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Author
Strom, E. Thomas.

Publication Date
1960-11-01
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THE CROSS SECTIONS FOR THE FORMATION
OF ASTATINE ISOTOPES MADE BY THE
BOMBARDMENT OF Bi²⁰⁹ WITH He³

E. Thomas Strom
(Master's Thesis)

November 1960
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OF ASTATINE ISOTOPES MADE BY THE
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THE CROSS SECTIONS FOR THE FORMATION
OF ASTATINE ISOTOPES MADE BY THE
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ABSTRACT

Bismuth-209 was bombarded with He^{3} on the Berkeley Heavy-ion linear accelerator. Cross sections for the formation of astatine isotopes were measured. The experimental cross sections are compared with theoretical cross sections, calculated using the Jackson model.

The results of this work are compared with those of other workers and proposals for further research are made.
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INTRODUCTION

In this work cross sections were measured for the formation of astatine isotopes in the bombardment of Bi$^{209}$ with He$^3$, using the Berkeley heavy-ion linear accelerator (Hilac). The agreement of the experimental cross sections with those predicted by the Jackson model for spallation reactions was thus checked.

Although He$^3$ was first accelerated many years ago, only recently has it been accelerated to energies above 20 Mev. Much of the work thus far has been done by Markowitz at the Berkeley Hilac, chiefly with the lighter elements. Therefore many other systems remained to be investigated.

There were several reasons for choosing Bi$^{209}$ as the target nucleus. Since 209 is the only bismuth isotope to appear in nature, the problem of a reaction product coming from a trace impurity of another bismuth isotope was nonexistent. Bismuth also vaporizes at a comparatively low temperature ($1490^\circ$C.), which simplified the making of targets. Also when He$^3$ combines with Bi$^{209}$ to form At$^{212}$, 5.45 Mev of energy is released. This means that one can give the At$^{212}$ nucleus a great deal of excitation energy at a relatively low bombarding energy.

A more important reason for bombarding Bi$^{209}$ was the possibility of comparing the results with earlier work done by Kelly$^1$ and by Ramler, Wing, Henderson, and Huizenga$^2$ in which Bi$^{209}$ was bombarded with alpha particles and deuterons. The differences in results between the deuterons and alpha particles and the He$^3$, which latter is intermediate in size and energy, promised to be interesting.

The Bi$^{209}$ was bombarded with He$^3$ particles of energies ranging from 22 to 31 Mev. Since the Coulomb barrier is 23.6 Mev, it was felt that
bombarding at energies lower than 22 Mev would result in little activity. The maximum bombarding energy available on the accelerator was 31 Mev.

In the range of bombarding energies used, one would expect the reactions to be described by the compound-nucleus theory of nuclear reactions. This theory, first proposed by Bohr \(^3\) can be stated in the following manner. Suppose the nuclear reaction \(x + X \rightarrow y + Y\) takes place. The target and residual nuclei are \(X\) and \(Y\), respectively, while the incoming and emitted particles are denoted by \(x\) and \(y\). According to the compound-nucleus theory, this reaction proceeds through an intermediate, \(I\), and really should be written as two equations, \(x + X \rightarrow I^*\) and \(I^* \rightarrow y + Y\), where the compound nucleus is obviously in an excited state. One can see that there is a striking analogy here with the activated-complex theory of chemical reactions. The equation \(x + X \rightarrow I^*\) describes the process by which the bombarding particle strikes the nucleus, losing its energy to several nucleons; this energy is distributed to the nucleus as a whole. The equation \(I^* \rightarrow y + Y\) describes the process in which this energy is again concentrated on one particular nucleon, and this nucleon is then emitted from the nucleus.

When such a compound nucleus is formed, its lifetime is hypothesized to be \(10^{-15}\) to \(10^{-18}\) sec. This is long compared to the amount of time necessary for an ordinary bombarding particle to traverse the nucleus (of the order of \(10^{-21}\) sec). During this time, the energy brought in is spread throughout the nucleus, and the nucleus has no "memory" of the way in which it was formed. A compound nucleus can be formed in two different ways, but as long as the nuclei are alike in charge, mass, angular momentum, and excitation energy, one cannot distinguish between them.

This above-mentioned fact provided still another comparison for this research. The compound nucleus \(\text{At}^{212}\) was also being investigated by Gordon.\(^4\) His method of formation was the bombardment of \(\text{Pt}^{198}\) with \(\text{N}^{14}\). Although these compound nuclei differed greatly as to excitation energy and angular momentum, something interesting still might be learned by comparison.

If it is known that a reaction in which particle \(A\) is emitted goes by a compound-nucleus mechanism, the cross section for the reaction, \(\sigma_A\), can be said to be equal to the probability of the reaction, \(P_A\), times the
cross section for compound-nucleus formation, \( \sigma_C \). For experiments in which
the reactions are likely to go by the compound-nucleus mechanism, one can
calculate theoretical cross sections to compare with the experimental ones,
provided the probability of the reaction and the cross section for compound-
nucleus formation are known. Compound-nucleus cross sections have been
calculated by using the square-well or diffuse-well models. Reaction proba-
bilities in the case where the emitted particles are neutrons can be calcu-
lated by using the Jackson model.

To calculate compound-nucleus cross sections, the square-well model
of Blatt and Weisskopf was used. The assumptions, as summarized in and
directly quoted from a paper by Thomas, are the following:

1. Both the target nucleus and the projectile nucleus are spheres
having well defined surfaces and radii, \( R_i = r_0 (A_i)^{1/3} \), where \( A_i \) is the
mass number of the nucleus in question.

2. The real part of the potential energy of the system is given
by
\[
V = \frac{Z_1 Z_2 e^2}{r} + \frac{\hbar^2}{2\mu} \frac{l(l + 1)}{r^2}, \text{ for } r > R_1 + R_2,
\]
\[
V = \frac{\hbar^2 K_0^2}{2\mu}, \quad \text{for } r < R_1 + R_2
\]
\[
K_0 = 10^{13} \text{ cm}^{-1}.
\]

Here \( Z_1 \) and \( Z_2 \) are the atomic number of target and projectile, \( r \) is the
distance between the centers of the two particles, \( \mu \) is the reduced mass
of the system, and \( l \) is the orbital angular momentum of the system.

3. There is an interaction radius, \( R = R_1 + R_2 \), such that for
\( r > R \) there is no nuclear interaction, and for \( r < R \), there is a strong
nuclear interaction causing the incident particle to be absorbed. Since
incident particles with \( r < R \) are not re-emitted, it is possible to
represent the wave function of the incident particle within the nucleus as
an incoming wave; i.e.,
\[
u \sim e^{-iKr} \text{ for } r < R
\]
where \( K \) is the wave number of the particle inside the nucleus.

Using these assumptions, Blatt and Weisskopf derived the following
formula:
\[
\sigma = \pi k^2 \sum_{l=0}^{\infty} \frac{4 k R S_l}{\Delta_l^2 + (k R + S_l)^2},
\]
where
\[
S_l = k R \frac{1}{F_l^2 + G_l^2},
\]
\[
\Delta = k R \frac{F_l F_l' + G_l G_l'}{F_l^2 + G_l^2},
\]
\[
K = (k^2 + k^2_0)^{1/2},
\]
\[\kappa = \frac{i}{k},\]
\[
F_l' = \frac{dF}{d(kr)}, \quad G_l' = \frac{dG}{d(kr)}.
\]

Here \(F \) and \(G \) are Coulomb functions -- that is, the ingoing and outgoing spherical waves -- and \(k\) is the wave number of the incident particle outside the nucleus. The Coulomb functions and their derivatives are evaluated for \(r = R\).

The compound-nucleus cross sections for \(\text{He}_3 + \text{Bi}^{209}\) were calculated by Thomas on an IBM-650 computer. An interaction radius \(R\) of 1.5 [\((209)^{1/3} + (3)^{1/3}\)] fermis was used.

The probabilities of neutron evaporation were calculated using the Jackson model for spallation reactions.\(^7\) The assumptions in this model are that for heavy nuclei only neutrons will be evaporated and the neutron energy spectrum will be \(\varepsilon \exp(-\varepsilon/T)\) where \(\varepsilon\) is the kinetic energy of the evaporated neutron and \(T\) is the nuclear temperature (assumed constant).

The probability that a nucleus with excitation energy \(E\) will emit exactly \(x\) neutrons is
\[
P(E, x) = I(\Delta_x, 2x - 3) - I(\Delta_{x+1}, 2x - 1),
\]
where \(I(z,n)\) is Pearson's incomplete gamma function,
\[
I(z,n) = \frac{1}{n!} \int_0^z x^n e^{-x} dx.
\]
and we have $\Delta_x = (E - \sum_{i=1}^{x} B_i)/T$. Here $B_i$ is the binding energy of the $i$th neutron. The binding energies of the neutrons were obtained from Cameron's semi-empirical mass formulas.\footnote{8}

Qualitatively one can see that the latter half of the probability formula shows the effect of $x+1$ neutrons being evaporated and is the means by which the theoretical cross sections show the customary sharp dropoff as the probability of one more neutron being evaporated becomes greater. The nuclear temperature is the sole adjustable parameter if one uses the square-well model with $r_0$ of 1.5 fermis. Changing the nuclear temperature both changes the absolute magnitude of the cross section and shifts the peak of the cross section. In cases where nuclear fission can occur, the Jackson model can also be modified to account for fission probabilities.\footnote{9}

The above-mentioned formulas thus give one all the tools necessary to calculate theoretical neutron-evaporation cross sections to compare with experimental cross sections.
II. EXPERIMENTAL PROCEDURES

A. Target Preparation

The targets were prepared by evaporating chemically pure Bi\textsuperscript{209} upon 1-mil-thick aluminum. A tungsten filament was placed between two electrodes, and the Bi\textsuperscript{209} was placed upon the filament. The whole apparatus was then covered with a bell-jar. At the top of the inside of the bell-jar was taped a piece of 10-mil-thick aluminum with a square of known area removed. A section of 1-mil aluminum was placed between the 10-mil aluminum and the top of the bell-jar. The bell-jar was then evacuated by means of a diffusion pump to a pressure of less than 1 micron, and the filament was heated very slowly until the bismuth began to vaporize. The entire vaporization was carried out over a period of 30 min. It was important not to heat the bismuth very quickly, as this could cause splattering of liquid bismuth upon the 1-mil aluminum. The end result was that a known area of 1-mil aluminum was coated. The thickness of the Bi\textsuperscript{209} was determined by the difference in weight of the section of 1-mil aluminum before and after vaporization. The great advantage of this method is that no inaccuracies are introduced into the area measurement because of the presence of tape. The 1-mil aluminum was placed high enough above the filament that inhomogeneities between the center and the edge of the foil were minute. The thicknesses of the Bi\textsuperscript{209} targets used were from 50 to 150 $\mu$g/cm\textsuperscript{2}, which constitutes a thin target. For targets on which a chemical separation was to be performed, the thicknesses were increased.

B. Experimental Arrangement at the Accelerator

The He\textsuperscript{3} was accelerated at the Berkeley Hilac. This accelerator can accelerate particles to $10.4 \pm 0.2$ Mev per nucleon. The gas used was a mixture of from 4 to 12% He\textsuperscript{3} in He\textsuperscript{4}. The He\textsuperscript{3} was separated from the He\textsuperscript{4} by its charge-to-mass ratio. It was accelerated as a singly-charged particle, and the second electron was removed by a 1/4-mil aluminum stripping foil before the particle struck the target.

The target holders used were of two types, an aluminum helium-cooled holder (see Fig. 1) and a copper water-cooled holder (see Fig. 2). The stacked-foil technique was used; that is, the targets were stacked on
Fig. 1. Helium-cooled tag assembly (general).
Fig. 2. Water-cooled tag assembly (general).
top of each other, separated by various thicknesses of aluminum energy-
degrading foils. In addition, the targets were separated from each other
by a thick aluminum plate (a "Gordon") with a circle of known and constant
area cut from the center. Each "Gordon" was thick enough to stop the beam,
thus insuring that each target foil was bombarded on the same area.

The target holders were placed behind a steering magnet, and the
beam was passed through either a 3/8-in. or 1/4-in. collimator. The
entire target assembly served as a Faraday cup to measure the amount of
beam. Whenever possible, the Faraday cup was shielded from stray electrons
by magnets. On the occasions when no shielding was used, corrections
could be made by means of the monitor reaction.

The reaction used as a monitor was \( {^{27}}\text{Al}(^{3}\text{He},^{4}\text{He},2\text{p}){^{24}}\text{Na} \), for which
the excitation function had been obtained earlier by Markowitz. The foil
was always placed at 29.0 to 29.6-Mev bombarding energy. Since in this
region the cross section increased rather steeply, it was necessary to
know the bombarding energy more accurately than was actually feasible;
however, by means of the monitor reaction, it would be possible to detect
any drastic errors in beam measurement. The fact that on some earlier
work occasional large errors occurred in beam measurement made the use of
a monitor reaction advisable.

In every case all stripping, degrading, and target-backing foil
thicknesses were obtained by weighing known areas.

C. Counting Techniques

The amounts and energies of the astatine and polonium isotopes
formed during the bombardment were determined using an ionization chamber
and a 50-channel pulse-height analyzer. Standards were counted before
each experiment in order to be sure which channel corresponded to a
certain energy. The geometry of each counter was determined anew with
each experiment. A standard was counted on an alpha counter of known
constant geometry and then counted on the pulse-height analyzer. Over a
period of six months the geometry varied by only four parts in 400. Back-
ground was determined before each experiment, and background corrections
were made for the \( ^{209}\text{Bi}(^{3}\text{He},n){^{211}}\text{At} \) and \( ^{209}\text{Bi}(^{3}\text{He},2n){^{210}}\text{At} \) reactions.
The monitor foil was counted on the third shelf of a beta counter for a period of 24 hr. The efficiency of the counter was determined by comparison of the activity of a uranium standard counted on a beta counter of known constant efficiency with that obtained by using the counter in question. The half-life obtained was always within 10% of that of Na$^{24}$.

D. Chemical Procedures

Usually the foils were counted directly, but in order to determine the At$^{210}$ cross section, an astatine separation had to be carried out. The astatine was separated by a double volatilization method. The target foil was crumpled, placed in a quartz cup, and then heated with a methane-oxygen blowtorch. The astatine vapor condensed on an aluminum disk at the bottom of a water-cooled "cold finger." The aluminum disk was then placed in another quartz cup and heated gently with a microburner, and the astatine vapor condensed on a platinum dish at the end of a "cold finger." During the first vaporization a great deal of polonium is also vaporized; Gordon has shown that the second vaporization effectively removes all polonium. As a check, an alpha pulse-height analysis showed that shortly after the chemical procedure, essentially no Po$^{210}$ was present -- which would introduce great error.

E. Assignment of Energies to the Target Foils

The energy at which each foil was bombarded was determined by using a theoretical range-energy curve for He$^3$ in aluminum. It was assumed that the He$^3$ particles were at full energy (31.2 Mev) when striking the stripping foil and that degradation of the beam energy in the thin bismuth targets was negligible.

The range-energy curve for He$^3$ in aluminum was calculated by Markowitz using the experimental proton range-energy relationships of Bichsel. The range of a 30-Mev He$^3$ ion was taken as three-fourths that of a 10-Mev proton.
III. EXPERIMENTAL RESULTS

A. Determination of Cross Sections

When the amount of activity of each isotope at the end of the bombardment is obtained and corrected for the alpha branching ratio and the efficiency of the counter, the number of disintegrations per minute at the end of the bombardment is determined.

The formula for the cross section, \( \sigma \), for a given reaction is

\[ \sigma = \frac{N}{nIt} \]

where \( N \) is the number of atoms of product formed during the bombardment, \( n \) is the number of target nuclei per square centimeter, and \( It \) is the number of particles striking the target.

Since the number of disintegrations per minute is given by

\[ \frac{d}{m} = \frac{N}{t} \left(1 - e^{-\lambda t}\right) \]

where \( t \) is the length of the bombardment and \( \lambda \) is the decay constant of the product, the cross section formula can be written \( \sigma = \frac{(d/m)}{(1-e^{-\lambda t})nI} \). For the case in which the half life of the product is long compared to the bombardment time, as was the case in most of the bombardments, we can use \( \sigma = \frac{(d/m)}{\lambda nIt} \).

B. The Reaction Bi\(^{209}\)(He\(^3\),n)At\(^{211}\)

Astatine-211 has a half life of 7.5 hr and decays 40.9\% by alpha emission and 59.1\% by electron capture. The alpha decay energy is 5.86 Mev. The electron capture product, Po\(^{211}\), decays by alpha emission with a half life of about 0.5 sec. Its alpha decay energy is 7.41 Mev. When the foils are counted it then follows that the At\(^{211}\) peak will be accompanied by another peak, falling at the energy range for Po\(^{211}\), but with a half life equal to that of At\(^{211}\). As a general practice, the energy spread of the pulse-height analyzer was set so that the Po\(^{211}\) peak appeared in the integrating channel. This eliminated the necessity of graphical integration, although on various occasions the amount of At\(^{211}\) determined by use of the integrating channel was checked by graphical integrations. The results always agreed to within 5 to 10\%. One source of error in the integrating-channel method but not in the graphical integration is the presence of lower-energy counts in coincidence.
The excitation function obtained is given in Table I and is shown graphically in Fig. 3. There is a sharp increase in cross section from 23 to 25 Mev, and throughout the rest of the energy range the cross section seems to be reasonably constant within experimental error.

Table I
Cross sections for At²¹¹ formation at various bombarding energies

<table>
<thead>
<tr>
<th>He³ energy (Mev)</th>
<th>Run No.</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4</td>
<td>2</td>
<td>1.16</td>
</tr>
<tr>
<td>29.1</td>
<td>1</td>
<td>1.35</td>
</tr>
<tr>
<td>29.1</td>
<td>4</td>
<td>1.38</td>
</tr>
<tr>
<td>27.1</td>
<td>1</td>
<td>1.31</td>
</tr>
<tr>
<td>25.9</td>
<td>2</td>
<td>1.15</td>
</tr>
<tr>
<td>25.4</td>
<td>4</td>
<td>1.03</td>
</tr>
<tr>
<td>25.2</td>
<td>3</td>
<td>1.02</td>
</tr>
<tr>
<td>24.8</td>
<td>1</td>
<td>1.09</td>
</tr>
<tr>
<td>24.7</td>
<td>2</td>
<td>0.91</td>
</tr>
<tr>
<td>23.6</td>
<td>1</td>
<td>0.77</td>
</tr>
<tr>
<td>22.8</td>
<td>3</td>
<td>0.66</td>
</tr>
</tbody>
</table>

C. The Reaction Bi²⁰⁹(He³,2n)At²¹⁰

Astatine-210 has a half life of 8.3 hr, decaying only 0.17% by alpha emission and 99% by electron capture. Alpha particles of three different energies are seen: a 5.52-Mev alpha (32%), a 5.44-Mev alpha (31%), and a 5.36-Mev alpha (37%).

Although it appears that these three peaks are present during pulse-height analysis, any attempts to obtain the At²¹⁰ cross section from them result in answers in error by orders of magnitude. The number of counts obtained is usually so low as to have a great statistical error, and a large percentage of those counts undoubtedly come from At²⁰⁹ alpha particles, degraded in energy by passing through the bismuth.
Fig. 3. Cross section vs energy for the reaction \( \text{Bi}^{209}(\text{He}^3,n)\text{At}^{211} \).

Experimental excitation function

- Run I ○
- Run II □
- Run III △
- Run IV ▽
Another method attempted was to allow the astatine activity to die away and to count the Po\textsuperscript{210} grown in from the At\textsuperscript{210}. Polonium-210 has a 138.4-day half life, decaying by emitting 5.30-Mev alpha particles. For this method to work, however, the At\textsuperscript{210} must be the only source of Po\textsuperscript{210}. This neglects the possibility of the Bi\textsuperscript{209}(He\textsuperscript{3};p,n)Po\textsuperscript{210} or Bi\textsuperscript{209}(He\textsuperscript{3},d)Po\textsuperscript{210} reaction and the Bi\textsuperscript{209}(He\textsuperscript{3},n)Bi\textsuperscript{210} reaction. The latter product decays by beta emission with a 5-day half life to Po\textsuperscript{210}. Pulse-height analysis showed the presence of Po\textsuperscript{210} shortly after bombardment, indicating that the Bi\textsuperscript{209}(He\textsuperscript{3},d)Po\textsuperscript{210} or Bi\textsuperscript{209}(He\textsuperscript{3};p,n)Po\textsuperscript{210} reaction did take place.

The method finally used was to separate the astatine activity chemically, let it decay, and then count the Po\textsuperscript{210}. The greatest problem was to find a good method of determining chemical yield. The best tracer, At\textsuperscript{211}, was a product of the reaction. It was decided to do a chemical separation on a foil and to obtain the chemical yield by comparing the uncorrected cross section for formation of At\textsuperscript{209} and At\textsuperscript{211} with that of a foil bombarded at 0.2 Mev lower energy during the run. This method involves great uncertainties. From statistical considerations, the At\textsuperscript{209} cross section would appear to be the best for obtaining the chemical yield. But as will be shown later, the excitation function is sharply increasing or decreasing over the energy range involved, which makes extrapolation hazardous. The At\textsuperscript{211} cross section is constant over a greater range, but it is more prone to statistical errors, and is sharply increasing in the region of greatest interest.

As is shown in Table II and graphically in Fig. 4, the excitation function for the reaction Bi\textsuperscript{209}(He\textsuperscript{3},2n)At\textsuperscript{210} leaves much to be desired. The errors are of such magnitude as to make it difficult to say anything about the shape of the curve, consequently only the experimental points are shown. A theoretical excitation function for the reaction using the Jackson model with a nuclear temperature of 1 Mev is also shown in Fig. 4.
Fig. 4. Cross section vs energy for the reaction $\text{Bi}^{209}(\text{He}^3, 2n)\text{At}^{210}$.

Theoretical excitation function ———
Experimental excitation function:
Run II □ Run III △ Run IV ▼
Table II
Cross sections for At$^{210}$ at various bombarding energies

<table>
<thead>
<tr>
<th>He$^3$ energy (Mev)</th>
<th>Run No.</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.3</td>
<td>4</td>
<td>1.32</td>
</tr>
<tr>
<td>26.1</td>
<td>2</td>
<td>2.49</td>
</tr>
<tr>
<td>25.6</td>
<td>4</td>
<td>0.99</td>
</tr>
<tr>
<td>25.5</td>
<td>3</td>
<td>0.86</td>
</tr>
<tr>
<td>23.0</td>
<td>3</td>
<td>1.36</td>
</tr>
</tbody>
</table>

D. The Reaction Bi$^{209}$(He$^3$,3n)At$^{209}$

Astatine-209 has a half life of 5.5 hr and decays 5% by alpha emission and 95% by electron capture. The energy of the alpha particle is 5.65 Mev. As is seen in Table III and on the graph in Fig. 5, this isotope is formed in greatest abundance during bombardment. The theoretical excitation function is also shown on the graph. The cross sections for the formation of this isotope could be determined with the greatest statistical accuracy because of the large amounts of activity always present. From another standpoint, however, the At$^{211}$ cross sections were more accurate. The alpha branching ratio for At$^{211}$ is known to within three significant figures while the alpha branching ratio for At$^{209}$ is known to be only approximately 5%. An error of 0.5 to 1% in this 5% would mean an error of 10 to 20% in the cross section.

The Jackson-model cross section was calculated using a nuclear temperature of 1 Mev.
Fig. 5. Cross section vs energy for the reaction $\text{Bi}^{209}(\text{He}^3,3\text{n})\text{At}^{209}$.

- Theoretical excitation function
- Experimental excitation function

- Run I
- Run II
- Run III
- Run IV
Table III
Cross sections for \(^{209}\text{At}\) at various bombarding energies

<table>
<thead>
<tr>
<th>He(^{3}) energy (Mev)</th>
<th>Run No.</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4</td>
<td>2</td>
<td>347</td>
</tr>
<tr>
<td>29.1</td>
<td>1</td>
<td>345</td>
</tr>
<tr>
<td>29.1</td>
<td>4</td>
<td>339</td>
</tr>
<tr>
<td>27.1</td>
<td>1</td>
<td>384</td>
</tr>
<tr>
<td>25.9</td>
<td>2</td>
<td>264</td>
</tr>
<tr>
<td>25.4</td>
<td>4</td>
<td>273</td>
</tr>
<tr>
<td>25.2</td>
<td>3</td>
<td>273</td>
</tr>
<tr>
<td>24.8</td>
<td>1</td>
<td>256</td>
</tr>
<tr>
<td>24.7</td>
<td>2</td>
<td>232</td>
</tr>
<tr>
<td>23.6</td>
<td>1</td>
<td>157</td>
</tr>
<tr>
<td>22.8</td>
<td>3</td>
<td>126</td>
</tr>
</tbody>
</table>

E. The Reaction Bi\(^{209}\)(He\(^{3}\),4n)At\(^{208}\)

Astatine-208 has two isomers, one of which decays by electron capture with a 6.3-hr half life. The other decays 99.5% by electron capture and 0.5% by emission of a 5.66-Mev alpha particle. The half life of this isomer is 1.6 hr. The energy of this alpha particle was too close to the energy of the 5.65-Mev alpha particle for the activities to be separated by pulse-height analysis. Fortunately the half lives of \(^{209}\text{At}\) and \(^{208}\text{At}\) were sufficiently different to allow the decay curves to be resolved into two components.

What is present of the excitation function of \(^{208}\text{At}\) is shown in Table IV and in Fig. 6. The Jackson-model calculation using a nuclear temperature of 1 Mev is also shown in Fig. 6. The experimental cross section is for the formation of the 1.6-hr isomer alone.
Fig. 6. Cross section vs energy for the reaction
\[ \text{Bi}^{209} \rightarrow (\text{He}^3, 4\text{n}) \text{At}^{208} \]

- Theoretical excitation function
- Experimental excitation function:
  - Run I 
  - Run II 
  - Run IV
Table IV.
Cross sections for $\text{At}^{208}$ formation at various bombarding energies

<table>
<thead>
<tr>
<th>He$^3$ energy (Mev)</th>
<th>Run No.</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4</td>
<td>2</td>
<td>178</td>
</tr>
<tr>
<td>29.1</td>
<td>4</td>
<td>165</td>
</tr>
<tr>
<td>29.1</td>
<td>1</td>
<td>202</td>
</tr>
</tbody>
</table>

F. Determination of Errors

Errors were calculated for each point on the excitation function. These errors were determined by the average deviation from the line extrapolated to the end of the bombardment. In general, the percent error was inversely proportional to the counting statistics. Thus the $\text{At}^{209}$ points were less in error than the $\text{At}^{211}$ points, which in turn were less in error than the $\text{At}^{208}$ points. The sole exception was the $\text{At}^{210}$ points which, although counted to good statistics, had great uncertainties in the determination of chemical yield. Also, the extrapolation to the end of the bombardment in the case of $\text{At}^{210}$ had to be carried out with few experimental points.
IV. DISCUSSION OF RESULTS

When Jackson-model calculations were made of the Bi\(^{209}\)(He\(^3\),n)At\(^{211}\) reaction, it was found that this reaction peaked in the region around 10 Mev and had a negligible cross section in the energy range of the experiments. As can be seen in Fig. 3, the experimental results show that this reaction has a small but noticeable cross section. The excitation function seems to increase fairly rapidly in the region from 23 to 25 Mev and then to remain reasonably constant at higher energies. The shape of this excitation function together with the Jackson-model calculations lead one to speculate that the Bi\(^{209}\)(He\(^3\),n)At\(^{211}\) reaction may go by a direct-interaction mechanism. The sharp increase around 23 to 25 Mev may well be a barrier effect, since in this region the probability of the He\(^3\) particles approaching the bismuth nucleus increases rapidly.

The form of the direct-interaction mechanism will be a matter of speculation until further experiments are done. One could postulate a mechanism similar to stripping from a deuteron except in this case two protons would be removed. Angular distribution work would throw light upon this mechanism.

The possible presence of this direct interaction can lead one to certain conclusions as to the likelihood of other direct interactions. One would expect the stripping of two protons to have the lowest cross section of the possible stripping reactions due to polarization effects. It then follows that the stripping of a proton, neutron, or deuteron would have a higher cross section. Since it appears that Po\(^{210}\) is present other than as a result of At\(^{210}\) decay, it seems that the stripping of one proton may occur. Markowitz at present is investigating the reaction Bi\(^{209}\)(He\(^3\),2p) Bi\(^{210}\), which will tell something about the probability of the stripping of one neutron.

Since the Bi\(^{209}\)(He\(^3\),2n)At\(^{210}\), Bi\(^{209}\)(He\(^3\),3n)At\(^{209}\), and Bi\(^{209}\)(He\(^3\),4n) At\(^{208}\) reactions are all presumably of the compound-nucleus type, they will be discussed together. Figures 7, 8, and 9 show the experimental results of Ramler, Wing, Henderson, and Huizenga with the system Bi\(^{209}\) + He\(^4\) and Bi\(^{209}\) + d and of Gordon with the system Pt\(^{198}\) + N\(^{14}\). The solid lines in these graphs give the Jackson-model cross sections. The nuclear temperature used by Gordon is 1.3 Mev, that used by Ramler et al. is 1.5 Mev. The
Fig. 7. Excitation functions of deuterons on Bi$^{209}$ (from Ramler, Wing, Henderson, and Huizenga).
Fig. 8. Excitation functions of alpha particles on Bi$^{209}$
(from Ramler, Wing, Henderson, and Huizenga).
Fig. 9. Excitation functions of $^N_{14}$ on Pt$^{198}$ (from Gordon).
compound nuclei involved are $^{213}\text{At}$ and $^{212}\text{At}$. Since the results of Ramler et al. agree well with those of Kelly, Kelly's results are not shown. The obvious difference between these results and the results described herein are the good agreements obtained with Jackson-model calculations by Gordon and by Ramler et al. The excitation function for $^{209}\text{At}$, for example, is about 30% below that calculated from the Jackson model.

The important thing to note in explaining this discrepancy is that in fitting experimental results to Jackson-model curves, discrepancies are the rule rather than the exception. Jackson's model used the results of Monte Carlo calculations by McManus, Sharp, and Gellmann and by McManus and Sharp. These calculations were made for proton bombardments; thus one would not expect very accurate results for bombardment with heavier ions. Jackson-model calculations are generally used to predict the shapes of excitation functions rather than the absolute magnitude, and they do predict the shape of the $^{209}\text{At}$ curve rather well.

Errors also could arise from the use of Cameron's binding energies. The neutron binding energies can be in error in some cases by as much as 0.5 Mev.

Closer examination of the manner in which Ramler et al. obtained their theoretical cross sections show some important differences from the way in which the theoretical cross sections were arrived at in this work. They used the neutron binding energies of Wapstra and Huizenga rather than those of Cameron. More important, the compound-nucleus cross section they used was experimental, obtained by summing the experimental neutron evaporation cross section, whereas the compound-nucleus cross sections used in the Jackson-model calculations for this work were arrived at independently, using the square-well model described earlier. The use of an experimental compound-nucleus cross section can be said to "remove one degree of freedom," so it is not at all surprising that the results of Ramler et al. fit the Jackson-model curve so well. In all fairness, it should be pointed out that these experimental cross sections fit those calculated by the square-well model fairly closely.

At first glance the discrepancies in this work between Jackson-model calculations and theory become more serious when Gordon's work is considered. His work was done with the same compound nucleus, although it had greater excitation energy and angular momentum. Because of this,
the assumption that only neutrons are evaporated becomes poor because of
the increased probability of fission and charged-particle evaporation. The
other processes can be taken into account by multiplying the neutron-
evaporation cross section by the product of the values of $\frac{\Gamma_N}{\Gamma_T}$ (ratio of
level width for neutron emission to total level widths, called F by Gordon)
for each of the compound nuclei preceding the final product. Gordon used
this F factor as an adjustable parameter. Although a nuclear temperature
of 1.3 Mev reproduced the shapes fairly well, he found it necessary to
use this F factor to make the absolute magnitudes coincide. A look at
some of the F factors used shows that the correction could be quite large.
Thus any comparisons between this work and Gordon's do not mean much
because of Gordon's use of an extra parameter. He was entirely justified
in using this extra parameter, however, because of the presence of reactions
other than neutron evaporation.

There are several other possible ways of explaining the difference
in cross sections between this work and the Jackson-model calculations.
If the listed branching ratio for At$^{209}$ is in error by 1% out of the 5%,
the experimental cross section error would be 20%. The fact that the At$^{208}$
and At$^{210}$ cross sections are also below the theoretical values would lead
one to believe that this probably is not the answer.

Another explanation is that some charged-particle emission may be
taking place. It is doubtful that the proton-evaporation cross section
would amount to 30% of the neutron-evaporation cross section, however.

A third explanation is that the effective interaction radius of
He$^3$ on Bi$^{209}$ used by Thomas is too large, thus making the compound-nucleus
cross section large.

As was indicated earlier, direct interaction of He$^3$ with Bi$^{209}$ ought
to provide some interesting further experiments. Helium-3, being inter-
mediate in binding energy between the alpha particle and the deuteron, ought
to undergo stripping reactions more readily than the alpha particle.
Although the magnitude of deuteron stripping reactions ought to be greater,
He$^3$ can undergo at least two more stripping reactions than the deuteron.
The cross sections and angular distributions of the various possible strip-
ping products ought to be measured. It would also be interesting to see
the effect of greater excitation energy on this system. It may be that at
higher energies, charged-particle evaporation can be shown unambiguously.
The availability of the Berkeley 88-inch cyclotron in the future may make
this a reality.
V. ACKNOWLEDGMENTS

I wish to acknowledge the assistance and guidance of my research director, Professor Kenneth Street, Jr.

For his assistance in the use of He$^3$ and for his many helpful suggestions on my research, I should like to thank Professor Samuel S. Markowitz.

I am grateful for the encouragement and aid given me on my research in the last two years by Victor E. Viola, Robert Latimer, and Dr. Glenn E. Gordon.

I wish to thank Dr. T. Darrah Thomas for guiding me through the early part of this research and for calculating the compound-nucleus cross sections.

For many helpful discussions, I should like to thank Dr. H. Marshall Blann, Bruce Wilkins, Lawrence Altmann, John Morton, M. Lee Hyder, Eldon Haines, Richard Kiefer, and Paul Reeder.

The assistance of the crew of the Hilac and of the Health Chemistry group is deeply appreciated.

Finally, I especially thank my wife, Charlotte, for her help in processing data, for her typing of the original drafts of this thesis, and for her encouragement of this research.

This work was performed under the auspices of the U. S. Atomic Energy Commission.
VI. REFERENCES


10. Samuel S. Markowitz, Lawrence Radiation Laboratory and Department of Chemistry, University of California, private communication.

11. Robert M. Latimer, Lawrence Radiation Laboratory, University of California, private communication.


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