JOINT INSTITUTE FOR NUCLEAR RESEARCH

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The results of the investigation of tritium production in different elements at the proton energy 660 MeV are presented. The excitation functions for the reactions of tritium production in aluminium and lead in the energy region 120-660 MeV are given. The present research has been undertaken to complete the data obtained in [1-6], as well as to find new features of this phenomenon.

EXPERIMENTAL PROCEDURES

The samples of metals (2 x 6 x 15)mm^3 have been bombarded by the protons in the internal beam of the Joint Institute synchrocyclotron. For the irradiation the samples were kept on the massive aluminium holder by 4-6 pieces simultaneously. The proton beam traversed along the side of 6 mm. The energy variation of the bombarding particles has been achieved by changing the working radius of the target position in the synchrocyclotron. The samples were irradiated for 2-5 minutes, the intensity of the internal proton beam being 10^{11} - 10^{12} protons) sec. The quantity of tritium in the irradiated target was determined with the help of a special vacuum system, the scheme of which is given in Fig. 1. The arrangement consists of a tubular stove with a quartz tube for melting the targets; of the palladium filter

with an electroheater which serves to separate the hydrogen-tritium mixture from the other gaseous reaction products; of a trap with the activated carbon cooled by the liquid nitrogen (the trap was used to create the pressure overfall when the active gas was passed through); of the Geiger counter in the lead shielding). Besides, the arrangement was supplied with several reservoirs -for hydrogen, pure argon, alcogol and by a reserve volume for diluting the highactive mixture.

The irradiated target was melted in the quartz tube (140cm^3 in volume) in an atmosphere of hydrogen* (50 mm Hg pressure). The melting lasted for 1.5-2 hours at the temperature 900-1050^0 C**. Under these conditions the isolation of tritium from the sample is about 90%. The subsequent second melting under the above-mentioned conditions yields 8-9%, whereas the third melting gives 1-2% of all the tritium activity. The special check of the recoil of the active mixture by the activated carbon has shown that at the room temperature the carbon yields the gas practically completely.

The vacuum arrangement makes it possible to pass into

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* The hydrogen used in the experiments as a carrier was preliminarily passed through the palladium filter.

** The experiments were performed with the elements the melting temperature of which does not exceed 1100^0 C.

the volume of the counter from 0.057 up to 0.1 parts of the hydrogen-tritium mixture at the pressure of 1-6 mm Hg. As a detector of β -particles the glass cylinder counter with the copper cathode was used the volume of it was 60 cm^3. In addition to the hydrogen-tritium mixture the counter was filled with the steams of alcogol at the pressure of 15 mm Hg and with argon at the pressure of 95-100 mm Hg. Under the above-mentioned conditions the Geiger counter has the following characteristics: the counter has the plateau 100-150 v long, the incline of it does not exceed 10% for 100 v, the counter background is 80-100 counts min. The measured activities of tritium were 1000-10000 counts min. The recording effeciency of the β -particles from tritium disintegration was estimated as about 90%.

The aluminium foil 20 microns thick in which the samples during the irradiation were wrapped up served as a monitor of the proton beam. The dependence of the reaction $Al^{27}(p,3pn)Na^{24}$ upon the energy of the incident protons were taken from |7,8|. After the irradiation the aluminium foil was dissolved in 1 ml HCl, then the fall of the activity of 0.01 parts of the solution was measured. The monitor activity was measured on the counter with the mica window 3 mg/cm^2 thick. The arrangement detected 18% of all the activity of the monitor target.

EXPERIMENTAL RESULTS

The cross sections for tritium production in different elements in the energy region 120-660 MeV are given in the Table. These values are the average over not less than three determinations, except several magnitudes of tritium production cross sections in Mg, Sn, Au and Bi obtained in single measurement. (See Table). General inaccuracy in the determination of every point is estimated within ± 30%. This magnitude is the double halfwidth of the deviation curve from the mean experimental values in all the experiments. It was found to be close to the Gauss distribution curve.

The cross sections for the tritium production (σ_{H^3}) in aluminium and lead at 120 MeV almost coincide. With the proton energy increase on heavy elements the appreciable increase of σ_{H^3} is observed. In the energy region 300-500 MeV the increase of the tritium production cross section is slowing down, however, after 550 MeV it increases sharply. At the energy of 660 MeV σ_{H^3} in lead and bismuth exceeds almost two times the magnitude of the cross section of the plateau (300-500 MeV) and reaches 10% of the geometric cross section. The described dependence displays clearly in Pb

and Bi. In aluminium and magnezium this dependence is very slightly different from the linear one. The data for tin lie between the points for lead and aluminium.

In Fig. 2. The dependence σ_{H^3} has been plotted against atomic weight of the elements at 660 MeV. Excitation energy of nuclei of different elements at the energy of the bombarding protons 450 MeV is shown in the same Fig. by the dashed lines.

The material of the target	Proton energy (MeV)	Average cross section	Number of experiments
Magnesium	660	43 ± 13	2
Aluminium	660	46 ± 14	17
Copper	660	73 ± 22	6
Zink	660	67 ± 20	7
Argentum	660	76 ± 23	4
Cadmium	660	95 ± 28	3
Tin	660	122 ± 37	3
Antimonium	660	88 ± 26	2
Gold	660	139 ± 41	1
Lead	660	186 ± 56	11
Bismuth	660	167 ± 50	4
Aluminium	600	44 ± 13	2
Tin	600	86 ± 26	1
Lead	600	157 ± 47	3
Magnezium	550	26 ± 8	2
Aluminium	550	33 ± 10	6
Tin	550	69 ± 21	1
Lead	550	87 ± 26	3
Bismuth	550	75 ± 22	1
Aluminium	500	37 ± 11	5
Magnezium	450	30 ± 9	1
Aluminium	450	24 ± 7	3
Lead	450	91 ± 27	3
Magnezium	300	19 ± 6	2
Aluminium	300	25 ± 7	3
Tin	300	38 ± 11	2
Lead	300	73 ± 22	4
Bismuth	300	73 ± 22	1
Aluminium	200	18 ± 6	3
Aluminium	120	16 ± 5	3
Lead	120	17 ± 5	3

In this Figure, one can also see the cross sections obtained experimentally at the same energy or by interpolating the energetic dependence curves. The data of [1] are given there too. There is a good agreement of our data for aluminium and lead at 450 MeV with the those of[1]. The monotonous increase of the cross-sections with the increase of "A" is characteristic for Fig. 2. At the proton energy 660 MeV the cross section of σ_{H^3} from aluminium to bismuth changes approximately three times whereas "A" changes approximately eight times.

THE DISCUSSION

It is of interest results how the cross sections for tritium production are dependent upon the proton energy when passing into the region of higher energies. In Fig.3 the data on tritium production in Al and Pb by high-velocity particles are presented. These data were obtained in the present research and known from literature[1,4,6]. The experimental data taken from literature are given in Fig. 3 in the form of open circles and squares. The crosses denote the cross sections for tritium production in iron by the protons with the energy 0.16; 1.0; 3.0; and 6.2 BeV[4] and in the energy range 50-170 MeV[6]. It can be seen from the

Fig. 3 that the observed increase of σ_{H^3} on lead after 550 MeV goes on further. For 2.05 BeV σ_{H^3} exceeds the cross section for tritium production in the enrgy range 300-500 MeV more than five times and reaches 25% of the geometric cross section. In case of aluminium the magnitude of σ_{H^3} does not almost change up to 2.05 BeV. σ_{H^3} on iron grows monotonously with the proton energy increase but the curve for Fe is closer to that for Al than for Pb. Only in the energy range 0.1-0.17 BeV σ_{H^3} in iron[6] are below the data for Al. Thus, one may observe with the proton energy increase relatively greater increase of the cross sections for tritium production on heavy elements than on light ones.

The curves plotted in Fig. 3 show the probability of tritium emission from Pb and Al, calculated according to evaporation theory in the proton energy interval 120-500 MeV. The calculated curves were brought into agreement with the experimental data in such a way so that the greatest number of points would coincide. The calculation was made by the formulas given by Hagedorn and Makke in[9], the magnitudes of the excitation energies for the corresponding nuclei pointed out in[10] being involved. (For case of Pb the magnitudes of the excitation energies calculated for Bi were used). The dependence given in[11] was taken as a ratio determining the temperature of the nucleus at the given excitation energy.

The magnitudes for Pb $V'_{H_3} = \frac{V_o}{2}$ = 8.1 MeV for Al $V'_{H_3} = \frac{V_o}{2}$ = = 2.3 MeV served as an effective barrier in tritium emission. It can be seen that evaporation theory yields the dependence of σ_{H^3} variation upon the proton energy approximately identical with the experiment.

The relative probahility of tritium emission $\frac{\gamma_{H^3}}{\gamma_{total}}$ where γ_{tot} is the total probability of the evaporation of neutrons, protons, α-particles etc.

$$\gamma_{tot} = \gamma_n + \gamma_p + \gamma_d + \gamma_{H^3} + \gamma_{He^3} + \gamma_{He}$$

also coincides with the experimental ratio $\frac{\sigma_{H^3}}{\sigma_{geom.}}$ at the proton energy 120 and 550 MeV. For Al $\frac{\gamma_{H^3}}{\gamma_{tot.}}$ has been obtained to be 10^{-2} and 3.10^{-2}, whereas $\frac{\sigma_{H^3}}{\sigma_{geom.}}$ is $2.5.10^{-2}$ (without taking into account the transparency). In case of Pb $\frac{\sigma_{H^3}}{\sigma_{geom.}}$ is equal to 3.10^{-3} and $1{,}1.10^{-2}$ at the same proton energies. The magnitude of $\frac{\gamma_{H^3}}{\gamma_{tot.}}$ (without taking into account the transparency) is equal to 8.10 and 4.10, respectively. Thus, the relative probability of tritium emission changes as well as the experimental ratio $\frac{\sigma_{H^3}}{\sigma_{geom.}}$ and the difference between them is not more than three times. This discripancy is not essential due to the approximate character of the calculations.

The coincidence of the dependence σ_{H^3} upon the proton energy (Fig. 3) and $\frac{\sigma_{H^3}}{\sigma_{geom.}}$ with the predictions of evaporation theory points out that in our experiments the tritium nuclei obtained as a result of the evaporation process are mainly detected. The coincidence of the excitation

energy curves and the production cross section in different elements at the proton energy 450 MeV.(See Fig. 2) declares in favour of such a conclusion.

At the proton energy above 500 MeV the evaporation theory gives the appreciable increase of the probability of tritium emission if compared with the experimental cross section, though the ratio $\frac{\gamma_{H^3}}{\gamma_{tot}}$ remains approximately the same. If one assumes that the theory is in agreement with the experiment in the energy range 120-500 MeV, then for 2 BeV the probability of tritium emission in Al exceeds the experimental value approximately seven times, whereas for Pb it exceeds approximately 13 times. Such an increase of the calculated magnitudes is very likely to be due to the fact that the evaporation theory is not applicable at such high energies of the bombarding protons.

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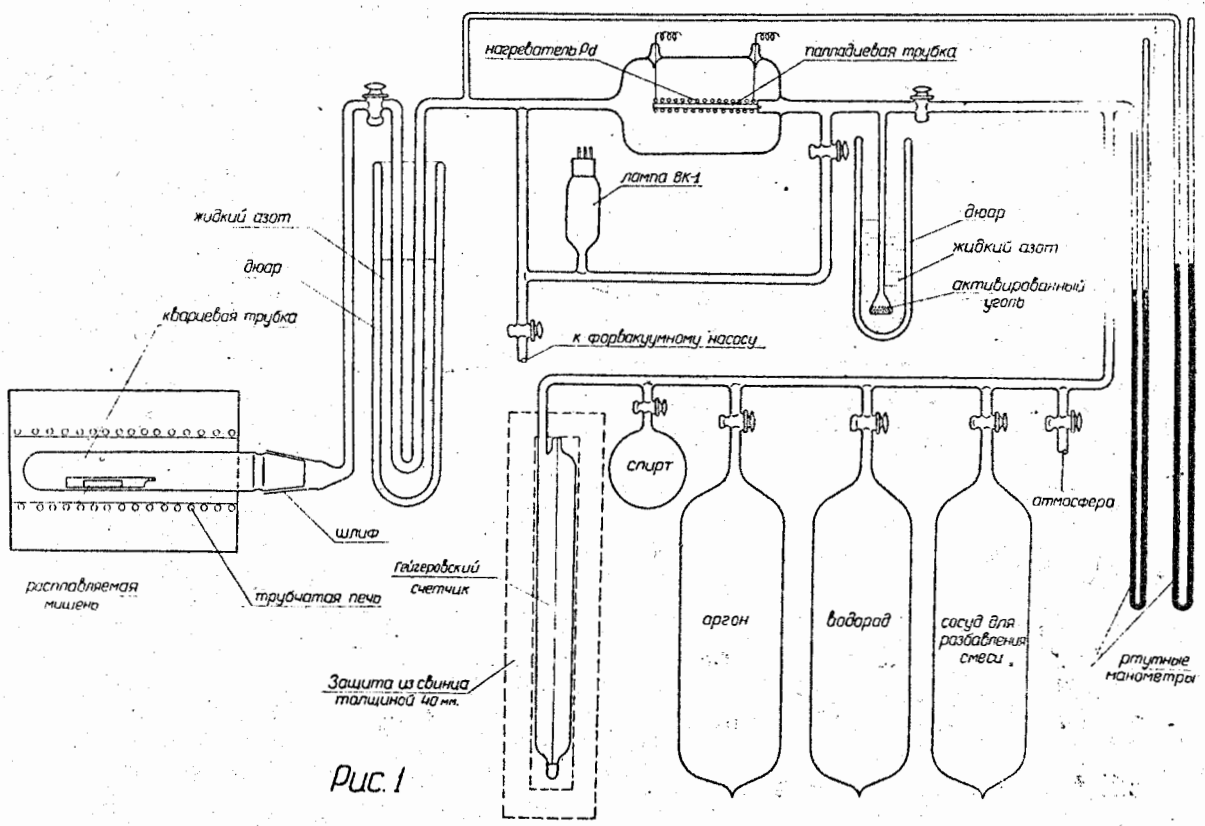

Рис. 1

Fig. 1.

Vacuum arrangement for the determination of the quantity of tritium produced by high energy protons in different elements.

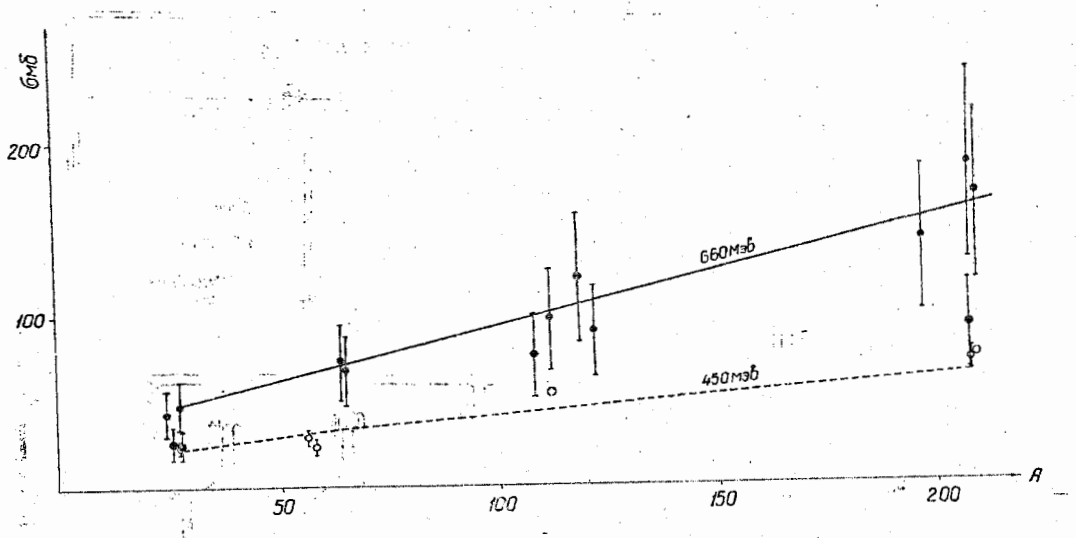

Fig. 2.

Tritium production cross section at 660 MeV and 450 MeV is plotted against the atomic weight of the target material.

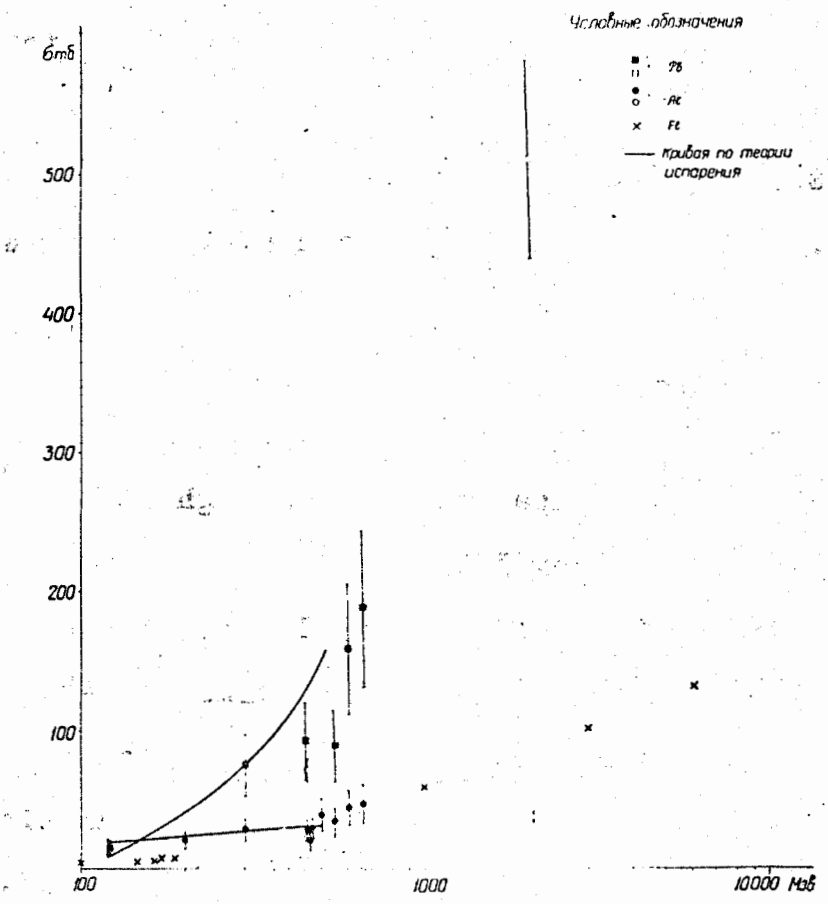

Fig. 3. The dependence of the tritium production cross section in Al, Pb, and Fe upon the proton energy.

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