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Author
Steiger, Naftali H.

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Naftali H. Steiger

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Naftali H. Steiger

Lawrence Radiation Laboratory
University of California
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ABSTRACT

The internal-ionization effect that follows a heavy-ion-induced nuclear reaction has been studied experimentally by means of magnetic analysis of the product atoms. The effect was investigated for the reaction $Pr^{141}(O^{16}, 8n)Ho^{149}$. Target thicknesses from 26.2 $\mu g/cm^2$ down to 9.7 $\mu g/cm^2$ were used. For target thicknesses lower than about 25 $\mu g/cm^2$, non-equilibrium ionic-charge spectra are obtained that tend toward lower probabilities for the charge states lower than the equilibrium mean charge, and tend toward higher probabilities for the charge states higher than the equilibrium mean charge. As a result, the mean ionic charge increases from 17.6 ± 0.5 for the equilibrium case to 19.4 ± 1.0 for a target thickness of 9.7 $\mu g/cm^2$. By extrapolation to target thickness zero, an ionic-charge spectrum is obtained which we consider illustrates the "instantaneous internal ionization" obtained from the interaction between two complex nuclei. The shape of the extrapolated charge spectrum can be explained as being mainly composed of the two processes responsible for the internal ionization: (a) the non-adiabatic part of the transition following a change in nuclear charge, (b) the development of vacancy cascades as a result of internal conversion. Based on experimental results, the part of the ionization which has been caused by process (a) was estimated to be somewhat less than 800 eV.

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Naftali H. Steiger†

Lawrence Radiation Laboratory
University of California
Berkeley, California

I. INTRODUCTION

Several mechanisms can lead to internal excitation and ionization in atoms that result from a nuclear transformation. The most important are (1) the development of vacancy cascades by successive Auger events; (2) an electrostatic "shake-off" process caused by a change in nuclear charge; and (3) a nonnuclear "shake-off" produced by the change in electric field following the sudden loss of an atomic electron. One of these effects or a combination of them may occur as a result of various kinds of spontaneous or nonspontaneous nuclear transformations.

These effects have been studied experimentally and theoretically for different modes of radioactive decay. A short compilation of these studies made prior to 1958, including a summary of references, has been published by Baulch and Duncan.[1] More recent work has been published by several authors.[2-4]

It has been shown that the ionic-charge spectra of the product atoms resulting from nuclear transformations reflect a sensitivity to the nature of the nuclear change that caused the ionization, as well as represent the statistical outcome of the complex atomic rearrangements that follow electron loss from any of the several electron shells of the atoms.[3-8] Ionization following beta decay, internal conversion, orbital electron capture and various combinations of these processes have been studied extensively by applying charge spectrometry to the product atoms.[3-8] However, no experimental data on

internal ionization obtained in products of induced nuclear reactions appear to exist at present.

In two previous papers we reported on a detailed study of ionic-charge distributions of products of heavy-ion-induced nuclear reactions.[9,10] These distributions were for an equilibrium state achieved by the reaction products within the target material. Heavy particles passing through matter can lose or capture electrons in collisions with stationary atoms of the medium traversed. This very complicated process results in the establishment of an equilibrium distribution of charges. This distribution relates to an element of the path of the penetrating particles, which is long enough to include a large number of charge-exchange collisions but too short to appreciably slow down the particles. For a reaction product of certain nuclear charge, these charge distributions depend mainly on the velocity of the product, and are independent of the kind and characteristics of the nuclear transformation. Target thicknesses utilized in these experiments were of the order of 100 $\mu g/cm^2$. It was found that equilibrium-charge distributions were practically obtained for target thicknesses larger than 25 $\mu g/cm^2$.

In the present report we present initial results on ionic-charge spectra of Ho^{149} particles obtained as products of a heavy-ion induced nuclear reaction when target thicknesses of less than 25 $\mu g/cm^2$ have been used. We hope that an extrapolation to zero target thickness will reflect--at least qualitatively--the "instantaneous internal ionization" obtained as a result of the interaction between two complex nuclei. By "instantaneous internal ionization" we mean the ionization that occurs before the resulting species of a nuclear reaction starts to move inside the target material and is given the chance of charge-changing collisions. We have mentioned some preliminary results of these experiments in a recent report.[9]

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

The experimental method chosen was similar to the one used for the studies of equilibrium-charge distributions of products of heavy-ion-induced nuclear reactions in the rare-earth region; this method was previously described by us in detail.[10]

In the experimental setup, targets of various thicknesses were bombarded by a well-collimated heavy-ion beam which passed through a narrow slit before hitting the target. The heavy-ion beam was obtained from the Berkeley heavy-ion linear accelerator (Hilac), which accelerates heavy ions to an energy of 10.4 ± 0.2 MeV/amu.[11] The resulting reaction products that emerged from the target and passed through a second narrow slit were magnetically analyzed and then collected on a thin aluminum catcher foil. The experiments were performed at a pressure of 10^{-4} mm Hg. The horizontal distribution of the collected reaction products, which is proportional to the ionic-charge state of the particle, was recorded by taking an autoradiograph of the catcher foil. The distribution was then determined by counting on the nuclear emulsion under a microscope, the particle tracks that originate from the alpha disintegration of a decay product of the primary reaction product.

The following points of view have been considered while choosing a suitable nuclear reaction for the experiments described here:

(a) Large difference in nuclear charge between reaction product and target atom.

This would increase the internal ionization effect, which is expected to originate mainly from the change in nuclear charge. Because it is practically impossible to perform experiments with targets below a certain thickness, a crude method of extrapolation to target thickness zero had to be used. As the difference between the investigated internal ionization and the ionization

obtained as a result of charge-changing collisions may be relatively small, it was desirable to have an internal ionization effect as high as possible.

(b) High reaction cross section.

Because of the very thin target thicknesses to be used, the low reaction yield thus obtained would create a demand for very highly integrated beam levels of the bombarding heavy ions. This introduces a serious factor of interference, because of the alpha activity induced in heavy-element impurities existing in the catcher-foil material. As this induced alpha activity is proportional to the integrated beam level, a high reaction cross section would minimize this interference; however, as can be seen from the results, it was impossible to eliminate this interference completely.

(e) Bombarding energies that could be obtained without the use of degrading foils.

Because of the low reaction yield obtained when using very thin targets, high beam levels of heavy ions had to be used. These high beam levels would eventually burn the degrading foils.

(d) A target material which could be obtained in extremely thin layers by being evaporated onto a suitable backing material.

After taking into account all these considerations, we chose the reaction $Pr^{141}(O^{16}, 8n)Ho^{149}$. For this reaction, the difference in nuclear charge is equal to $\Delta Z = +8$. For the full energy beam, which after a slight energy degradation by the backing material of the target, has a lab. energy of 161.0 MeV, the reaction cross section has the acceptable value of 200 mb.[12]

Pr^{141} targets of various thicknesses were obtained by vacuum evaporation of the natural metal onto thin Ni-backing foils.[13] The thickness of the targets was determined by area and weight determinations.

The decay characteristics of Ho^{149} are as follows:

$$_{67}Ho^{149} \xrightarrow[EC]{1\ min} {}_{66}Dy^{149} \xrightarrow[EC]{15\ min} {}_{65}Tb^{149g} \xrightarrow[0.1\,(3.95\ MeV)]{4.1\ h} \cdots\cdots$$

As detecting method we used the technique of alpha-particle track counting of the decayed $_{Tb}149g$ described previously.[9,10]

As has been shown by us for the experimental arrangement,[10] the horizontal deflection D on the catcher foil of a particle of certain mass A_1, velocity v, and charge state z is given by

$$D = \frac{A_1 c v}{He z}\left[1 - \cos\left(\arcsin\frac{\ell He}{A_1 c}\frac{z}{v}\right)\right] + L\ell\frac{He}{A_1 c}\frac{z}{v}\left[\cos\left(\arcsin\left(\frac{\ell He}{A_1 c}\frac{z}{v}\right)\right)\right]^{-1}. \tag{1}$$

Here, H is the magnetic-field strength applied to the reaction products, ℓ is the length of the magnetic field, L is the distance between the end of the magnet and the catcher foil, e is the elementary charge, and c is the velocity of light. This relation was tested and calibrated by making use of the fully ionized O^{16} beam from the accelerator.[10]

In Fig. 1, a graphic representation of the charge state z versus the deflection distance D, in accordance with Eq. (1), is given for the actual experimental conditions applied. The identification of the charge spectra obtained for the nuclear reaction products was made by use of Eq. (1) and Fig. 1.

By taking into consideration the mechanism of the nuclear reaction studied, we have shown that the mean velocity of the reaction products is given by

$$\langle v \rangle = \frac{(2 A_b E_b)^{1/2}}{A_b + A_T}, \tag{2}$$

where A_v and A_T are the masses of the bombarding ion and the target atom respectively, and E_b is the lab. energy of the bombarding ion.[9,10] Similarily, we have shown that the velocity spread caused by neutron evaporation

is given by

$$\frac{\sigma_v}{\langle v \rangle} = \left[\frac{\left(\frac{E_b A_T}{A_b + A_T} + Q - T_\gamma \right) m_n}{E_b A_b} \right]^{1/2} \frac{A_b + A_T}{A_b + A_T - \frac{x+1}{2} m_n} , \qquad (3)$$

where Q is the mass difference between reactants and final products, T is the average total energy of the system emitted as photons, x is the number of neutrons evaporated during the decay of the compound nucleus, and m_n is the mass of the neutron.[9,10]

Because we had to use very high integrated beam levels, very large amounts of beam-induced alpha activity in the catcher foil were obtained, which superimposed themselves on the experimental scanning curves. The scanning curves represent alpha-track density as a function of the deflection distance D on the nuclear-emulsion plate.

In Fig. 2, an example of an experimental scanning curve for target thickness 9.7 $\mu g/cm^2$ is shown. It can be seen that the induced alpha-activity curve introduces a serious factor of interference for the accurate evaluation of the left side of the experimental charge spectrum, which is represented by the alpha-track distribution of the rare earth alpha tracks only. To determine the induced alpha-activity curves, we performed a number of bombardments under conditions similar to those of the regular experiments, but where we used instead of the target, an equivalent foil of its backing material only. In this way a fairly good correction of the experimental scanning curve for the beam-induced alpha activity could be obtained.

The curve thus obtained was corrected for velocity spread caused by neutron evaporation in accordance with Eq. (3), and for geometrical spread caused by the collimation system used. Because of the very thin target thicknesses utilized, the velocity spread caused by target thickness could be

neglected. The resultant curve can then be converted into a histogram for integer z values to represent the actual ionic-charge spectrum for the nuclear-reaction products emerging from a target of a certain thickness.

III. RESULTS

In Figs. 3 to 6, histograms representing corrected charge spectra of recoiling Ho^{149} particles for various target thicknesses are given. In these histograms the relative probability of a certain charge state ϕ_z in %, as a function of the charge state is shown. Each curve represents the mean result of a repeated number of experiments. Whereas the charge spectrum that corresponds to a target thickness of 26.2 $\mu g/cm^2$ (Fig. 3) within the experimental limits is still identical with the equilibrium-charge distribution,[9,10] the charge spectra that correspond to thinner targets are different from the equilibrium values. These spectra show a tendency toward lower probabilities for the charge states lower than the equilibrium mean charge and toward higher probabilities for the charge states higher than the equilibrium mean charge. These charge spectra may be considered as the sum of a number of charge spectra; they are composed of (a) an equilibrium-charge distribution, valid for all the reaction products originating from a depth in the target equal to or larger than the "minimum equilibrium thickness," and (b) a large number of nonequilibrium charge spectra, changing for each successive atomic layer from the equilibrium value toward the real "instantaneous" value of the charge spectrum for the outermost atomic layer of the target. Reaction products originating from the outermost target layer do not undergo any charge changing collisions and their charge spectrum could therefore be considered as a reflection of the nature of the nuclear changes which are able to cause ionization. Unfortunately, such an analysis of the experimental charge spectra

could not be made. The experimental conditions did not enable us to determine the "minimum equilibrium layer" in terms of the $\mu g/cm^2$ target material. Furthermore, because it was extremely difficult to get targets of equally distributed material thinner than about 10 $\mu g/cm^2$, and because the reaction yield obtained from such targets would have been too low, this target thickness determined the lower limit for our experiments. We therefore chose a rough method of linear extrapolation of relative probabilities obtained for each charge state in the spectrum, to target thickness zero. It must, however, be emphasized that this way of extrapolation is considered somewhat arbitrary and crude because of the complicated mechanism of ionization involved.

In Table I, we give our data as read from the corrected charge histograms for the relative probabilities ϕ_z (in %) for the different charge states as a function of target thickness. In the last column of the table, the spectrum for target thickness zero obtained by linear extrapolation is given.

Figure 7 shows a graphic representation of this extrapolated charge spectrum. For each charge spectrum, an average charge for the whole spectrum may be obtained from

$$\langle z \rangle = \Sigma \phi_2 z \, . \qquad (4)$$

In Fig. 8, the mean charge as a function of target thickness, extrapolated to target thickness zero, is shown.

IV. DISCUSSION

Consideration of the nuclear interaction investigated shows that the quantitatively dominating source for internal excitation and ionization is the effect of the "shaking" of the atomic core, which is caused by the large change of nuclear charge; in the present investigation this change is $\Delta z = +8$.

When the nuclear charge of an atom that undergoes a nuclear transformation changes from Z to $Z + dZ$, the energy of the atom will change by the amount $dE(Z)$. This change will be given by

$$\frac{dE(Z)}{dZ} = e\,\Phi(Z)\,, \tag{5}$$

where $\Phi(Z)$ is the electrostatic potential produced by the atomic electrons at the surface of the nucleus that undergoes the nuclear transformation, and e is the elementary charge.

If in any nuclear reaction, the charged particles entering or leaving the nucleus have velocities considerably greater than the velocities of the orbital electrons of the target atom, the electronic cloud cannot adjust adiabatically to the sudden change in nuclear charge. Thus, a certain amount of electronic energy is available for atomic excitation, which in an adiabatic process would be absorbed by the incoming or emerging charged particles. Following an approach which has been outlined by Serber and Snyder,[14] it can be shown that this energy ΔE is given by the difference between the energy absorbed by the charged particle in a reorientation of the electronic cloud in an adiabatic transition, and that energy absorbed in the actual non-adiabatic process. We then have

$$\Delta E = -[E(Z') - E(Z)] + e(Z' - Z)\,\Phi(Z), \tag{6}$$

where $E(Z)$ is the total atomic energy of the target atom and $E(Z')$ is the total atomic energy of the nuclear reaction product. The energy difference ΔE

appears as excitation and ionization energy of the final reaction product. According to Foldy,[15] the best E(Z) values for heavy elements can be obtained when using the atomic model of Hartree, which gives

$$E(Z) = - RZ^{12/5} , \qquad (7)$$

where R is Rydbergs constant in energy units. Differentiating Eq. (7) and introducing this result into Eq. (5) we obtain

$$e\,\Phi(Z) = - 32.64\, Z^{7/5}\,(eV). \qquad (8)$$

When $E(Z') - E(Z)$ in Eq. (6) is expanded in a Taylor series in $Z' - Z$, and combined with Eq. (8), we obtain an expression for the average energy of excitation of a heavy nuclear reaction product, following a change in nuclear charge from Z to Z':

$$\Delta E = 22.85\, Z^{2/5} (Z' - Z.)^2 \quad (eV). \qquad (9)$$

This value is an average taken over the probability distribution for the transition from the ground state of the target atom to the various final states of the reaction product. Applying Eq. (9) to the heavy-ion induced nuclear reaction studied, and stating that $Z' - Z = 8$ and $Z = 59$, we obtain $\Delta E = 7473$ eV. However, for two reasons, the actual value of ΔE for this case will be considerably smaller.

(a) Equation (8), considered as an interpolation formula between integral values of Z, corresponds to the charge on the electrons being kept equal to the charge on the nucleus as the atomic number varies from Z to Z'; however, this is actually not the case. The number of electrons involved in this process will be equal to the nuclear charge of the target atom (59) whereas the energy difference obtained from Eq. (9) takes into account the difference in energy between the neutral atom of the reaction product and the neutral target atom.

(b) A comparative estimate of the velocity of the bombarding O^{16} ion and the velocities of the atomic electrons of the Pr^{149} target atom shows that,

in the case considered here, the transition is largely adiabatic and to a lesser degree nonadiabatic. The bombarding energy of the O^{16} ion corresponds to a velocity of $4.5 \cdot 10^9$ cm/sec. This particle velocity is smaller than the velocity of the K electrons of the target atom and comparable with the velocity of its L electrons. For the change in binding energy of these electrons as the result of the change in nuclear charge of the atom, the transition is thus adiabatic. For the change in binding energy of the remaining electrons which occupy the outermore shells, the transition will be nonadiabatic and this energy difference will partly be available for internal excitation and ionization of the reaction product.

Consequently, the actual mean excitation energy of the final atom will only be a small fraction of the energy difference of $\Delta E = 7473$ eV as estimated before from Eq. (9) for the case of a complete nonadiabatic transition.

Let us now briefly discuss further possible sources for internal excitation and ionization that follows the type of nuclear reaction under investigation. As mentioned in the introduction, another main source for internal ionization is the development of vacancy cascades. The main transitions responsible for this process are internal conversion and orbital electron capture. To discuss the possible contribution of internal conversion to the ionization effect, we need data concerning the gamma-ray spectra of heavy-ion-induced compound nucleus reactions in the rare earth region. Measurements of gamma spectra of this kind give results of mean energies of emitted gamma rays of about 1.2 MeV, with lower side energies down to less than 0.5 MeV.[16] Furthermore theoretical considerations seem to indicate a probability for the occurrence of even lower energy gamma cascades of the order of 100 to 200 keV. For such low gamma energies, a high probability for internal conversion will exist, and the development of vacancy cascades will

occur. Unfortunately, there do not exist any experimental data on these low energy gamma cascades and consequently no quantitative statement can be made about the internal-conversion probabilities and their relative importance in the measured charge spectrum. Qualitatively however, it can be stated that the shape of the charge spectrum, which would have been obtained from vacancy cascades alone is determined by the probabilities of internal conversion, the fluorescence yields associated with the various electron shells, the relative probabilities of competing x-ray transitions, and the natures of the competing radiationless transitions.[7]

The electron-capture decay of Ho^{149} is certainly slow in comparison to the time of flight of the final reaction product (of the order of 10^{-8} sec) prior to its magnetic analysis. This process may therefore be excluded completely.

The third main source for ionization, which has been mentioned in the introduction is the non-nuclear "shake off," which has been suggested by Wolfsberg and Perlman.[17] According to these authors, the departure of Auger electrons will cause electrostatic perturbations in a similar way as would a change in nuclear charge. In this way excitation and ionization can arise. At present there seems to be no way to measure this effect experimentally. However, in general one can expect this effect to be present to a certain extent in case of occurrence of vacancy cascades.

Finally, an additional, but minor source for ionization may be mentioned. As a result of collisions between the bombarding heavy ion and the atomic electrons of the target atom, some of these electrons may be "knocked out." The probability for this process (P_{dc}) as compared with the probability for ejection due to the effect of "nuclear shaking" (P_s) has been estimated by Feinberg[18] for the case of beta decay in light atoms and found to be of the order of 1/1000. In heavier atoms and for collisions with heavy ions, P_{dc}

and P_s may become of the same order of magnitude only for electrons in the inner shells. As P_s is small for these electrons[19] the contribution of P_{dc} to the total ionization probability will always be negligible. Since, however, the removal of one of the inner electrons will to a certain extent give rise to a cascade of Auger electrons, the direct collision may become important for that small fraction of the reaction products that are highly ionized.

We may now come to the conclusion that two processes are mainly responsible for the internal ionization which occurs in the product atoms of the investigated reaction and which is reflected in the charge spectrum of the Ho^{149} particles:

(a) The nonadiabatic part of the transition following a change in nuclear charge.

(b) The development of vacancy cascades as a result of internal conversion.

Before considering the obtained charge spectrum as a result of the experiments, it may be interesting to speculate what approximate shapes of charge spectra could be expected for each of the two mechanisms separately.

Even in the case of a completely adiabatic transition following the change in nuclear charge, the minimum state of ionization for the reaction product is expected to be +8. This charge state results from the fact that the bombarding O^{16} ion enters the target nucleus in a completely ionized state.[20] Any additional effect of ionization caused by the nonadiabatic part of the transition will therefore result in still higher charge states. As the highest probability for ionization as a result of "shaking" will be for the existing outer electrons of the atom, almost no vacancy cascades can be expected from this process. As a result of process (a) alone we would therefore expect a charge spectrum starting from $z \geqq +8$ and dropping toward higher charges. As a result of mechanism (b) alone we would expect a start of low intensity for the lower

charge states, rising to a maximum and then decreasing again for high charge values. The low charge-state side of the spectrum may be explained by two types of events. First, the occurrence of radiative transitions when primary vacancies are filled mainly by x-ray transitions. Second, conversion occurring in the outer part of the atom so that even for the radiationless part of the transitions no significant vacancy cascades can develop. The high charge side of the spectrum may be explained by the occurrence of multiplying radiationless transitions which develop as a result of an original vacancy created in the inner part of the atom. The position and height of the maximum of the spectrum will depend on the character and relative probabilities of the various processes involved. Spectra of this kind have been obtained experimentally for isomeric transitions, where internal conversion alone was responsible for the ionization effect.[7]

The resultant spectrum obtained in our case by a combination of both processes can be expected to start at the lower charge-state side with a certain probability for charge $z \geq +8$, rising to a maximum and then decreasing again.

The charge spectrum obtained for target thickness zero, by crude extrapolation of our experimental charge spectra for various target thicknesses (see Fig. 6) may be considered as approximately following this expectation.

If the entire internal ionization process were caused by primary ionization effects only, an estimate of the expended ionization energy could be made, based on the charge spectrum given in Fig. 7. This energy will be the sum of the binding energies of all the electrons involved in the ionization effect. We have made this estimate, starting with a $[Ho^{149}]^{+8}$ ion, representing the instantaneous product of the nuclear reaction after the evaporation of all the 8 neutrons has been completed, and before any internal ionization

could have happened. We have further assumed that the electronic configuration of the hypothetical $[Ho^{149}]^{+8}$ ion is equal to the electronic configuration of the neutral Pr^{141} target atom, only with different electron binding energies. All additional ionization as represented by the charge spectrum was calculated by taking into account the binding energies of the outer electrons involved, and proceeding successively into inner shells for the higher charge-state probabilities. This estimate gives approx. 800 eV.

However, as discussed, "vacancy cascades" caused by internal conversion, as well as "primary ionization" caused directly by the "nonadiabatic" part of the transition following "shake off," are responsible for the internal ionization. Because the relative importance of these two processes is unknown, it can only be stated that the part of the ionization which has been caused by the "shaking" effect, will be somewhat less than 800 eV. More detailed calculations of the expected absolute magnitude of the nonadiabatic transition of the shaking effect, are in progress.

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Table I. Relative probabilities ϕ_2(in %) for various charge states in the charge spectrum, as functions of target thickness.

	Pr^{141} target thickness ($\mu g/cm^2$)				
ϕ_z(%)	26.2	21.6	14.6	9.7	0(extrapolated)
ϕ_7	1.1 ± 0.2				
ϕ_8	1.3 ± 0.2				
ϕ_9	1.8 ± 0.2	0.9 ± 0.2			
ϕ_{10}	2.4 ± 0.3	1.3 ± 0.2			
ϕ_{11}	3.1 ± 0.3	2.2 ± 0.2	1.0 ± 0.2		
ϕ_{12}	3.8 ± 0.3	3.1 ± 0.3	1.8 ± 0.2	1.2 ± 0.3	
ϕ_{13}	4.6 ± 0.3	3.9 ± 0.3	2.7 ± 0.3	1.0 ± 0.3	
ϕ_{14}	5.4 ± 0.3	4.8 ± 0.3	3.8 ± 0.3	2.9 ± 0.4	1.3 ± 0.3
ϕ_{15}	6.6 ± 0.5	6.0 ± 0.4	4.8 ± 0.3	4.2 ± 0.4	2.5 ± 0.4
ϕ_{16}	7.5 ± 0.5	6.8 ± 0.5	6.4 ± 0.5	5.6 ± 0.6	4.2 ± 0.4
ϕ_{17}	8.2 ± 0.5	7.8 ± 0.5	7.4 ± 0.5	7.0 ± 0.6	5.8 ± 0.6
ϕ_{18}	8.1 ± 0.5	8.3 ± 0.5	8.3 ± 0.5	8.4 ± 0.7	7.5 ± 0.7
ϕ_{19}	7.8 ± 0.5	8.2 ± 0.5	8.9 ± 0.5	9.0 ± 0.8	10.2 ± 1.0
ϕ_{20}	7.1 ± 0.5	8.0 ± 0.5	9.4 ± 0.6	10.6 ± 1.0	12.2 ± 1.2
ϕ_{21}	6.2 ± 0.5	7.5 ± 0.5	8.9 ± 0.5	10.3 ± 1.0	12.4 ± 1.2
ϕ_{22}	5.5 ± 0.3	6.8 ± 0.5	8.0 ± 0.5	9.1 ± 0.8	10.8 ± 1.0
ϕ_{23}	4.5 ± 0.3	5.4 ± 0.4	6.5 ± 0.5	7.3 ± 0.7	8.5 ± 0.7
ϕ_{24}	3.7 ± 0.3	4.3 ± 0.3	5.2 ± 0.4	5.0 ± 0.6	6.4 ± 0.6
ϕ_{25}	3.1 ± 0.3	3.4 ± 0.3	4.3 ± 0.3	4.7 ± 0.5	5.5 ± 0.5
ϕ_{26}	2.4 ± 0.3	2.5 ± 0.3	3.3 ± 0.3	3.5 ± 0.4	3.9 ± 0.4
ϕ_{27}	1.8 ± 0.3	2.0 ± 0.2	2.5 ± 0.3	2.7 ± 0.4	3.2 ± 0.4
ϕ_{28}	1.2 ± 0.2	1.3 ± 0.2	1.8 ± 0.2	2.1 ± 0.3	2.4 ± 0.4
ϕ_{29}		1.0 ± 0.2	1.2 ± 0.2	1.6 ± 0.3	1.9 ± 0.3
ϕ_{30}			0.9 ± 0.2	1.1 ± 0.3	1.3 ± 0.3
ϕ_{31}					0.9 ± 0.2

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† On leave of absence from the Israel Institute of Technology, Haifa, Israel.

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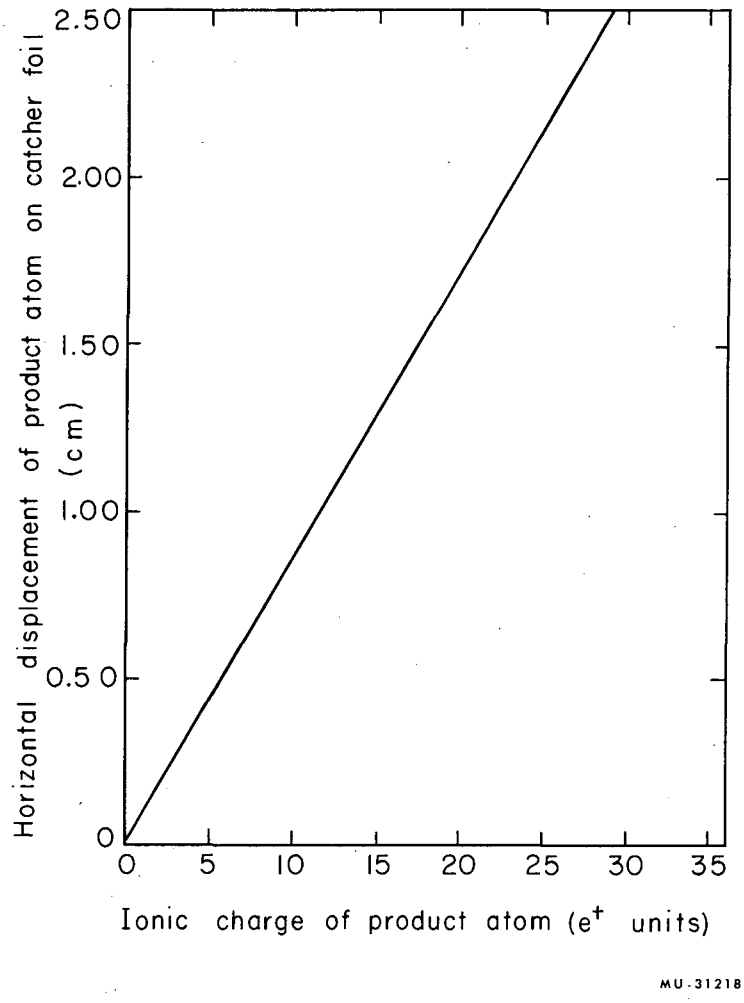

Fig. 1. Horizontal displacement of product atom on catcher foil, in cm, as a function of the ionic charge of the reaction product according to Eq. (1) for A_1=149, $\langle v \rangle = 4.5 \times 10^8$ cm/sec, H = 3150 gauss, t = 15.2 cm, and L = 5.3 cm. (The symbols are explained in the text.)

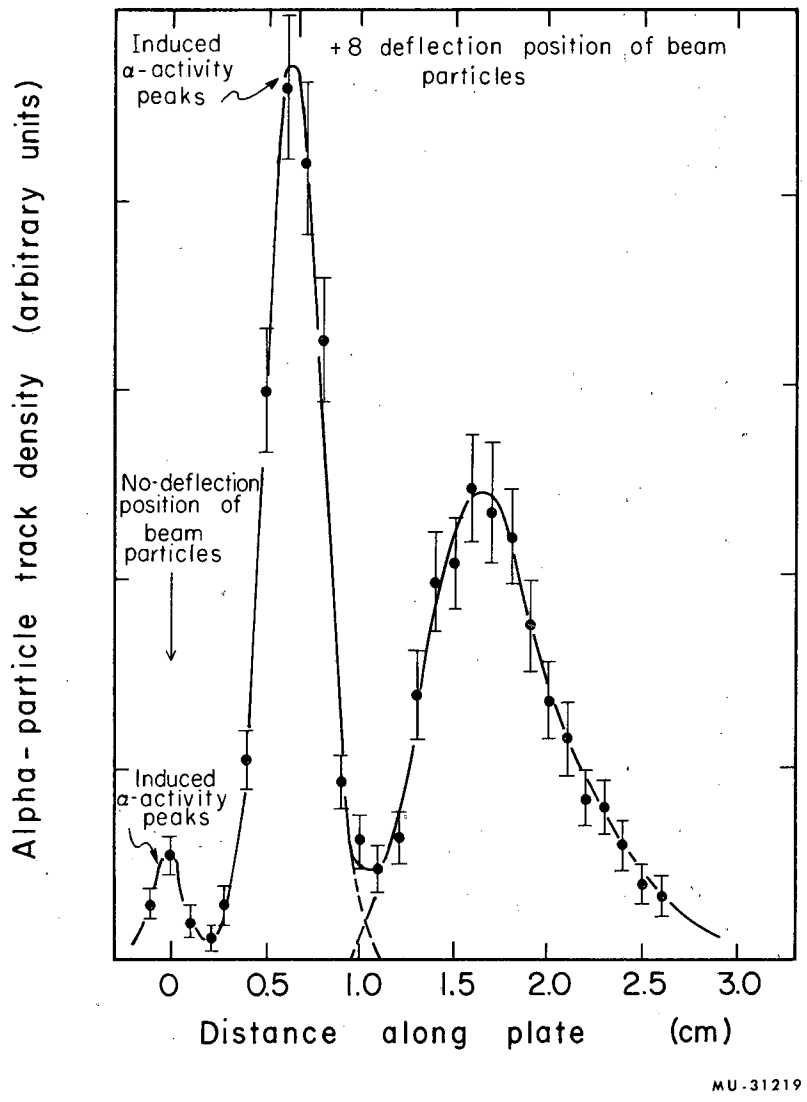

Fig. 2. Experimental scanning curve. The horizontal displacement of particles on the catcher foil (D) equals the distance along the plate as a function of the α-particle track density. The target thickness is 9.7 $\mu g/cm^2$. (The experimental conditions are described in the text).

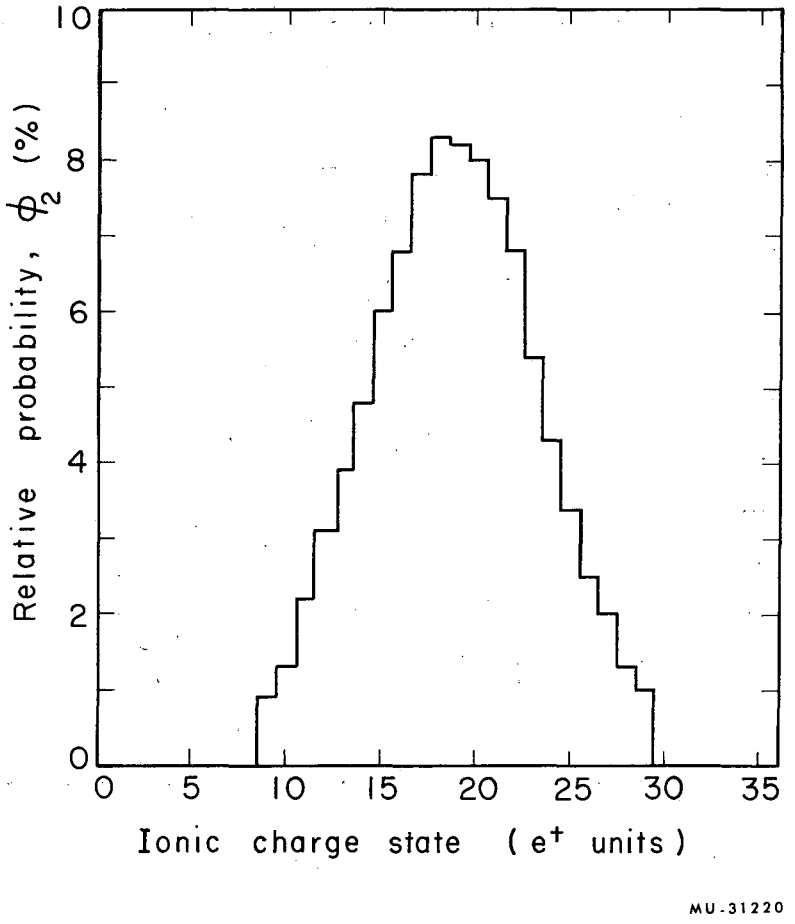

Fig. 3. Charge-spectrum histogram. Relative probability ϕ_z (%) as a function of the ionic charge state of the nuclear-reaction product. Target thickness: 26.2 $\mu g/cm^2$.

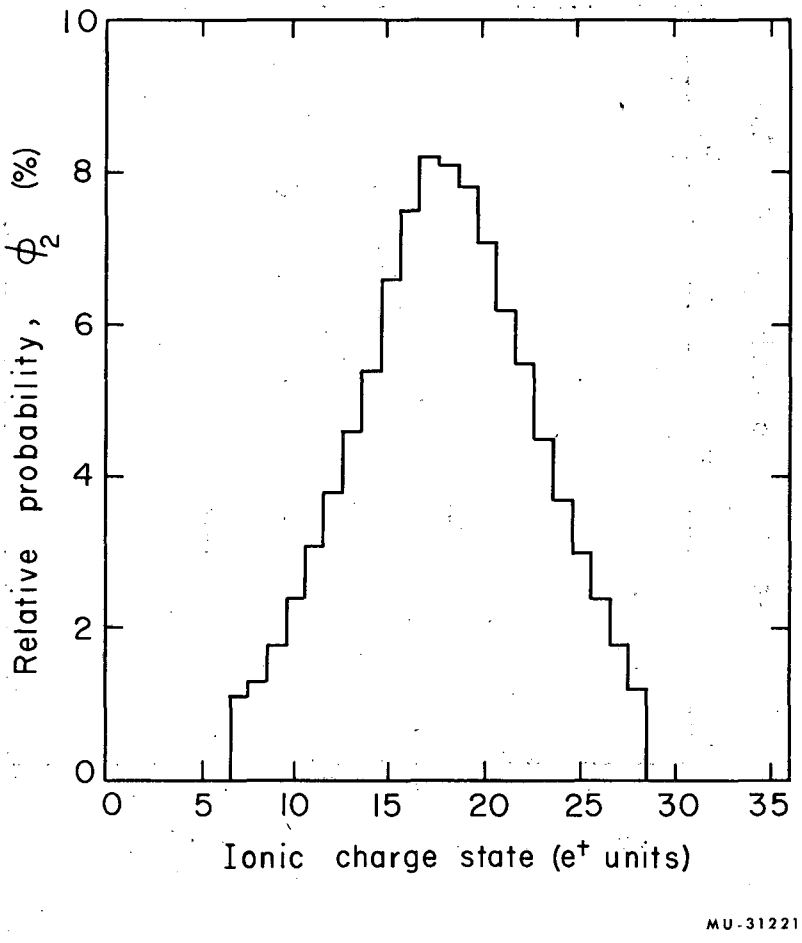

Fig. 4. Charge-spectrum histogram. Relative probability ϕ_z (%) as a function of the ionic charge state of the nuclear reaction product. Target thickness: 21.6 $\mu g/cm^2$.

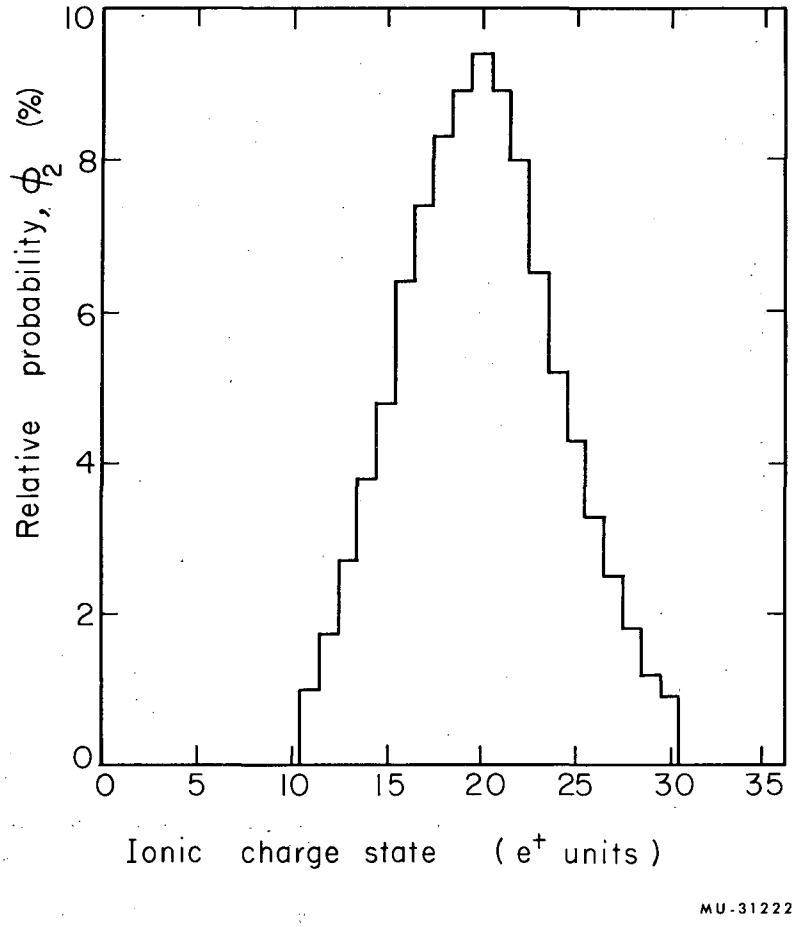

Fig. 5. Charge-spectrum histogram. Relative probability ϕ_z (%) as a function of ionic charge state of nuclear reaction product. Target thickness: 14.6 $\mu g/cm^2$.

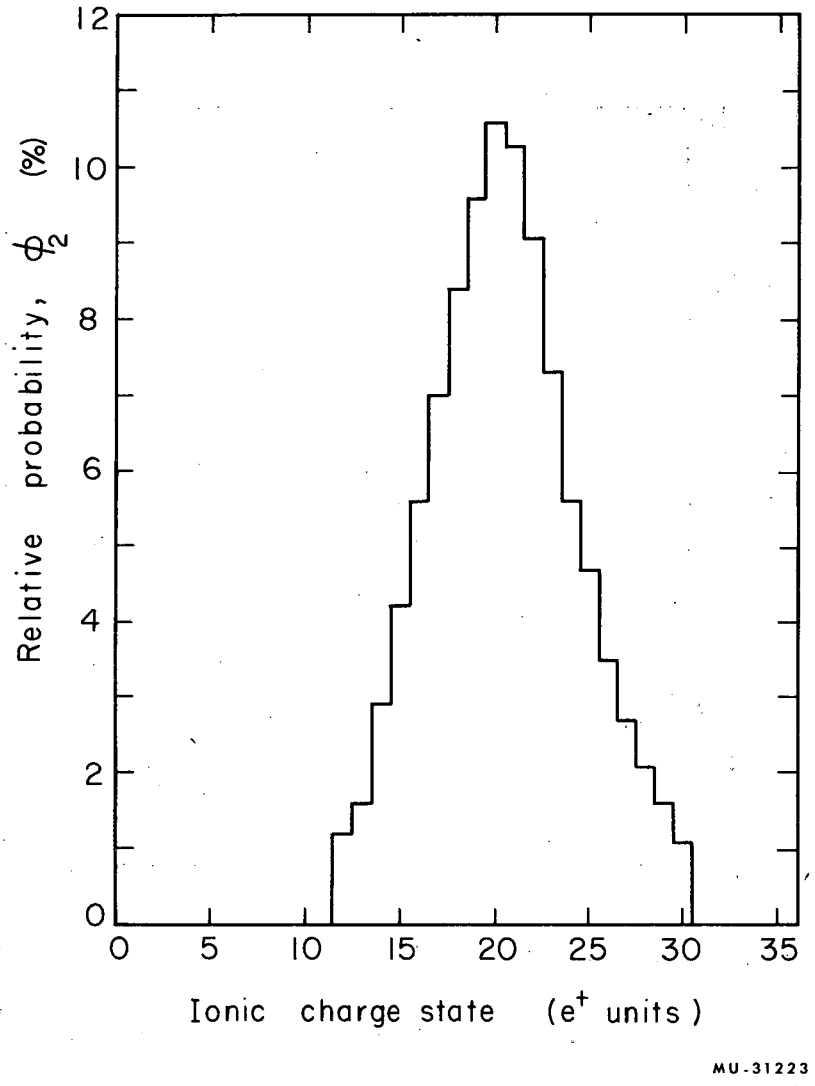

Fig. 6. Charge-spectrum histogram. Relative probability ϕ_z (%) as a function of ionic charge state of nuclear reaction product. Target thickness: 9.7 $\mu g/cm^2$.

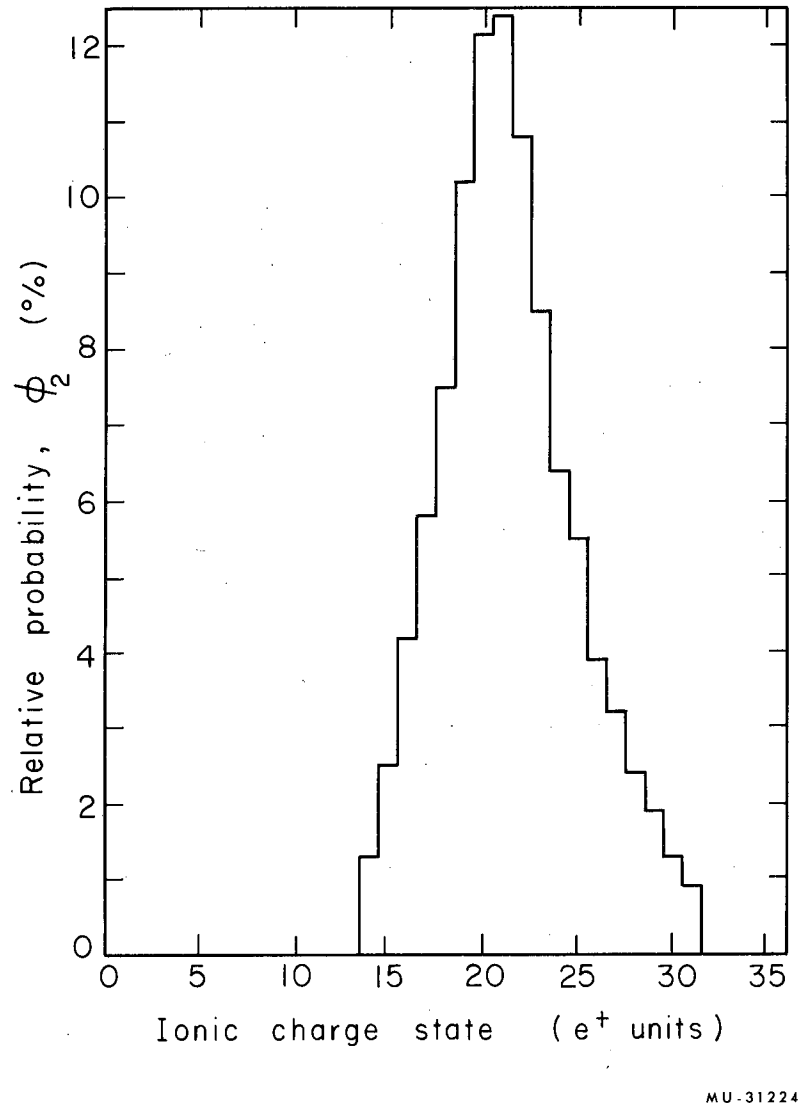

Fig. 7. Charge-spectrum histogram for zero target thickness obtained by linear extrapolation for the various charge-state probabilities to zero target thickness.

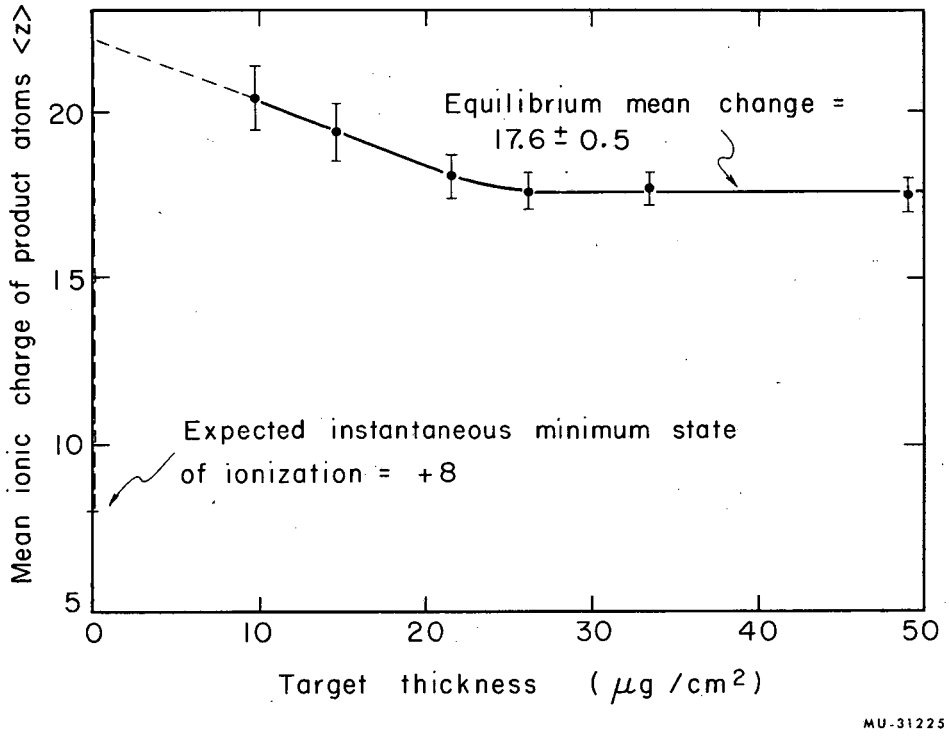

Fig. 8. Mean ionic charge of the product atom as a function of target thickness. The equilibrium mean charge is 17.6 ± 0.5. [9,10]