SECONDARY REACTIONS OF ASTATINE PRODUCTION DURING BOMBARDMENT OF Bi AND Pb WITH 3 TO 10 BeV PROTONS

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The cross sections for At^{211} production by 3, 6, and 10-BeV proton bombardment of bismuth and lead are determined by a radiochemical method. For bismuth the cross sections are (1.5 ± 0.5), (2.0 ± 0.6), and $(1.0 \pm 0.3) \times 10^{-28}$ cm^2 and for lead (3.3 ± 1.0), (5.0 ± 1.5), and $(10 \pm 4) \times 10^{-30}$ respectively. The yields of At^{210}, At^{209}, At^{208}, and At^{207} from bismuth relative to the At^{211} yield at 10 BeV are determined by measuring the α spectra. The relative yields are 1.2 ± 0.72, 0.88 ± 0.08, 0.89 ± 0.47, and 0.53 ± 0.04 respectively. The At^{209} and At^{207} yields relative to the At^{211} yield in lead at the same proton energy are 1.87 ± 0.22 and 0.98 ± 0.08. The data obtained are compared with the cross sections for At^{211} production and the relative yields of the light astatine isotopes produced by bombarding the same targets with protons of lower energies, and also with other literature data on the fragmentation process.

THE investigation of the secondary reactions of production of astatine (Z = 85) by bombardment of bismuth (Z = 83) or lead (Z = 82) with high-energy particles is a convenient method of studying the features of the production of super-barrier α particles or lithium nuclei[1-5]. This is brought about, on the one hand, by the possibility of obtaining targets with the required degree of purity with respect to the contents of elements heavier than the original element, and on the other hand by the lesser difficulties with the chemical purification and detection of the α-active astatine isotopes. No less significant is the relatively low background of scattered α radiation, which facilitates reliable detection of small amounts of the product (≤ 10 decays/minute).

The purpose of the present investigation was to measure the cross sections of the secondary reactions in thick specimens and obtain information on the probabilities of the production of super-barrier α particles and lithium nuclei at proton energies of several BeV. The experiments were carried out with an internal proton beam of pulsed intensity $(1-3) \times 10^{10}$ protons from the proton synchrotron of the high-energy laboratory of the Joint Institute for Nuclear Research. The targets were plates of bismuth and lead measuring $70 \times 20 \times \sim 2.0$ mm and weighing 10—15 grams. Bismuth of high purity obtained from the State Institute for Rare Metals was employed[2] and the lead was especially purified by us[3].

The metal plates, wrapped in 50 μ aluminum foil which served as a monitor for the proton beam, were mounted on the plunger probe of the proton synchrotron. They were secured to the yoke of the probe in such a way that their plane was perpendicular to the proton beam. The plunger probe was used to bring the targets into the orbit of the beam at specified instants of time relative to the start of the acceleration cycle, thereby bombarding the targets with protons of the required energy (3, 6, and 10 BeV).

To reduce the accelerator operating time, the bismuth and lead specimens were irradiated simultaneously in most experiments. The irradiation times were from 1.5 to 3.0 hours. Measurements and plots of the total activity level of the bombarded specimens have shown that in our experiments both specimens were approximately equally irradiated, and that the greatest activity was in the forward edge of the specimen. Separate bombardment of the targets had the same effect as simultaneous bombardment.

Following the bombardment, the edges that had been clamped in the yoke of the probe were cut off and discarded, and the remaining material cut in two. Thus, two specimens of the materials, weighing 4—6 grams, were processed following each bombardment.

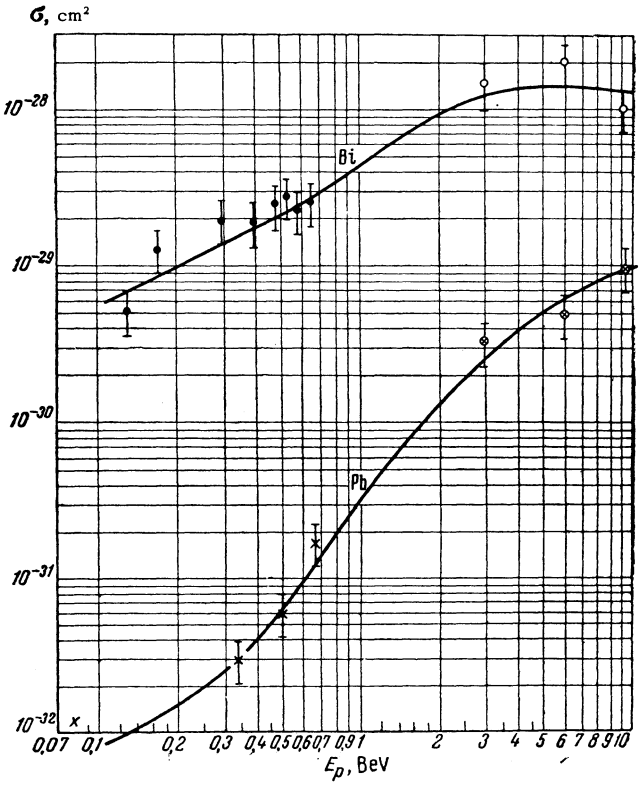
The methods for chemical separation of the astatine from the lead and from the bismuth were the same as in [2,3,5]. Since heavier targets were

used, the chemical yield of the astatine was especially checked in our cases. At the indicated weight of the bismuth target, (65 ± 5)% astatine was separated in our experiments; in the case of lead the amount was 55 ± 4%, in agreement with [6].

The cross sections for the production of At^{211} and the relative yields At^{210}/At^{211}, At^{209}/At^{211}, At^{208}/At^{211}, and At^{207}/At^{211} were determined in the same way as previously described [1-3,5]. The absolute cross sections for the production of At^{211} in thick specimens were determined relative to the yield of Na^{24} from an aluminum monitor. A value of 10 mb was assumed for the Na^{24} production cross section in the proton energy interval under consideration [7-9]. The yields of the other astatine isotopes relative to the yield of At^{211} were obtained from the measurements of their α spectra [5].

The separated astatine activities were small, ~ $10-10^2$ decays/min in the case of lead and one order of magnitude lower for bismuth. Nonetheless, the low background of the α detector (~ 0.3 decays/min) has made it possible in all cases to observe reliably a decrease in the At^{211} activity, lasting for three and more half-life periods of 7.3 hours each. In the measurements of the α spectra [1] the astatine compounds from bismuth were found to be sufficiently intense to be counted with a mechanical collimator (which corrected the α-spectra appreciably), and also to estimate the production of the α-active daughter isotopes Po^{210} and Po^{208}. The astatine compounds from lead were weak and were measured without mechanical collimators.

The cross sections for the production of At^{211} by 3—10 BeV protons are shown in the figure (light circles—bismuth, circles with crosses—lead). Each point is an average of two determinations. The accuracy with which the cross sections for the production of At^{211} are given is estimated, as in earlier work [1-3], at approximately ±30%. The figure also shows the cross sections for the production of this isotope from bismuth (full circles) and lead (crosses) at proton energies up to 660 MeV [2-3]. As seen from the figure, the yields of At^{211} from bismuth, and particularly from lead, increase with increasing proton energy. The yield of At^{211} from bismuth increases approximately 4—5 times on going from 660 MeV to 10 BeV. It is difficult to state for the time being whether the



cross section of this isotope has a maximum at 3—6 BeV or whether a plateau exists, starting with 3 BeV. In the case of lead specimens, the cross section of At^{211} increases more strongly, and on going from 660 MeV to 10 Bev the yield of this isotope increases approximately 60 times. It seems that at 6—10 BeV there is a tendency for the growth of the cross section to slow down.

The yields of the other astatine isotopes relative to the At^{211}, and their possible maximum errors, are shown in the table, which lists the relative yields obtained in the present investigation with 10 BeV protons and the previously obtained values [5] for 660-MeV protons. The relative yields of At^{210} and At^{208} were determined from the yields of the daughter isotopes Po^{210} and Po^{208}, and could be estimated only in the case of the bismuth target. The large errors in the determination of the relative yields of these isotopes, and also of At^{209} and At^{207} in the case of lead specimens, were due to the low activities of the measured compounds.

Comparing the relative yields of the different isotopes of astatine at proton energies of 10 BeV and 660 MeV, we see that in the case of bismuth they coincide for all the isotopes, within the limits of experimental error. In the case of lead, the relative yield of At^{209} agrees with the previous value, while that of At^{207} is approximately one and a half times larger. From these results we

[1] The measurements with the α spectrometer were performed together with B. N. Belyaev of the Radium Institute of the Academy of Sciences, to whom the authors express their gratitude.

Specimen	Yield relative to At^{211}				Proton energy
	At^{210}	At^{209}	At^{208}	At^{207}	
Bi	0.81±0.08 1.2 ±0.72	0.72±0.06 0.88±0.08	0.40±0.04 0.89±0.47	0.5±0.04 0.53±0.04	660 MeV 10 BeV
Pb	— —	1.43±0.43 1.87±0.22	— —	0.61±0.13 0.98±0.08	660 MeV 10 BeV

can conclude that even at 10 BeV no noticeable change occurs in the energy spectrum of the super-barrier α particles or lithium nuclei participating in the reaction. This agrees with the tendency noted earlier [5] for the lower proton energies.

It is curious that the increase in the yield of the secondary α particle capture by copper (Z = 29) and bismuth with increasing proton energy is practically the same. Turkevich and Sugarman [10] have found that as the proton energy is increased from 340 MeV to 2.2 BeV, the yield of gallium (Z = 31) from copper increases by a factor of 4. In our case, on the other hand, the yield of At^{211} from bismuth increased by 4—5 times for the same energy interval. The situation is somewhat different in the case of the yields of the secondary lithium capture by copper and lead. In the case of copper [10] the yield of the germanium isotopes (Z = 32) increases tenfold on going from 340 MeV to 2.2 BeV whereas in lead the yield increases by 20—100 times in the same interval, taking into account the possible errors. On the other hand, the previously noted increase in the cross section for the production of At^{211} from lead on going from 660 MeV to 10 BeV (~ 60 times) does not disagree with the increase in the yield of fragments with charge $Z \geq 4$ in emulsion [11] for approximately the same proton energy interval. The fragment yield in stars increased in the cited investigation by 40 times on going from 660 MeV to 9.0 BeV; the cross section for the production of stars with fragments accounted for about a factor of 10, and the multiplicity for the production of fragments in the stars at these energies was approximately 4. It follows therefore that the small increase in the yield of the secondary capture of lithium by copper [10] is apparently due to the great difficulty of observing the pure effect on such a light target element.

The absence of major changes in the energy spectra for super-barrier α particles or lithium nuclei on going over to an energy of 10 BeV makes it possible to estimate the over-all probability of production of super-barrier fragments from bismuth and lead at this energy. The cross section for the production of super-barrier α particles at the indicated energy is $\sim 1 \times 10^{-24}$ cm^2, whereas for lithium nuclei we obtain $(0.17—0.23) \times 10^{-24}$ cm^2. We take account here of the fact that in the secondary reaction of At^{211} production on bismuth, the produced super-barrier α particles are captured approximately once every 8×10^3 events (see [2]), whereas the similar reaction, the capture of lithium nuclei by lead, occurs once every $(1.8—2.4) \times 10^4$ events [3]. Since a 10-BeV proton interacts with the bismuth or lead nuclei with a cross section close to geometric ($\sigma_{geom} \sim 2 \times 10^{-24}$ cm^2), we find that the formation of super-barrier α particles occurs practically in every interaction between the proton and the nucleus, whereas the super-barrier lithium fragments are produced in approximately 20% of the interactions.

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148