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PHYSICS

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Radiochemical Study of the Reaction $Si^{30}(p, \pi^+)Si^{31}$

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One of the authors of this work had already shown in 1950 the presence of the radioisotope Ni^{65} in the products of the bombardment of $Cu^{63,65}$ with fast protons (1). The formation of this isotope was explained by the occurrence of the secondary reaction with neutrons $Cu^{65}(n, p)Ni^{65}$. However, a study of the dependence of the yield of Ni^{65} on the energy of the incident protons showed that the formation of this isotope proceeds by the reaction $Cu^{65}(p, p\pi^+)Ni^{65}$ (2). In this way the possibility of applying the radiochemical method for the detection of π^+ mesons was demonstrated.

In the present work an attempt was made to detect, by the radiochemical method, the reaction $Si^{30}(p, \pi^+)Si^{31}$. Since all other radioactive isotopes of silicon have a very short half-life, it becomes possible to detect the isotope Si^{31} ($T = 2.65$ hours) even in the case when the cross section for its formation is small. To prove the existence of the above-mentioned reaction, the dependence of the value of the cross section for the formation of Si^{31} on the energy of the bombarding protons was studied in the interval from 120 to 660 MeV.

Procedure. A target weighing 60–80 mg, made of spectrally pure powdered silicon and measuring 8×8 mm, was wrapped in two layers of aluminum foil and irradiated with protons of various energies in the internal beam of the synchrocyclotron of the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research. The irradiation time was 1–2 hours.

After irradiation, the silicon was dissolved in several milliliters of a 3 M NaOH solution. The solution was filtered through a paper filter to remove partially undissolved silicon. To the filtrate were added 2 M HCl and several milligrams of salts of $BeCl_2$ and $MgCl_2$, and the solution was evaporated to dryness. The residue was treated with concentrated HCl, centrifuged, washed 3–4 times with the same acid, then dissolved in a 3 M NaOH solution, and after the addition of Be and Mg salts all operations were repeated two more times; on the last occasion the evaporation was carried out with concentrated H_2SO_4. The separated SiO_2 precipitate was dried, ignited at 900° for 45 min, and weighed. The

Fig. 1. Decay curve of silicon

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chemical yield of silicon was 20%. The duration of the separation was 4 hours.

A definite amount of SiO_2 (usually 18 mg) was placed on a backing of tracing cloth of thickness 8 mg/cm^2, and then the activity of the silicon was measured. For this purpose an end-window counter TM-20 was used (diameter of the mica window 20 mm, thickness 4 mg/cm^2). The end-window counter was placed in a standard lead shield with a Plexiglas stand for the targets. The activity was measured at a distance of 23 mm from the window of the counter. The activity of the silicon was measured over 24 hours at intervals of 1-2 hours. The statistical counting error was less than 3%. To check the operation of the counter, a standard in the form of RaD + RaE was measured over the course of of the total time of measurement of the silicon. After the decay of the silicon activity, its decay curve was constructed; as is seen from Fig. 1, it contained one component, corresponding to T = 2.6–2.7 hours. In addition, the absorption of the β-radiation of silicon in aluminum was measured. The energy of this radiation, determined by the Feather method, was found to be 1.47 MeV. These values are in good agreement with the literature data (^{3}) for the radioisotope Si^{31}, which attests to the radiochemical purity of the isolated silicon.

Fig. 1. Decay curve of silicon

The values of the cross section for the formation of Si^{31} ($\sigma_{Si^{31}}$) were calculated by the well-known formula (^{4}). To determine the proton flux, the outer aluminum foil was weighed and dissolved in 5 ml of a 50% HCl solution. Active portions of this solution (usually 0.15 ml) were deposited on tracing-paper backings, and their activity was measured under the same conditions as the activity of Si^{31}. The proton flux was calculated from the activity of Na^{24} formed by the reaction $Al^{27}(p, 3pn)Na^{24}$. The cross section of this reaction is equal to $(10.8 \pm 1.1) \cdot 10^{-27}$ cm^2 over a broad interval of proton energies (^{5}). In calculating $\sigma_{Si^{31}}$, this value was taken equal to 10^{-26} cm^2. In calculating $\sigma_{Si^{31}}$, the content of Si^{30} in the natural mixture of silicon isotopes was taken into account.

Results. The results obtained in the work for the value of $\sigma_{Si^{31}}$ at various proton energies are given in Table 1. From these data it follows that $\sigma_{Si^{31}}$ changes hardly at all in the region of proton energies 120–220 MeV, but increases considerably when their energy is increased from 220 to 680 MeV. To explain this dependence of the value of $\sigma_{Si^{31}}$ on proton energy, let us consider all possible reactions of Si^{31} formation under irradiation of silicon with protons.

Formation of Si^{31} in the spallation of impurities in silicon. Activation-analysis data showed the presence in the irradiated silicon of impurities of Cu, Zn, and Ga in an amount of about 10^{-4}%. In their spallation the yield of Si^{31}

should not exceed $1 \cdot 10^{-33}$ cm^2 and therefore cannot make a significant contribution to the found value of $\sigma_{\mathrm{Si}^{31}}$. The impurities K and Ca were not determined, but their presence (even about 0.1%) cannot account for the increase in the yield of Si^{31} with increasing proton energy, since the spallation cross section does not change in the above-mentioned energy interval.

Reaction with secondary deuterons and neutrons. The reaction with secondary deuterons $\mathrm{Si}^{30}(d,p)\mathrm{Si}^{31}$ undoubtedly must play a significant role in the formation of Si^{31}. Reactions with secondary deuterons have not yet been studied, but there is reason to believe that the secondary (d,p) reaction should have a cross section of the same order as the reaction with secondary α-particles (α,n). This follows, first, from the fact that the cross section of the (α,n) reaction is practically the same as that of the (d,p) reaction at their energy of 10–15 MeV, which, according to the data of work (6), corresponds to the maximum of the energy spectrum of α-particles (and, apparently, deuterons) evaporated from Ag and Br nuclei excited to 170 MeV. For example, the cross section of the reaction $\mathrm{Ni}^{60}(\alpha,n)\mathrm{Zn}^{63}$ is equal to $2 \cdot 10^{-25}$ cm^2 (7), while the cross section of the reaction $\mathrm{Cu}^{63}(d,p)\mathrm{Cu}^{64}$ is $1.5 \cdot 10^{-25}$ cm^2 (8).

Second, the number of secondary deuterons, as follows from the theoretical calculations of Le Couteur (9), is only 2–2.5 times smaller than the number of α-particles evaporated from nuclei with $A = 100$ at an excitation energy of 170 MeV.

It has been established by many investigators (10,11) that the cross section of the secondary (α,n) reaction is equal to $(3 \div 9) \cdot 10^{-29}$ cm^2 and depends little on the atomic number of the irradiated nucleus. The good agreement of the value of $\sigma_{\mathrm{Si}^{31}}$ at an energy

protons of 120 MeV with this value indicates the formation of Si^{31} by reaction with secondary deuterons at this proton energy. It should be noted, however, that the cross section of the secondary reaction (α, n) depends only slightly on the energy of the bombarding protons. For example, the cross section of the reaction $\mathrm{Cu}^{63}(\alpha, \mathrm{n})\mathrm{Ga}^{66}$ at a proton energy of 190 MeV is equal to $2.4 \cdot 10^{-29}$ cm^2, and at a proton energy of 480 MeV it is $3.1 \cdot 10^{-29}$ cm^2 (1). Therefore the considerable increase in $\sigma_{\mathrm{Si}^{31}}$ with increasing proton energy cannot be explained by the formation of Si^{31} through the secondary reaction $\mathrm{Si}^{30}(\mathrm{d, p})\mathrm{Si}^{31}$.

Table 1

E_p, MeV	$\sigma_{\mathrm{Si}^{31}}$ (10^{-28} cm^2), found	$\sigma_{\mathrm{Si}^{31}}$ (10^{-28} cm^2), average	$\sigma_{\mathrm{Si}^{30}}(p,\pi^+)\mathrm{Si}^{31}$ (10^{-28} cm^2), average
120	0.60	0.56	
120	0.52	0.56	
220	0.54	0.59	0.03
220	0.55	0.59	0.03

Fig. 2. Dependence of the cross section of the reaction Si^{30}(p, π^+)Si^{31} on proton energy

Figure 2: Fig. 2. Dependence of the cross section of the reaction Si^{30}(p, π^+)Si^{31} on proton energy

E_p, MeV	$\sigma_{Si^{31}}$ (10^{-28} cm^2), found	$\sigma_{Si^{31}}$ (10^{-28} cm^2), average	$\sigma_{Si^{30}}(p, \pi^+)Si^{31}$ (10^{-28} cm^2), average
220	0.67	0.59	0.03
340	0.85	0.78	0.22
340	0.72	0.78	0.22
480	1.31	1.24	0.68
480	1.17	1.24	0.68
660	1.87	1.74	1.18
660	1.60	1.74	1.18

The contribution of the reaction with secondary neutrons Si^{30}(n, γ)Si^{31} is negligibly small. The cross section of this secondary reaction can be estimated by comparing the magnitudes of the cross sections of the reactions (α, n), (n, γ), and the secondary reaction (α, n). If one takes into account the above value for the cross section of (α, n) reactions, the value of the cross section of the (n, γ) reaction, which in the region of nuclei under study will be equal to $1 \cdot 10^{-27}$ cm^2 for neutrons with energy $\simeq 1$ MeV ([12]), and the ratio of the number of evaporated neutrons and α-particles, equal to 2.5 at an excitation energy of 170 MeV ([10]), then the cross section of the secondary (n, γ) reaction for silicon will be no greater than $1 \cdot 10^{-30}$ cm^2.

Reaction Si^{30}(p, π^+)Si^{31}. If from the values of $\sigma_{Si^{31}}$ one subtracts the value $0.56 \cdot 10^{-28}$ cm^2, corresponding to the secondary reaction Si^{30}(d, p)Si^{31}, then this difference will apparently correspond to the cross section of the reaction Si^{30}(p, π^+)Si^{31} (Table 1). Consideration of the latter values indicates a very large increase in the cross section of this reaction with increasing energy of the incident protons. The cross section increases by a factor of 22 in the energy interval from 220 to 480 MeV. This change in the cross section is in good agreement with the increase in the cross section for the formation of π^+ mesons on carbon with increasing proton energy ([13]). According to these data, the yield of π^+ mesons at an angle of 90° increases by a factor of 25 when the proton energy is increased from 240 to 440 MeV. Such agreement is evidence of the reliability of the reaction Si^{30}(p, π^+)Si^{31}.

Fig. 2. Dependence of the cross section of the reaction Si^{30}(p, π^+)Si^{31} on proton energy

The curve of the dependence of the cross section of this reaction on proton energy (Fig. 2) made it possible to estimate the value of its threshold. The value found for the threshold, $\simeq$ 200 MeV, corresponds to the threshold for meson production for nuclei of medium atomic weight (^{14}).

All that has been stated above indicates that, at high energies of the bombarding particles, the (p, π^+) reaction is present, a characteristic feature of which is the emission of π^+ mesons possessing high energy. In this reaction the incident proton transfers all its energy to the nucleus, which is expended only on the formation of the π^+ meson and the kinetic energy of the latter. Therefore the cross section of the reaction Si^{30}(p, π^+)Si^{31} can give an estimate of the yield of π mesons with maximum energy at a given proton energy in the interaction of protons with silicon nuclei.

An attempt to detect by the radiochemical method the (p, π^+) reaction on bo-

heavier nuclei, for example germanium and bismuth, did not lead to successful results, owing to the significantly larger yield (approximately 100 times greater than $\sigma(p, \pi^+)$) of other radioactive isotopes of these elements, formed in various nuclear reactions.

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