respectively. In order to estimate the yields of ^{42}K and ^{43}K for a thick target from the cross sections indicated above, it was assumed that the cross section of these reactions increases linearly from the effective threshold of the reaction to E_p = 21.5 MeV. Upon integration over the range of the excitation functions obtained for these reactions the values of the yield of ^{42}K and ^{43}K for E_p = 21.5 MeV are as shown in Table 1 and on Fig. 1.

Upon the irradiation of natural calcium the ^{43}K yield is small in comparison with the irradiation of argon, and the admixture of ^{42}K is very appreciable. The situation is radically altered when enriched ^{44}Ca is used. For example, the irradiation by protons of calcium enriched in ^{44}Ca to 95% increases the yield of ^{43}K by a factor of 45, and the content of the ^{43}K impurity decreases by a factor of 100-200 (depending on the ^{43}Ca content in the enriched ^{44}Ca). Upon irradiation of natural calcium by deuterons the contribution, according to our estimates, of the reaction $^{44}Ca(d2pn)^{43}K$ to the ^{43}K yield amounts to ~70% (with E_d = 22 MeV). Therefore, when enriched ^{44}Ca is irradiated, one can expect an increase of the ^{43}K yield by approximately a factor of 30.

The admixture of ^{42}K due to the reaction $^{44}Ca(d\alpha)^{42}K$ can be reduced by using a thin target. Thus when a target of enriched ^{44}Ca is used, the ^{43}K yield and the content of the ^{42}K impurity are comparable to the analogous characteristics of the target (Ar + α) $\rightarrow$ $^{42,43}K$. The well-known difficulties associated with the creation and operation of a gaseous target are eliminated. Recording of the ^{44}Ca from the irradiated targets for repeated irradiation will permit reducing the cost of using enriched ^{44}Ca.

LITERATURE CITED

1. J. Clark et al., Int. J. Appl. Rad. Isotopes, 23, 329 (1972).
2. M. Guillaume, Nucl. Instrum. Methods, 131, 185 (1976).
3. N. G. Gusev and P. P. Dmitriev, Quantum Radiation of Radioactive Nuclides (Handbook) [in Russian], Atomizdat, Moscow (1977).
4. P. P. Dmitriev et al., At. Energ., 46, No. 3, 185 (1979); 48, No. 2, 122 (1980); 48, No. 6, 402 (1980).
5. B. Cohen and E. Newman, Phys. Rev., 99, 723 (1955).
6. P. P. Dmitriev and M. V. Panarin, At. Energ., 46, No. 1, 53 (1979).
7. D. Williams and J. Irvine, Phys. Rev., 130, 259 (1963).

IMPLANTATION OF LOW-ENERGY HYDROGEN IONS IN LITHIUM

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The possibility of using liquid lithium in controlled thermonuclear fusion systems for pumping large fluxes of nonthermal atoms and ions of hydrogen isotopes (having an energy in excess of tens of electron volts) by means of the implantation method was examined in [1-5]. The possibility of implantation of hydrogen ions with an energy above 2.5 keV per proton in liquid lithium can be considered as an experimentally established fact [1, 5]. However, this was not checked experimentally in the case of lower energies. We have attempted here to gain information on the implantation of hydrogen ions in lithium at an energy of 1.5 keV per proton. For work at energies below 3 keV, we had to modify the existing ion source [5]. This was necessary because, on the one hand, a reduction in the accelerating voltage causes a reduction in the optimum ion current to the target (i.e., the ion current corresponding to a minimal angular divergence), and, thus, a sensitivity loss in measuring the implantation factor, while, on the other hand, a low accelerating voltage produces a smaller discharge current in the source plasma, so that optimum focusing occurs under conditions of unstable arcing [6]. These disadvantages are eliminated to a considerable degree by a source design incorporating an expansion chamber (expander) [7] and a small accelerating gap [6], which is shown in Fig. 1.

The plasma formed in the arc discharge between the lanthanum-hexaboride heating cathode 1, and the walls of the discharge chamber 2, emerges through the opening in anode 3. The an-

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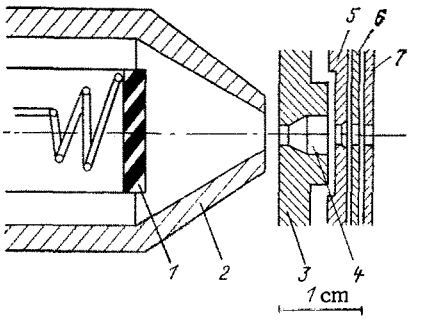

Fig. 1. Schematic diagram of the ion source for producing low-energy beams.

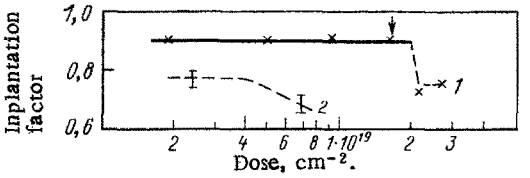

Fig. 2. Factor of hydrogen ion implantation in lithium as a function of the proton dose (ion energy, 1.5 keV per proton): ———) and -----) implantation in liquid and solid lithium, respectively. 1) Initial lithium temperature, 230°C; final temperature, 130°C (the arrow indicates the time the heating was switched off); 2) lithium temperature, 20°C.

ode ends with an expansion chamber, 4 [6]. The voltage between the anode 3 and the emission lens 5 is equal to 200-400 V. The emerging ion beam is focused by an intermediate lens 6 (to which a negative potential is applied) and the ground electrode 7. The accelerating voltage, which determines the ion energy, is supplied to anode 3. The shape and dimensions of the expansion chamber are designed to ensure the plasma density at the exit opening of the emission lens necessary for sharp beam focusing with stable arcing in chamber 2. The spacings between lenses 5, 6, and 7 and their thicknesses were determined on the basis of the recommendations given in [7]. We succeeded in providing an accelerating gap of 0.4-0.5 mm between the electrodes.

As a result of additional focusing along the beam channel [5], such an ion source design made it possible to produce, at a target located at 1.3 m from the source, H_2^+ ion currents of up to 70-90 μA with an energy of 3 keV and a spot area of 0.1 cm^2. The surface area of the spot was determined by visually observing the luminescence of quartz glass covered with a molybdenum grid and measuring the surface area of the ionic etching spot on a stainless-steel mobile slide, placed in the immediate vicinity of the target.

The procedure of filling the target with lithium and the method of measuring the implantation factor have been described in [5]. The lithium target design was modified so as to remove the lithium crucible heaters from the vacuum and bring them out into the atmosphere. This made it possible to reduce by almost one order of magnitude the background pressure in the measuring chamber with the crucible heated to 250-300°C. The chamber walls remained cold. An improved system for stabilizing the accelerating voltage and the separator magnet current maintained during prolonged irradiation the stability of the spot position on the target with an accuracy not worse than 10% of the spot area.

The experiments were performed at 200-250°C with a current density of 0.5-0.9 mA/cm^2 and a H_2^+ ion energy of 3 keV, which corresponded to the injection of protons with an energy of 1.5 keV [8]. The implantation was carried out in liquid, setting, and cold (room temperature) lithium. The lithium pressed out into the crucible had a mirror surface and did not require additional cleansing by scraping. The thickness of the lithium layer in the crucible amounted to a few millimeters. A positive voltage (40-70 V) with respect to ground was applied to the target in order to suppress secondary electron emission from the lithium surface.

A typical dependence of the implantation factor on the irradiation dose during one measurement cycle is shown in Fig. 2. The dose was calculated with respect to the target current, which remained constant, and the irradiation time, with an allowance for the number of protons per incident ion. At the points marked on the curve, the complete procedure of measuring the implantation factor was carried out by using the molybdenum slide [5]. In the intervals between these measurements, implantation was estimated with respect to the steadiness of the pressure rise in the chamber, caused by desorption from irradiated lithium, and the constancy of the beam current to the target.

When the proton irradiation dose reaches ~$2 \cdot 10^{19}$ cm^{-2}, the target heating is switched off, and lithium starts to cool under continued irradiation. The irradiation is stopped when the lithium temperature drops to 130°C, which is considerably below the crystallization temperature. The time of lithium crystallization is recorded with respect to the temperature, with respect to the increasing pressure rise in the chamber, and visually.

It is evident that implantation in liquid lithium occurs with constant efficiency and is independent of the temperature up to the melting point. After crystallization, the implantation factor drops sharply to 0.7-0.75. Implantation in cold (20°C) lithium occurs at the same level. After solidification, the metal surface changes from a shiny one to a dull, rough surface, and, as the ion beam is moved over the surface of solid lithium, it is possible to obtain implantation factors which differ by 0.1-0.15 from each other. This is possibly connected with ion reflection at glancing angles with respect to the roughnesses. The factor of hydrogen ion implantation in a " thick" liquid lithium film in the range from the melting point (180°C) to 250°C remains high, 0.9-0.94, for proton doses not lower than $2 \cdot 10^{19}$ cm^{-2}.

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LITERATURE CITED

1. S. Erents, G. McCracken, and P. Goldsmith, J. Phys. D. Appl. Phys., 4, 672 (1971).
2. B. Badger et al., UWFDM-68, Nucl. Eng. Dept., Univ. of Wisconsin (1974).
3. B. Badger et al., UWFDM-112, Nucl. Eng. Dept., Univ. of Wisconsin (1975).
4. E. V. Murav'ev, Vopr. At. Nauki Tekh., Ser. Termoyadernyi Sintez, No. 2 (6), 57 (1980).
5. O. G. Voronkov and V. F. Zubarev, in: Reports at the Second All-Union Conference on Engineering Problems Concerning Thermonuclear Reactors [in Russian], Vol. 4, NIIÉFA, Leningrad (1981), p. 217.
6. J. Copeland et al., Prib. Nauchn. Issled., No. 9, 101 (1973).
7. Th. Slyuters, in: Proc. Second Int. Conf. on Ion Sources, Vienna (1972), p. 190.
8. G. McCracken and J. Maple, Brit. J. Appl. Phys., 18, 919 (1967).