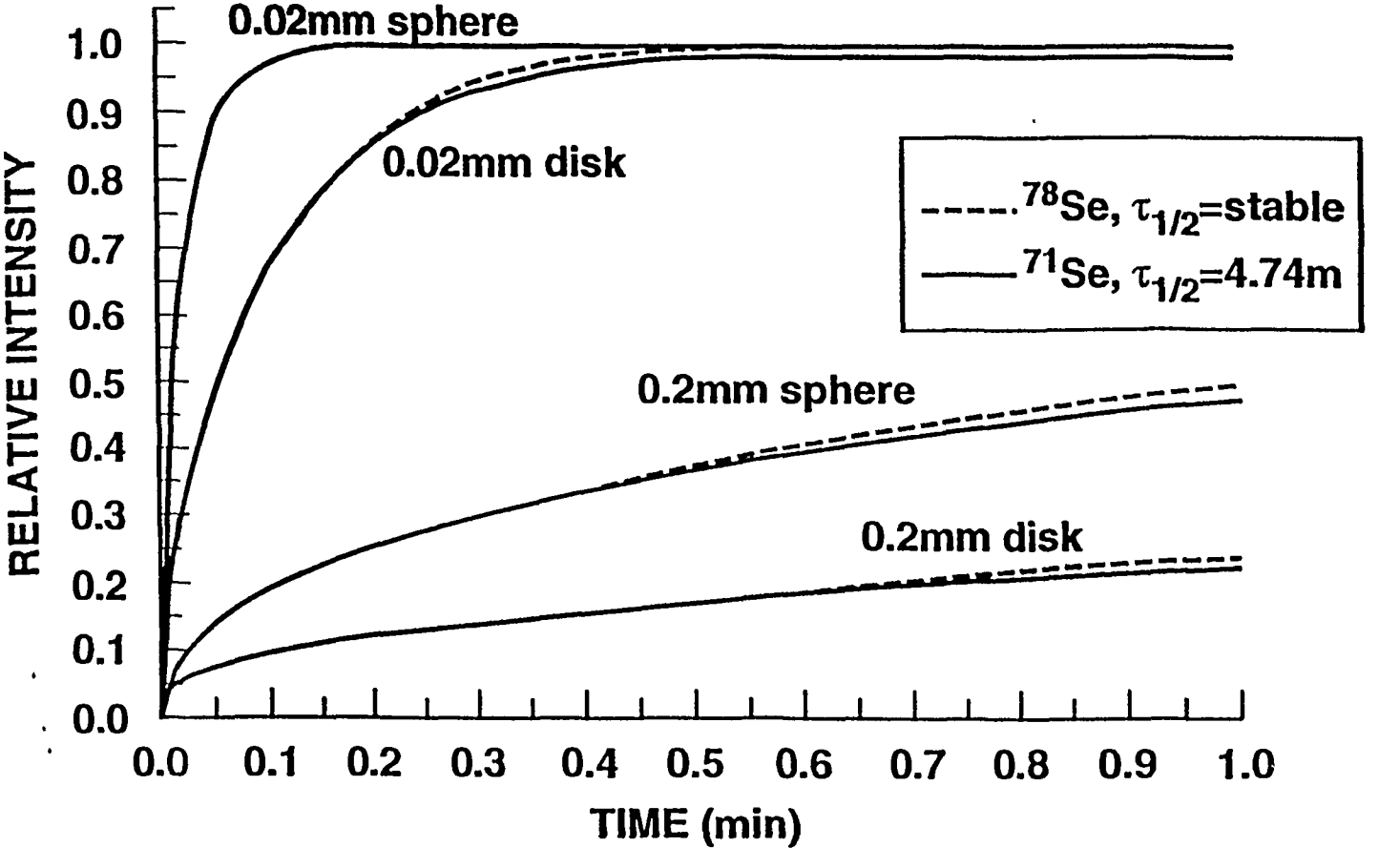
0.02mm sphere
0.02mm disk
0.2mm sphere
0.2mm disk
^{78}Se, $\tau_{1/2}$=stable
^{71}Se, $\tau_{1/2}$=4.74m
RELATIVE INTENSITY
TIME (min)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Fig.10