Energy deposition accompanying pion double charge exchange: Radiochemical study of the ^{209}Bi($\pi^+,\pi^- xn$)$^{209-x}$At reactions

J. L. Clark,* P. E. Haustein, T. J. Ruth,† and J. Hudis
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973

A. A. Caretto, Jr.
Department of Chemistry, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 23 December 1981)

The pion double charge exchange reactions, ^{209}Bi($\pi^+,\pi^- xn$)$^{209-x}$At, have been studied by radiochemical techniques for incident pion energies of 100, 180, and 300 MeV. Cross sections for the chemically separated At isotopes (A = 205–209) were determined by alpha-particle and gamma-ray spectroscopy. The contribution of secondary processes, such as ^{209}Bi(π^+,^{3,4}He)X followed by ^{209}Bi(^{4}He, xn)$^{213-x}$At and ^{209}Bi(^{3}He, xn)$^{212-x}$At, which mimic the double charge exchange process, was evaluated through a study of the ^{209}Bi(π^-,X)At reactions, since double charge exchange channels cannot contribute to At production in such π^- interactions. Such secondary reactions were further characterized through target thickness studies employing 100–300 MeV π^- beams. An upper limit of the cross sections for ^{209}At production via elastic or inelastic double charge exchange below particle emission thresholds was determined to be 6 μb—a result which is roughly consistent with independent spectrometer measurements. Double charge exchange processes in which 8–50 MeV of excitation energy remains in ^{209}At (to be later dissipated by neutron evaporation) are found to be much more probable as evidenced by the ^{209}Bi($\pi^+,\pi^- xn$)$^{209-x}$At, x = 2–4 excitation functions which are seen to be strongly and inversely dependent on the incident pion energy.

NUCLEAR REACTIONS ^{209}Bi($\pi^+,\pi^- xn$)$^{209-x}$At, E_{π^+} = 100–300 MeV; ^{209}Bi(π^-,X)$^{207-211}$At, E_{π^-} = 100–300 MeV; measured $\sigma(E)$, deduced secondary contributions; alpha particle and γ-ray spectroscopy, Si and Ge(Li) detectors, high purity targets, carrier-free radiochemistry.

I. INTRODUCTION

Among the types of nuclear processes which can be studied with pions, great interest has developed around the class of reactions known as charge exchange. In addition to the study of the single charge exchange (SCX) reactions, ($\pi^\pm,\pi^0$) and ($\pi^0,\pi^\pm$), there is considerable interest in double charge exchange processes (DCX). Such reactions, represented in general terms by Eq. (1),

$$\pi^\pm + {}^AZ \rightarrow \pi^\mp + {}^A(Z\pm 2) , \qquad (1)$$

proceed through a charge changing mechanism wherein the incident and emitted pions are of opposite charge with a concomitant change of two in the proton number of the target and product nuclei.

Until the availability of high current proton accelerators such as at SIN, TRIUMF, and LAMPF, studies of pion charge exchange processes were severely limited by the lack of intense secondary meson beams. Becker and Batusov,[1] Eisenstein,[2] and Miller and Spencer[3] have reviewed early studies of pion charge exchange done in the mid 1970's. The earliest theoretical calculations suggested that DCX reactions could be expected to have cross sections on the order of a few microbarns and that they would populate primarily the double isobaric analog state (DIAS) of the product nucleus.[4] The recent coupled channels approach of Miller and Spencer, which invokes two consecutive single charge exchange steps for this process, has been used to calculate cross sections for the DCX analog state transitions as functions of incident pion energy and target mass for both Kisslinger-type and Laplacian-type potentials.[3] These calculations, which extract excitation functions for pion DCX from estimates of sequential SCX probabilities, predict small DCX cross sections ($\sigma = 10$ nb–10 μb) with deep minima at ≈ 180 MeV owing to the availability of other reaction channels, such as pion absorption, which become increasingly important near the (3,3) πN resonance. These double charge exchange cross sections are also predicted to fall about a factor of 5 as the target mass varies from $A \approx 18$ to $A \approx 88$, and then to remain approximately constant for target masses up to $A \approx 200$. Under certain circumstances, nucleon-nucleon correlations might appreciably enhance the DCX cross section. Unfortunately, calculations dealing with inelastic DCX processes that populate nonanalog states are less well developed at present.[5]

Two studies of pion DCX in a heavy nucleus, ^{209}Bi, have been published. Batusov *et al.*,[6] by a radiochemical technique, determined a cross section of (120 ± 30) μb for the ^{209}Bi$(\pi^+,\pi^- 2n)^{207}$At reaction at 90 MeV and estimated an upper limit of 10 μb for the ^{209}Bi$(\pi^+,\pi^-)^{209}$At reaction. These experiments were hindered by low pion beam intensities which necessitated the use of thick (≈ 5 g/cm^2) Bi_2O_3 targets. Such thick targets enhance secondary reactions, e.g., ^{209}Bi$(^4$He$,4n)^{209}$At, which can lead to the same products that are formed in the DCX process. Batusov *et al.* were not able to determine the importance of these secondary reactions. A second study of ^{209}Bi DCX has been done with 292 MeV π^+ at the LAMPF EPICS facility.[7] An energy spectrum of the emitted π^- at 5° shows a significant, but very small, signal above a broad continuum, at the location expected for the population of the DIAS in ^{209}At.

The current investigation was undertaken to reexamine and improve the radiochemical method of measuring the DCX reactions of ^{209}Bi. The availability of much higher pion fluxes at LAMPF over those used by Batusov *et al.* permitted the use of a range of target thickness better suited to the assessment of and correction for the contributions of secondary reactions such as $(^{3,4}$He$,xn)$ that can produce astatine isotopes by processes other than DCX pathways. Additions of known amounts of 7.2 h ^{211}At ("chemical spikes") at various stages of the chemical separation and purification procedures coupled with the eventual assay of the ^{211}At by alpha counting in the final sources permitted the determination of cross sections. In addition, reactions induced by π^- (as simulators of the secondary particle production characteristics of the $\pi^+ + {}^{209}$Bi interaction) were examined to establish quantitative limits on the size of the secondary corrections. Finally, the radiochemical isolation of all astatine isotopes produced by DCX or secondary processes provides at present the only way to measure cross sections reliably and simultaneously for *both* elastic and inelastic double charge exchange reactions. Such measurements yield otherwise unobtainable information on the nature of energy deposition in DCX processes and its subsequent dissipation.

II. EXPERIMENTAL

The bismuth targets used in the current investigation were prepared by subjecting a suitable quantity of bismuth metal powder to pressures of 500 to 1500 bars. These self-supporting targets were 1.5 cm$\times$2.0 cm rectangular pellets having thickness of ≈ 400 mg/cm^2 to ≈ 2 g/cm^2. Pure bismuth metal (> 0.999999) was utilized in the target preparation for most of the pion irradiations. In some cases, e.g., the developmental studies of the astatine chemistry with activated targets, bismuth of lesser purity was employed. In each instance, potential contributions to astatine production cross sections due to the spallation of trace thorium or uranium contaminants were evaluated and found to be negligible.

The pion irradiations described in the present study were performed at the P^3 channel of LAMPF. The channel was tuned to deliver 100, 180, and 300 MeV positive or negative pion beams with about a 6% FWHM momentum bite. Average pion beam intensities, as measured by monitor foil activation, ranged from about 10^7 sec^{-1} for 100 MeV π^- to about 10^9 sec^{-1} for 300 MeV π^+. The lengths of the pion irradiations varied from 2 to 8 h.

In addition to the pion experiments, a number of alpha particle irradiations of bismuth metal targets were performed at the BNL cyclotron in order to produce 7.2 h ^{211}At via ^{209}Bi$(^4$He$,2n)^{211}$At for use in studies of the tracer level astatine chemistry and via air freight shipment to LAMPF for "spikes" in the chemical yield determinations there.

Absolute beam intensities for the pion experiments were determined through use of the ^{27}Al$(\pi^\pm,x)^{24}$Na or ^{27}Al$(\pi^\pm,x)^{18}$F monitor reactions. The values employed for the cross sections of these reactions at the pion energies studied were obtained from existing excitation functions.[8] The Te column separation procedure, modified from that of Bochvarova *et al.*,[9] was chosen for isolation of At from Bi targets. The fact that this procedure yields purification factors of $> 10^6$ from undesired Po, Bi, and Pb activities makes this separation scheme particularly attractive since the At production cross sections in the DCX reactions of interest are expected to be about 10^3–10^4 times smaller.

Since there exist no stable isotopes of At, standard carrier techniques could not be employed for the determination of chemical separation efficiencies. Therefore preassayed quantities or spikes of ^{211}At were added to the target solution. The spike assays were performed by plating ≈ 1 nCi of the cyclotron prepared ^{211}At onto a thin silver disc. The plating yield was then determined by counting the 79.3 keV x rays which occur in the ^{211}At decay in the original aliquot relative to the plating supernatant. From the plating yield and an assay of the number of ^{211}At atoms determined through α counting of the plated source at known geometry, the absolute ^{211}At content of the spike was calculated. The efficiency for a given separation procedure was then determined by the measurement of the yield of any lighter At isotope ($A \leq 210$) relative to the yield of the ^{211}At spike. The chemical yields as determined by this spike technique range from about 20% to 50%.

Following the chemical separation, At production cross sections were determined through the use of standard α and γ spectroscopic techniques. The α and γ decay characteristics of the At isotopes, as well as their Po daughters, were taken from the *Table of Isotopes.*[10] Of particular importance is the fact that all of the At isotopes either decay with large probability by α emission to Bi isotopes or decay by electron capture to Po isotopes which in turn decay primarily by emitting α particles. In the current experiments α and γ decay data were collected simultaneously through the use of an evacuable aluminum chamber, outfitted with a Si surface barrier detector, and placed over the face of a standard Ge(Li) detector. Observed γ detection efficiencies in this geometry varied from about 2% for $E_\gamma = 1181$ keV to about 14% for $E_\gamma = 177$ keV. Random summing effects were found to be negligible at the counting rates employed; however, true coincidence summing corrections[11] were found to be as large as 5% in some cases. The α detector efficiency was determined by the absolute calibration of a plated ^{211}At source ($\approx 1-5$ μCi in strength) through the measurement, by Ge(Li) counting, of the low-level 687 keV γ ray of ^{211}At followed by α assay of the source. Typical α detection efficiencies were on the order of 30% and were determined to approximately $\pm 6\%$. Surface barrier detectors were utilized for the α counting studies, and their typical resolution was $\approx 20-30$ keV FWHM for the 5.866 MeV α transition of ^{211}At. Data aquisition in all experiments was carried out through the use of standard analog electronics interfaced to computer based analyzer processors. For cases where both α and γ decay branches were detectable, e.g., $^{207-209}$At, it was found that the nearly 2π source-detector geometry made alpha counting the more sensitive and accurate technique for low level At assays.

III. CONTRIBUTIONS BY SECONDARY REACTIONS

In the current study of DCX reactions on ^{209}Bi, inclusive cross sections were obtained from radiochemical determinations of the yields of At isotopes. Such measurements provide an important complimentary means of determining DCX cross sections to that performed with pion spectrometers. The radiochemical method is simultaneously sensitive to both elastic and inelastic reaction channels, while spectrometer measurements are typically limited to examination of the DCX population of a single discrete state in the product nucleus. Some limitations arise, however, for the applicability of the radiochemical method because of the existence of secondary reaction pathways which can lead to At isotopes. Production, in the initial pion-bismuth interaction, of any products which can subsequently react within the target to yield At isotopes obviously mimics the DCX process. A number of secondary reaction pathways need to be considered. The most important of these are (^{3}He,xn), (^{4}He,xn), and ($p,\pi^- xn$).

All three of these reactions on ^{209}Bi have been studied in detail. The difficulty arises in estimation of the yield of protons, ^{3}He, and ^{4}He from the pion interaction with ^{209}Bi from that with lighter targets.[12] Two approaches to this problem have been used. Firstly, published[13–16] characteristics of ^{3,4}He production in medium energy reactions of ^{209}Bi were examined. While little data are available on ^{3,4}He production from ^{209}Bi with pions, data for proton induced reactions can be used to arrive at a qualitative understanding of the magnitude of the secondary reaction effects in the present study. This was done using data from previously published work and results for At isotope production from 200 MeV protons on ^{209}Bi, an investigation performed in parallel with the DCX experiments. Secondly, yields of At isotopes produced by π^- irradiation of Bi, where DCX channels do not occur, were examined. These measurements were performed at the same energies and with the identical radiochemical procedures as were used in the π^+ studies. As such, these serve as "internal indicators" of the extent of ^{3,4}He production in the pion-Bi interaction. Differences between π^+ and π^- production of ^{3,4}He from Bi affect the usefulness of this internal correction method. However, indications[17] that inclusive helium ion production with π^- is *greater* than that for π^+ by as much as 30–40% implies that this method of correction for ^{3,4}He secondaries is more likely to *overcorrect* than undercorrect the raw π^+ yields. A third approach, and one which would allow definitive correction for secondary contributions, was attempted. This involved the measurement of At yields as a function of target thickness. Useful data were obtained for targets as thin as 0.4 g/cm^2 (10 times thinner than those used by Batusov *et al.*), but still comparable to the ranges of ^{3,4}He secondaries which mimic DCX reactions; see below. Pion flux and beam time limitations preclude the use of even thinner targets (ideally <50 mg/cm^2) from which energetic protons and ^{3,4}He can escape without significant interaction.

A brief quantitative examination of the size of the various secondary reaction cross sections and their energy dependence is useful. Energy spectra of ^{3}He and ^{4}He from medium energy proton reactions on heavy targets have been reported.[13–16] Such data are dominated at all angles by an evaporation component. The most probable energy for ^{4}He ranges from 20—30 MeV, and this is indicative of the ≈ 25 MeV Coulomb barrier experienced by the alpha particle. Yields of ^{3}He are typically ≈ 10 percent of the ^{4}He yields.

Using the assumption that similar ^{3,4}He spectra might be expected from medium energy proton and pion interactions with ^{209}Bi and taking a "worst case" example of the use of infinitely thick targets, one can estimate At isotopic yields from (^{3,4}He,xn) secondary processes. Excitation functions[18,19] for ^{209}Bi(^{3}He,xn)$^{212-x}$At and ^{209}Bi(^{4}He,xn)$^{213-x}$At typically have peak cross sections $\lesssim 1$ b. Yields of At isotopes are affected by these cross sections and the interplay of the increasing reaction Q values for the lighter At isotopes and the diminishing availibility of progressively higher energy ^{3,4}He secondaries required to produce the At products. Analysis of these trends with the above assumptions shows that contributions of fast helium induced secondary processes to the At yields will decrease from ≈ 10 μb for ^{211}At to ≈ 1 μb for ^{206}At. Despite the smaller yields of ^{3}He relative to ^{4}He (approximately 1:10), differences between the (^{3}He,xn) Q values and those for (^{4}He,$(x+1)n$) indicate that the ^{3}He contributions remain approximately as important as for ^{4}He.

An alternative production mode for At via the ^{209}Bi(π^+,p)X reaction, followed by the ^{209}Bi(p,$\pi^- xn$) reaction, may also be considered. The inclusive proton cross sections for 220 MeV π^+ interaction with a heavy nucleus (^{181}Ta) has been reported[20] to be ≈ 1.2 b. From recently measured[21] cross sections for the ^{209}Bi(p,$\pi^- xn$)$^{210-x}$At reactions at 200 MeV one can estimate the contributions of (π^+,p) (p,$\pi^- xn$) processes. For a typical product, ^{207}At, in an infinitely thick Bi target, one estimates that the contribution from this secondary reaction will be less than 0.4%. In actuality this will be reduced very substantially by escape in the thinner targets of the proton and the high Q value (>140 MeV) of the (p,$\pi^- xn$) reaction. It should be remembered that the 1.2 b cross section for the ^{181}Ta(π^+,p) reaction is inclusive in proton energy; thus only a small portion of that cross section is associated with proton energies above ≈ 140 MeV.

In light of the foregoing discussion, it is apparent then that yields of the heaviest At isotopes, ^{211,210}At, contain valuable information about the yields of light ion secondaries. Yields of lighter At isotopes, $A = 207$—209, will require some corrections because of competing secondary processes, and the still lighter At isotopes, $A < 207$, are essentially unaffected. By comparing At isotopic yields from both π^+ and π^- interactions, DCX processes become evident in those cases where there is a significantly enhanced yield for π^+ over that for π^-.

IV. RESULTS AND DISCUSSION

The cross sections for the production of the various At nuclides in the 100, 180, and 300 MeV $\pi^\pm$ irradiations of bismuth are presented in Table I. The 100 and 300 MeV results are weighted averages of data from duplicate runs, while the 180 MeV cross sections are from a single determination. These cross sections have also been plotted in Figs. 1—3. The error bars in these cross sections reflect contributions from the uncertainties associated with the

TABLE I. Absolute cross sections for astatine production measured in the 100—300 MeV $\pi^\pm$ irradiations of bismuth. All values are in microbarns.

Incident particle	Astatine mass number 211	210	209	208	207	206	205[a]
100 MeV π^+	20.7±5.0	12.7±3.0	2.6±1.8		72 ±17	99±29	436±105
100 MeV π^-	18.7±7.7	21.3±8.7	8.6±3.5		3.0± 1.2		
180 MeV π^+	26.3±6.3	8.2±5.6	8.2±2.0		23 ± 6		60±20
180 MeV π^-	25.7±7.2	32 ±9	5.7±1.6		< 0.5		
300 MeV π^+	21.5±5.2	15.6±3.7	6.6±1.6		11 ± 3	< 10	40±10
300 MeV π^-	26.9±6.4	25.4±7.9	5.6±1.4		7.3± 1.8		

[a]See Ref. 22.

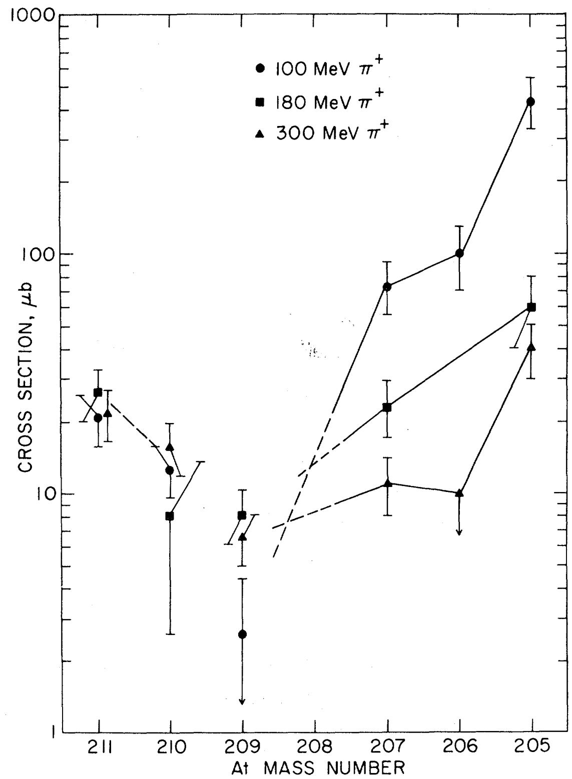

FIG. 1. Absolute astatine formation cross sections measured for the ^{209}Bi(π^-,He)Y followed by ^{209}Bi(He,xn)$^{213-x}$At reactions.

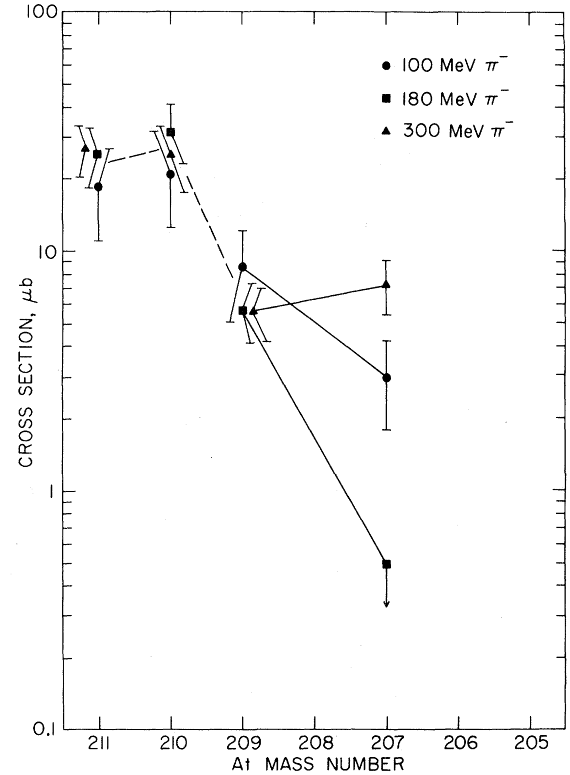

FIG. 2. Absolute astatine formation cross sections measured for the combined ^{209}Bi(π^+,He)Y followed by ^{209}Bi(He,xn)$^{13-x}$At and ^{209}Bi(π^+,$\pi^- xn$)$^{209-x}$At reactions.

beam flux measurements (10—12 %), the detector efficiency determinations ($\approx 6\%$), the spectrum integration and decay curve analyses ($\approx 3\%$), and most importantly, the $\approx 25\%$ uncertainty due to the spike chemical yield determination technique. In a few cases, most notably some of the low energy pion experiments, poor counting statistics contributed uncertainties as large as 30—50 %.

It is instructive to examine the cross section results at each At mass number for both pion charge states. Cross sections for ^{208}At are not reported because of unfavorable half-life and decay characteristics for this nuclide. The production of ^{211}At by both π^+ and π^- signals that (^{3,4}He,xn) secondary reactions occur. Differences between π^+ and π^- cross sections and their respective energy dependences do not appear to be significant based on the ^{211}At measurements and associated errors. For ^{210}At one notes that this isotope is produced more by π^- than by π^+ at all three energies. This enhancement is significant at 180 MeV, the πN resonance, while above and below it the π^- enhancement of ^{210}At is less dramatic. The cross sections for ^{209}At in general are smaller compared to ^{211}At or ^{210}At. This is taken as an indication of the diminishing influence of secondary reactions. The yield of ^{209}At samples that portion of the energy distribution of the ^{3,4}He evaporation spectra in which the number of these secondaries has begun to decline. At 180 and 300 MeV the π^+ ^{209}At cross section appears to be slightly higher than that for π^-. As a group then, the $^{211-209}$At cross sections suggest that the anticipated contributions of secondary reactions dominated the production modes for these isotopes. Elastic DCX at 180 or 300 MeV to yield ^{209}At is only feebly indicated (see the limits discussed below).

A significant departure from the trends observed in the $^{211-209}$At cross sections occurs at ^{207}At. Large enhancement of ^{207}At produced by π^+ at 100 and 180 MeV is observed. The 300 MeV results, where one expects secondary reaction contributions, if they still exist, to be more likely than at lower energy, shows a slight π^+ enhancement but not significantly so. Results for ^{206}At and ^{205}At extend this new trend. The shortening of the half-lives of these lighter At isotopes made their assay more difficult, a feature reflected in the size of the error bars for these cross sections. None the less, it is striking that the π^+ cross sections increase at the same time the π^- cross sections decrease below the limit of ra-

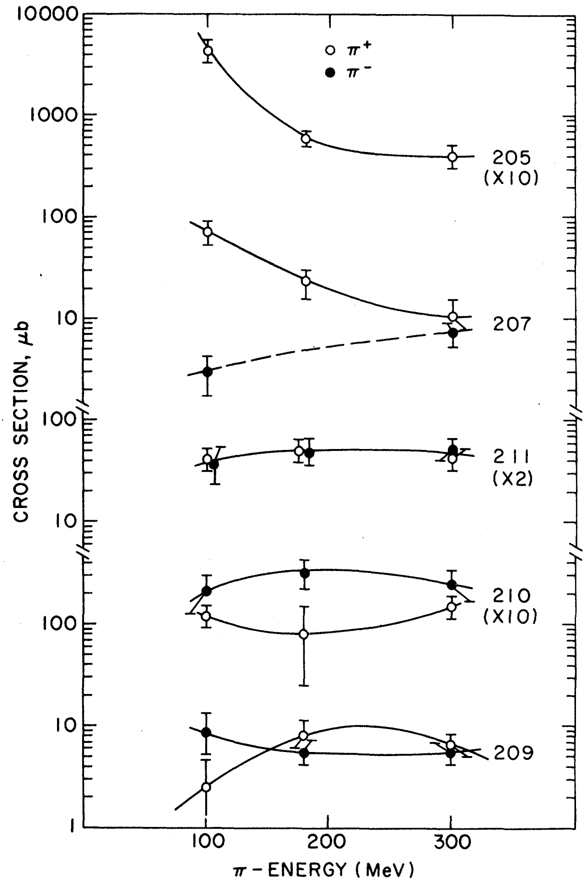

FIG. 3. Astatine isotope excitation functions for the pion bombardments of bismuth. All energies are in the laboratory frame. Curves have been drawn to guide the eye.

diochemical detection. Moreover, the enhancement of the light mass ($A=205$–207) astatine production with decreasing π^+ energy is inconsistent with the production of these isotopes *solely by secondary reactions.*

The shape of the ^{207}At excitation function, derived from the π^+ data and presented in Fig. 3, is presented as evidence of the primary reaction mode of double charge exchange. This is based on the characteristics of At production observed in the π^+ and π^- studies. The same situation exists for the formation of ^{206}At and ^{205}At in these studies. Evaluation of the π^+ DCX cross sections for the present investigation was made by assuming that all secondary reaction contributions were negligible in the 100 MeV π^+ production of $^{205-207}$At and in the 180 MeV π^+ production of ^{207}At. These results are summarized in Table II. Upper limits for the ^{209}Bi$(\pi^+,\pi^-)^{209}$At cross sections at 180 and 300 MeV were determined by subtracting the π^- cross

TABLE II. Cross sections in microbarns for pion double charge on bismuth.

DCX product (mechanism)	Incident pion energy (laboratory) 300	180	100	90[b]
^{209}At (π^+,π^-)	1.0 ± 3.0	2.5 ± 3.6	<6	<10
^{207}At (π^+,π^-2n)	3.7 ± 4.8	$22\ \pm 7$	69 ± 18	120 ± 30
^{206}At (π^+,π^-3n)	<10		99 ± 29	
^{205}At[a] (π^+,π^-4n)	$40\ \pm 10$	$60\ \pm 20$	436 ± 105	

[a]Reference 22.
[b]Reference 6.

section observed for ^{209}At at these energies, while the upper limit at 100 MeV was determined in an experiment in which a thinner target (less sensitive to secondary reactions) was employed. Significant differences in ^{3,4}He production for incident π^+ versus that for π^- could change these limits.

The π^+ cross sections are interpreted as evidence of pion double charge exchange reactions of the type

$$^{209}\text{Bi}(\pi^+,\pi^- xn)^{209-x}\text{At} ,$$

where products corresponding to $x=0$ and 2–4 have been observed. Although very little is known about DCX reactions in which nucleon emission occurs, a reasonable mechanism is one in which the initial charge exchange interaction is followed by the evaporation of one or more neutrons. Neutron separation energies indicate that about 8–10 MeV is required for the evaporation of each neutron from $^{209-206}$At. Charged particle evaporation from a residually excited ^{209}At nucleus would be retarded by the Coulomb barrier, but could, in principle, occur at high excitation. The present measurements would, of course, not be sensitive to such reaction channels.

It is instructive to use the present sets of measurements to examine qualitatively the general feature of energy deposition which can accompany pion double charge exchange in a heavy target nucleus like ^{209}Bi. Firstly, from analysis of the foregoing results the following observations can be made:

(1) The probability that the DCX interaction populates final states of ^{209}At up to its neutron separation energy (8.3 MeV) is relatively small.

(2) Population of states up to 40–50 MeV in ^{209}At must occur, as evidenced by the excitation functions for production of lighter At isotopes, $A=205$–207.

(3) Trends in the cross sections of the DCX reactions suggest that the distribution in excitation ener-

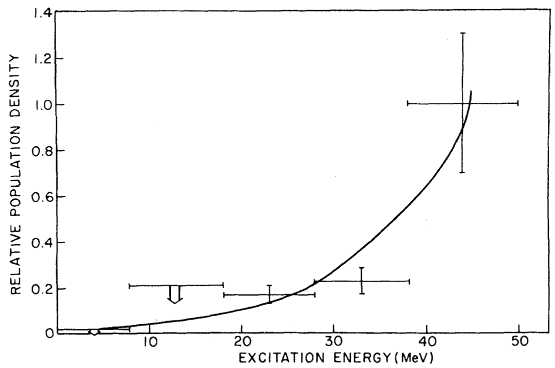

FIG. 4. Excitation energy distributions for residual nuclei produced by pion double charge exchange interactions on bismuth. Horizontal error bars reflect kinetic energy distributions predicted for evaporation neutrons, while vertical error bars are related to the experimental DCX cross sections for $^{205-209}$At.

gy following DCX interactions is relatively independent of incident pion energy.

Secondly, it is possible to obtain a quantitative picture of the excitation energy distributions for the residual nuclei from the 100 MeV π^+ DCX reaction on ^{209}Bi by making comparison of the yields of the light At isotopes, the excitation energies in ^{209}At required to promote single or multiple neutron emission, and the expected rapid increase in the ^{209}At level density at higher excitation energy. If one assumes (1) that there are no stringent isospin constraints for population of higher lying levels in ^{209}At, (2) that the production of such states correlates with the availability of a higher level density in ^{209}At, and (3) that such higher lying states, once formed, can deexcite via particle or gamma-ray emission in a purely statistical fashion, then the distribution of excitation energy shown in Fig. 4 is obtained. Error bars on the excitation energies reflect kinetic energy distributions predicted for the evaporation neutrons, while error bars on the relative population densitites are related to the experimental DCX cross sections for $^{205-209}$At. The trend shown in Fig. 4 indicates that a very considerable part of the DCX process occurs *well above* the region observed for the double isobaric analog state in ^{209}At.[7]

ACKNOWLEDGMENTS

The authors wish to thank Ms. E. Ritter for her help in target preparation and Ms. E. Norton for carrying out various chemical analyses. The assistance of Dr. S. Katcoff is appreciated. We wish to thank Dr. M. Hillman for useful discussions concerning evaporation theory and gratefully acknowledge many stimulating discussions with Dr. B. J. Dropesky, Dr. R. S. Rundberg, Dr. L. P. Remsberg, Dr. J. B. Cumming, and Dr. S. J. Greene. We wish to thank Dr. C. J. Orth and Dr. D. J. Vieira for their assistance in setting up the pion beam lines and Dr. G. C. Giesler for his help with the LAMPF data acquisition systems. Our deepest appreciation is extended to the staffs and operating crews of the Los Alamos accelerator and the Brookhaven LINAC and cyclotron. One of us (A.A.C.) acknowledges the financial support of the National Science Foundation and one of us (J.L.C.) wishes to express his warmest thanks to the Chemistry Department of the Brookhaven National Laboratory for its hospitality. This work was performed in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Carnegie-Mellon University. The research carried out at Brookhaven National Laboratory was under contract with the U.S. Dept. of Energy under Contract No. DE-AC02-76CH0016.

---

*Present address: General Physics Corp. 1000 Century Plaza, Columbia, MD 21044.

†Present address: TRIUMF, University of British Columbia, Vancouver, British Columbia, Canada V6T 2A3.

[1]F. Becker and Yu. A. Batusov, Rev. Nuovo Cimento 1, 309 (1971).

[2]R. A. Eisenstein, Bull. Am. Phys. Soc. 19, 1014 (1974).

[3]G. A. Miller and J. E. Spencer, Ann. Phys. (N.Y.) 100, 562 (1976).

[4]S. D. Drell, M. H. Friedman, and F. Zachariasen, Phys. Rev. 104, 236 (1956).

[5]Fermi gas model type calculations by W. R. Gibbs have recently succeeded in "fitting" single charge exchange cross sections measured radiochemically.

[6]Yu. A. Batusov, Z. Ganzorig, I. V. Dudova, B. P. Osipenko, V. M. Sidorov, V. A. Khalkin, and D. Chultem, Yad. Fiz. 18, 485 (1973) [Sov. J. Nucl. Phys. 18, 250 (1974)].

[7]C. L. Morris, H. A. Thiessen, W. J. Braithwaite, W. B. Cottingame, S. J. Greene, D. B. Holtkamp, I. B. Moore, C. Fred Moore, G. R. Burleson, G. S. Blanpied, G. H. Daw, and A. J. Viescas, Phys. Rev. Lett. 45, 1233 (1980).

[8]B. J. Dropesky, G. W. Butler, C. J. Orth, R. A. Williams, M. A. Yates-Williams, G. Friedlander, and S. B. Kaufman, Phys. Rev. C 20, 1844 (1979).

[9]M. Bochvarova, Do Kim Tyung, I. Dudova, Yu. V. Norseev, and V. A. Khalkin, Sov. Radiochem. 14, 889 (1972).

[10]*Table of Isotopes,* 7th ed., edited by C. Michael Lederer and V. S. Shirley (Wiley, New York, 1978).

[11]G. J. McCallum and G. E. Coote, Nucl. Instrum. Methods 130, 189 (1975).

[12]J. F. Amann, P. D. Barnes, M. Doss, S. A. Dytman, R. A. Eisenstein, J. Penkrot, and A. C. Thompson, Phys. Rev. Lett. 35, 1066 (1975).

[13]J. R. Wu, C. C. Chang, and H. D. Holmgren, Phys. Rev. C 19, 698 (1979).

[14]H. Dubost, M. Lefort, J. Peter, and X. Tarrago, Phys. Rev. 136, (1964).

[15]R. E. Segel, private communication.

[16]L. E. Bailey, University of California Radiation Laboratory Report No. UCRL-3334, 1956 (unpublished).

[17]A. Doron, A. Altman, D. Ashery, Y. Shamai, A. I. Yavin, J. Julien, Y. Cassagnou, H. E. Jackson, R. Legrain, A. Palmeri, and S. Barbarino, Phys. Rev. C 18, 961 (1978).

[18]J. D. Stickler and K. J. Hofstetter, Phys. Rev. C 9, 1064 (1974).

[19]E. L. Kelly and E. Segre, Phys. Rev. 75, 999 (1949).

[20]R. D. McKeown, S. J. Saunders, J. P. Schiffer, H. E. Jackson, M. Paul, J. R. Specht, E. J. Stephenson, R. P. Redwine, and R. E. Segel, Phys. Rev. C 24, 211 (1981).

[21]J. L. Clark, P. E. Haustein, T. J. Ruth, J. Hudis, and A. A. Caretto, Jr., Phys. Rev. C 26, 2073 (1982).

[22]Cross sections for ^{205}At are based on the 18.4% α branch for this decay reported by T. D. Thomas, G. E. Gordon, R. M. Latimer, and G. T. Seaborg, Phys. Rev. 126, 1805 (1962). The smaller α branch of 10% for ^{205}At, reported by P. Hornshoj, P. G. Hansen, and B. Jonson, Nucl. Phys. A230, 380 (1974), would, if used, enlarge the ^{205}At cross sections by a factor of 1.84.