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DEPTH OF PENETRATION AND CHARACTER OF DISTRIBUTION OF ATOMS INJECTED INTO Si^{30} *ISOTOPE TARGETS*

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We investigated the depth of penetration and distribution of silicon atoms injected in tantalum and copper backings. The targets, which were prepared in an electromagnetic separator by directly depositing the Si^{30} isotope on the backing, were bombarded with protons accelerated in an electrostatic generator. The shape of the resonance yield of gamma rays from a single gamma resonance in the $Si^{30}(p, \gamma) P^{31}$ reaction was observed in four targets and compared with the theoretical density distribution of the injected atoms. The penetration depth and nature of the distribution of the Si^{30} atoms injected in the tantalum backing are in satisfactory agreement with the theory.

INTRODUCTION

THE use of isotope targets in nuclear research is on the increase. The most effective among the various methods of preparing thin isotope targets is to force ions, accelerated in an electromagnetic separator to an energy of several tens of kev, to penetrate into a metal backing.

The essential characteristic of an isotope target prepared by the penetration method is the depth of penetration of the injected atoms and their distribution in the backing material. An investigation of the depth of penetration and of the character of distribution of the target atoms in the backing is of considerable interest both from the point of view of determining the optimum conditions under which isotope targets can be prepared in an electromagnetic separator, and from the point of view of the subsequent use of these targets in nuclear research. Furthermore, data obtained from these investigations can be of great importance in the formulation and verification of a theory of interaction between ions with energies of several kev and the backing substance, and also in the understanding of the phenomenon of cathode spattering. A theoretical examination of these problems is found in the papers by Bohr[1] and Nielson.[2]

Experimental data on the depth of penetration of injected atoms can be obtained from experiments on scattering of protons and alpha particles,[3] from resonant capture of protons,[2] and with the aid of tracer atoms.[4] One of the most convenient methods of investigating isotopic targets is the study of resonant capture of protons, for it yields directly the distribution density of the ions that penetrate into the backing.

The purpose of this study was an investigation of the depth of penetration of Si^{30} ions injected in copper and tantalum backings as a function of the backing material and ion energy. We also investigated the character of the distribution of the Si^{30} atoms injected into a surface layer of the backing. The depth of penetration and the character of the distribution were investigated on the basis of experimental data obtained in a study of the $Si^{30}(p, \gamma) P^{31}$ reaction. For the investigation of

TABLE I

Number of target	Backing material	Ion energy E_i, kev	Time of exposure in beam, min	Amount of silicon injected, μg
1	Ta	25	30	20
2	Cu	25	90	50
3	Cu	28	9	5
4	Cu	10	9	5

this reaction we used Si^{30} targets prepared as described in the following section. All the investigations were made at the same gamma resonance of the $Si^{30}(p, \gamma)P^{31}$ reaction at a proton energy of 940 kev, to permit ready comparison of the experimental data with each other and with experiment.

PREPARATION OF SILICON ISOTOPE TARGETS

The silicon targets were prepared in an electromagnetic separator by directly depositing the ions on metallic backings.[5] The ion source used for such a purpose is described in reference 6. The backings used were copper and tantalum disks 14 mm in diameter and 0.2 to 0.5 mm thick. The ion current into the target was 30 μa during the process. We prepared four Si^{30} targets. The conditions under which these targets have been prepared are listed in Table I.

The amount of Si^{30} injected into the backing, listed in the last column of Table I, is based on the measured target current. The total quantity of electricity flowing into the target during the time of the experiment was measured with a Coulomb meter. The actual concentration of the silicon atoms injected into the backing was determined by calorimetric analysis of several isotopic targets, prepared under analogous conditions. Experience has shown that at a given ion energy the fraction of trapped silicon atoms depends on the current density in the target. When the current density is increased to a fixed value that depends on the ion-metal combination, the number of penetrating atoms decreases. This decrease is due to an increase in the spattering coefficient of the backing material with increasing intensity of the bombarding ions. Thus, as the current density is increased from 20 to 200 $\mu a/cm^2$, the coefficient of spattering of copper by 25-kev silicon ions increases by one order of magnitude (from 0.3 to $\sim$ 3 atoms per ion[7]). At a target current density of $\sim 20\ \mu a/cm^2$, maintained during the experiments, the actual concentration of the Si^{30} ions amounted to 85 or 90 percent of the value estimated from the target-current measurement.

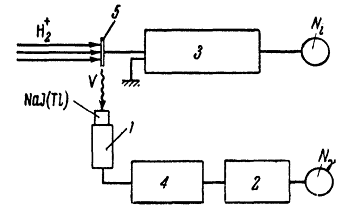

FIG. 1. Experimental setup and arrangement of apparatus: 1) FEU-19, 2) Ps-64, 3) beam-current integrator, 4) amplifier, 5) target.

PROCEDURE

The investigation of the depth of penetration and the character of distribution of Si^{30} atoms in a surface layer of the target backing consisted of measuring the resonance gamma yield at a proton energy $E_p = 940$ kev in the $Si^{30}(p, \gamma)P^{31}$ reaction, and a determination of the width of the resonance peak and of its shape. Si^{30} isotope targets with the characteristics listed in Table I were used in these measurements. The gamma-ray resonance peak was measured with the precision electrostatic generator of the Physico-technical Institute of the Academy of Sciences of the Ukrainian S.S.R.[8] The accelerating voltage of the generator was stabilized with an accuracy of $\pm 0.05\%$, and the energy of the bombarding protons was measured with an electrostatic analyzer[8] having an energy resolution $\Delta E/E \approx 10^{-4}$.

The gamma-ray yield was measured with an NaI(Tl) crystal and an FEU-19 photomultiplier, amplifier, and PS-64 scaler. The current into the target was measured with a current integrator. The arrangement of the apparatus is shown in Fig. 1.

The number of gamma quanta, N_γ, registered by the detector, was referred to the number of counts N_i of the current integrator, corresponding to the charge of the protons incident on the target. The relative gamma yield from extraneous radiation sources and from the backing material was plotted as a function of the energy of the protons incident on the target. The total gamma background amounted to not more than 10% of the main effect measured with the gamma-ray detector. The statistical errors in the measurement of the relative gamma yield did not exceed 3%. With this, equally good reproducibility was obtained for the shape of the resonance curve both in repeated measurements with the same target, and in repeated measurements on different targets prepared in the electromagnetic separator under analogous conditions.

The width of the resonant peak at half maximum, Γ_{exp}, which characterizes the depth of penetration of the Si^{30} ions into the backing material, was determined from the resonance-peak curve in kev. If the stopping powers for protons of given energy in the target and backing material are known, and if

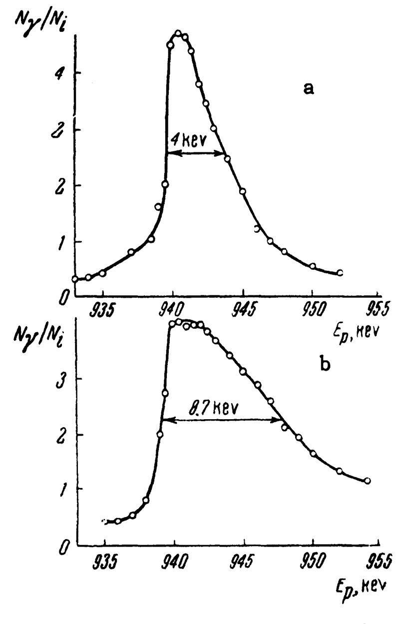

FIG. 2. Relative yield of gamma radiation from the $Si^{30}(p, \gamma) P^{31}$ reaction; resonance at $E_p = 940$ kev, a) target No. 1 – Si^{30} on tantalum backing; b) target No. 2 – Si^{30} on copper backing. Ion energy $E_i = 25$ kev.

the concentrations of the isotope atoms injected into the backing are also known, it is possible to determine from the width of the resonance peak (in kev) the depth of penetration of the ions of the target isotope in $\mu g/cm^2$.

Since the width of the resonance peak is determined by three independent quantities — the thickness Γ_t of the isotope target, the energy inhomogeneity Γ_i of the protons incident on the target, and the natural resonance width Γ_n, the experimentally determined with Γ_{exp} satisfies the relation

$$\Gamma_{exp}^2 = \Gamma_t^2 + \Gamma_i^2 + \Gamma_n^2. \quad (1)$$

The last two terms in (1) give the width of the gamma resonance for a thick target

$$\Gamma_{th} = \sqrt{\Gamma_i^2 + \Gamma_n^2}. \quad (2)$$

The width of the gamma resonance on a thick target was determined in a separate measurement, where a thick target of a natural mixture of silicon isotopes was used.

TABLE II

Target No.	Γ_{exp}, kev	Γ_t, kev	Γ_t, $\mu g/cm^2$	Γ_t^{theor}, $\mu g/cm^2$
1	4	3.46	30	31
2	8.7	8.45	35	13
3	6	5.65	42	15
4	3.7	3.11	21	5

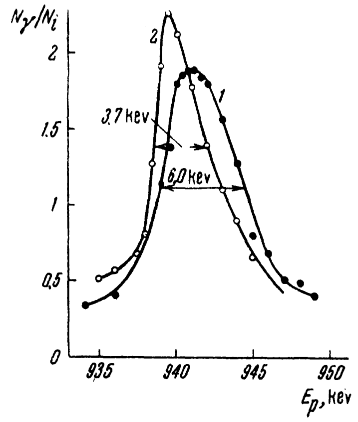

FIG. 3. Relative gamma yield in the Si^{30} (p, γ) reaction. 1) Target No. 3 – Si^{30} isotope on copper backing, ion energy $E_i = 28$ kev; 2) target No. 4 – Si^{30} on copper backing, ion energy $E_i = 10$ kev.

Inserting (2) in (1) we get

$$\Gamma_t = \sqrt{\Gamma_{exp}^2 - \Gamma_{th}^2}. \quad (3)$$

It is obvious that if

$$\Gamma_{th}^2 / \Gamma_{exp}^2 \ll 1 \quad (4)$$

the curve of the gamma-ray yield will reproduce with sufficient accuracy the density distribution of the target atoms injected into the backing.

MEASUREMENT RESULTS AND DISCUSSION

Figures 2 and 3 show the results of the measurements of the relative gamma yield N_γ/N_i as a function of the energy E_p of the bombarding protons. The resonant peaks for four Si^{30} targets indicate the experimental widths Γ_{exp}, expressed in kev. The value of Γ_{th}, measured on a thick silicon target (natural isotope mixture) for resonance in the $Si^{30}(p, \gamma) P^{31}$ reaction at $E_p = 940$ kev, was found to be 2 kev. Condition (4) is thus quite well satisfied for all the investigated targets. The gamma-yield curves represent quite well the density distribution of the Si^{30} atoms injected into tantalum and copper backings.

Table II lists the widths of the targets, in kev, determined from the experimental values, Γ_{th} and Γ_{exp}.

A theoretical analysis of the interaction between ions of energy less than 50 kev and the material of the backing is given in the paper by Nielson[2] for two limiting cases: $A_1 \ll A_2$ and $A_1 \gg A_2$, where A_1 and A_2 are the mass numbers of the ions and atoms of the backing material. In the case of interest to us $A_1 \ll A_2$, when the ion transfers on the average in a single collision only a small fraction of its energy, the analysis is quite analogous to that of diffusion of thermal neutrons. The density distribution of the penetrating ions is in this case

$$q(x) \sim e^{-x^2/4\tau}, \tag{5}$$

where x is measured from the surface of the backing and τ is a certain parameter.[2]

A natural quantity by which to specify the depth of penetration is the distance x in which the density diminishes by one half. Under this condition we obtain from (5)

$$t = 2\sqrt{\tau \ln 2}. \tag{6}$$

Nielson[2] has shown that

$$t = \Gamma_t = \frac{0.83}{\{\xi\,(1-\overline{\cos\varphi})\}^{1/2}} \frac{(z_1^{2/3}+z_2^{2/3})^{1/2}}{z_1 z_2} \frac{A_2^2 E_i}{A_1 + A_2}\ \mu g/cm^2, \tag{7}$$

where z_1 and z_2 are the charges of the ion and of the backing atoms, while ξ and $\overline{\cos\varphi}$ are quantities familiar from neutron-diffusion theory.[9]

As applicable to our own measurements, a satisfactory agreement with (7) is expected for the Si^{30}-Ta combination, for here $A_2/A_1 \approx 6$. To compare the experimentally-determined width Γ_t = 3.46 kev (Table II) with the depth of penetration determined from (7), it is necessary to convert the former into $\mu g/cm^2$ units of the backing material. For this we must know the stopping power of the material through which the protons pass. It is necessary to recognize here that a considerable contribution to the stopping power S_p is made by the silicon ions injected into the tantalum base. This contribution depends in turn on the thickness of the layer in which the given amount of silicon has been injected. We thus obtain a system of equations for the thickness of the Si^{30} layer:

$$\begin{aligned} &\Gamma_t\,[\text{kev}]/S_p\,[\text{kev}\cdot\text{cm}^2/\text{mg}] = \Gamma_t\ [\text{mg/cm}^2]\,; \\ &S_t = S_t^{Ta} + S_p^{Si}\delta\,[\text{mg/cm}^2]\ /\,\Gamma_t\ [\text{mg/cm}^2]\,. \end{aligned} \tag{8}$$

Here δ is the amount of the Si^{30} isotope (mg/cm^2) in a layer Γ_t (mg/cm^2), obtained by multiplying the silicon actually injected into the backing by a factor $^3\!/_4$, since, according to (5), a thickness $t = 2\sqrt{\tau \ln 2}$ contains approximately $^3\!/_4$ of all the atoms injected into the backing. Putting in (8) S_p^{Ta} = 60 kev-cm^2/mg and S_p^{Si} = 180 kev-cm^2/mg, we get Γ_t = 30 $\mu g/cm^2$, which is in good agreement with the width Γ_t^{theor} = 31 $\mu g/cm^2$, computed with the aid of Eq. (7).

Since the experimental and theoretical values of the depth of penetration of silicon atoms into tantalum are in good agreement, and the formula for the resonance peak represents accurately the distribution of the atoms injected into the backing, it becomes interesting to compare the theoretical distribution of the density of the injected atoms with the experimentally-observed shape of the resonance peak.

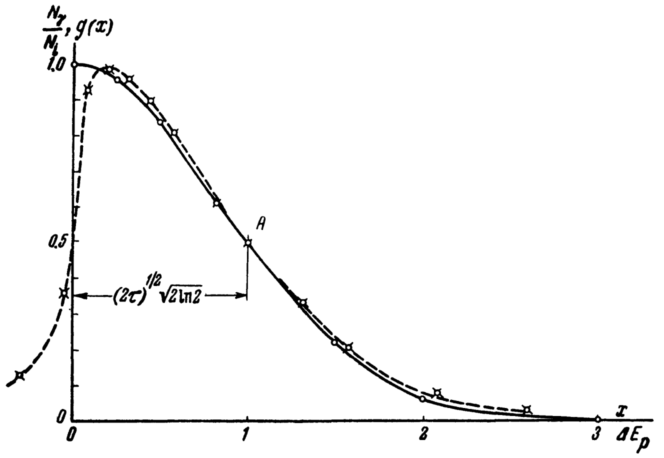

FIG. 4. Depth distribution of Si^{30} ions in a tantalum backing. Solid line – theoretical distribution. The experimental points for target No. 1 are joined by dotted lines.

Figure 4 shows a curve, calculated with the aid of Eq. (5), together with the experimental curve obtained with target No. 1. The curves are made to coincide at point A, where the density of the penetrated particles and the intensity of the gamma-ray yield decrease by one-half. Such an alignment of the curves determines their overall scale. The coordinates of the remaining points on the theoretical and experimental curves were recalculated to fit the scale so selected. We see that the experimental curve follows Eq. (5) rather closely. The portion of the experimental curve to the left of zero is apparently due to the "tail" of the Breit-Wigner curve, broadened by the energy inhomogeneity of the proton beam.

A simple calculation shows that in this case, a layer of thickness $\Gamma_t = 2\sqrt{\tau \ln 2}$, contains approximately two silicon atoms for each tantalum atom. Such a concentration ratio may correspond to the formation of an intermetallic compound $TaSi_2$. One might assume that so large an impurity of silicon atoms would also affect the character of diffusion of the silicon ions, causing a deviation from the law given by Eq. (5). However, one must take it into account that, firstly, the Si^{30}-Si^{30} and Si^{30}-Ta^{181} collision cross sections are related as the nuclear charges, i.e., the ratio of their cross sections is 14 : 73 = 0.19. Secondly, the 2 : 1 concentration ratio is attained only at the conclusion of the ion injection. Thirdly, one must consider that scattering at large angles (~180°) in the c.m. system cannot influence the diffusion of identical particles.

All these circumstances, apparently, make for only a slight effect of Si^{30}-Si^{30} scattering on the course of the diffusion process.

We must not expect satisfactory agreement with (7) in the case of the Si^{30}-Cu combination, which was derived by Nielson for $A_1 \ll A_2$, for in this case $A_2/A_1 \approx 2$. Actually, our experimental values of the depth of penetration of silicon ions into copper (see column 4, Table II) do not agree with the values calculated with Eq. (7). It is interesting that for all three copper-backing targets the depth of penetration of the silicon ions is 3 or 4 times greater than the theoretical value.

In Fig. 3 the maxima of the resonance peaks of targets 3 and 4 are displaced, owing to the different energies of the silicon ions (see Table I, data for E_i). This effect is expected both from the theory of N. Bohr and from Eq. (7).

It would be interesting to verify experimentally the correctness of Eq. (7) for several other ion and metal combination, and to investigate the other limiting case, when $A_1 \gg A_2$.

A very interesting fact is that isotope targets prepared by penetration in an electromagnetic separator were more stable in a proton beam than targets obtained by condensation of previously separated Si^{30} evaporated in vacuo.

CONCLUSIONS

1. The depth of penetration of Si^{30} ions into tantalum, at an ion energy of 25 kev, was found experimentally to be 30 $\mu g/cm^2$, a value in good agreement with theory.

2. The character of distribution of the silicon stoms penetrating in a tantalum backing is analogous to the distribution derivable from the theory of the diffusion of thermal neutrons.

3. A layer 30 $\mu g/cm^2$ thick contains on the average two silicon atoms for each tantalum atom; this indicates a considerable deformation of the tantalum lattice. It is probable that the penetration results in the formation of the intermetallic compound $TaSi_2$.

4. The experimental values of the depth of penetration of silicon ions into copper are 3 to 4 times greater than those computed by the Nielson formula, but smaller than those obtained from the theory of N. Bohr.

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1