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ABSTRACT

The unique constraints imposed on the interactions of energetic heavy ions as a result of the channeling effect are utilized to investigate the phenomenon of radiative electron capture (REC) for 17 to 40 MeV oxygen ions. Measured cross-sections and widths of the REC radiation are compared to calculations made specifically for the channeling situation.

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I. INTRODUCTION

Highly stripped heavy ion impurities (atomic numbers $Z > 1$) are known to be present in the discharges of most present day TOKAMAK devices[1–3] and will undoubtedly be present in future controlled thermonuclear reactors as a result of sputtering and desorption of atoms from the surfaces of the surrounding confinement vessels.[1,4–5] Since the presence of impurities can strongly effect the conditions necessary for a sustained plasma[1,6] a detailed knowledge of their interactions in the plasma is essential. Furthermore, since the role played by the impurities depends on the species[1,6], such knowledge may actually dictate the acceptibility of first wall materials and limiters in future reactor designs and is thus not completely separable from the problems of first wall surface effects.

Although small amounts of impurities can have a stabilizing influence[1,7,8], on the whole they adversely effect the plasma leading to increased power radiation from the plasma, reduced fuel density, increased particle transport (scattering) out of the plasma, and increased first wall erosion[1,4,6]. The specific impurity-ion interactions involved depend sensitively on the ionization state as well as the atomic number of the impurity, and the degree of ionization reached by the impurity depends in turn on the plasma parameters. In general, bremsstrahlung and recombination radiation are the more important radiation loss mechanisms for highly ionized, high Z, impurities, while line radiation is important for less highly stripped ions[6,9–18].

In order to predict acceptable concentrations of impurities which permit ignition of a plasma[1,6], it is necessary to accurately determine the functional dependencies of the various plasma impurity-ion interactions which contribute to the energy loss effects. Experimental measurements to test existing theories are difficult to perform because it is extremely difficult to simulate CTR-type plasmas in a controlled laboratory environment. This paper reports an experimental method for studying a variety of interactions experienced by highly stripped ions in a dense, energetic electron gas[18]. The technique is suitable for studying the phenomena of radiative electron capture, ion-electron bremsstrahlung, ion energy loss, excitation, ionization and charge exchange, and is equally applicable to heavy and light ions alike. The basis of the experimental technique arises from the unique constraints imposed on the interactions of energetic ions in single crystals as a result of the channeling phenomenon[18–25].

Specific results are presented for measurements of radiative electron capture (REC) by highly stripped 17 to 40 MeV O ions channeled through thin Ag and Si single crystals. The effects of channeling on the REC phenomenon are demonstrated. Radiation is identified which results from electrons captured directly into the ground state of the fully stripped oxygen ions as well as from direct ion-electron bremsstrahlung and excited state decay. Measured cross sections and widths of the REC radiation are compared to calculations made specifically for the channeling situation.

II. ION CHANNELING

The phenomena associated with channeling of energetic positive ions in single crystals have been studied for many years and are well understood in most instances[19]. A well collimated beam of ions directed parallel to a low-index direction in a single crystal encounters symmetrically arranged rows or planes of atoms and, consequently, the ions undergo sequential collisions with the lattice atoms in which the impact parameters are correlated. The result is that the vast majority of the incident ions acquire oscillatory trajectories in the open regions (channels) between the rows or planes of atoms. The main consequence of channeling is that it imposes unique constraints on the interactions of the channeled ions in contrast to the interactions of ions traveling in a polycyrstalline or amorphous solid, or in a random direction in a single crystal.

A number of these channeling effects that are relevant to the present investigation have been studied extensively[18–25] and form the basis for the experimental technqiue reported in this work[18]. The behavior of 10–40 MeV O ions transmitted parallel to the low index planar and axial directions of thin Au and Ag single crystals are well understood on the basis of channeling models which have been used to: 1) deduce the parameters of the interaction potential between the channeled ions and atoms of the solid[20,21]; 2) relate the stopping power of channeled ions to the ion trajectory and random stopping power[20,21]; 3) determine the charge-changing cross-sections of channeled versus randomly directed ions[18,22–24]; 4) determine the effects of dynamic screening and ionic charge state on the stopping power of fully and partially stripped, channeled oxygen ions[24]; and 5) completely characterize the axial channeling behavior of oxygen ions as a function of incident charge states[25].

The important consequences from these studies to the present investigation are that more than 95% of the oxygen ions are channeled along the major axial directions ([001] and [011]) and never approach closer than ~ 10^{-9} cm to atoms on normal lattice sites thereby eliminating interactions such as characteristic x-ray excitation which require close impacts (~ 10^{-12} cm). Because of the channeling effect[18,22–24] oxygen ions incident with charge states 8^+ (fully stripped), 7^+ and 6^+ are virtually unable to capture electrons in a channel. This can be seen from the measured charge distributions for 27.8 and 40 MeV oxygen ions shown in Fig. 1[24]. When O^{8+}, O^{7+}, or O^{6+} ions are incident in a random direction of a thin Ag single crystal, the emerging ions have an equilibrium charge state distribution independent of input charge states (dashed curves). However, when incident in a channeling direction ([011] axis) the emerging ions are predominately fully stripped (O^{8+}) and are not at equilibrium. Very recent measurements[25] suggest that much of the capture and loss that does occur for channeled ions occurs in the several monolayers of surface contamination present on the entrance and exit surfaces of the crystals. If this is so, then the charge state distribution inside the crystal would be even more heavily weighted toward O^{8+} than shown in Fig. 1. As we shall see, this behavior is very significant for the investigations reported here.

III. MEASUREMENTS AND RESULTS

1. Experimental Apparatus

The experimental arrangement is similar to that described previously[18–24]. Ion beams from a Tandem Van de Graaff were passed through a thin carbon stripper foil, charge selected in an analyzing magnet, collimated to an angular divergence $\lesssim 0.05°$ full width, and directed onto a thin single crystal held in a three axis goniometer. Oxygen ions transmitted through the crystal were charge and energy analyzed using an electrostatic analyzer or a high resolution magnetic spectrometer. Thin self-supporting single crystals of Ag and Si[26] were oriented relative to the incident beam with an accuracy of 0.01° using the goniometer. A Si(Li) detector with an active area of 25 mm^2 and 190 eV resolution (FWHM) for 5.9 KeV x-rays was positioned at 90° to the incident beam direction, 5.5 cm directly below the point where the beam intersected the crystal. The detector was isolated in its own vacuum by a 1.2×10^{-4} cm Be window. A calibrated beam monitor was used to obtain yield measurements.

2. Radiative Electron Capture (REC) and Bremsstrahlung

A wealth of phenomena contribute to the x-ray distributions observed when solids are bombarded with energetic heavy ion beams[9–18, 27]. Contributing effects observable for 10–40 MeV O ions bombarding Ag and Si single crystals were characteristics x-rays from the target atoms and projectile ions, inverse bremsstrahlung resulting from the action of the Coulomb field of the incident nucleus on the target electrons, secondary electron bremsstrahlung produced by recoiling knock-on electrons interacting with target atoms, and radiative electron capture. This paper will report detailed studies of the REC phenomenon only.

Capture of a target electron by a highly stripped projectile ion can proceed either radiatively or non-radiatively. Normally, non-radiative electron capture is the dominant mechanism but important constraints imposed on channeled heavy ions tend to favor the radiative process. The accepted mechanisms of non-radiative capture require that a bound electron be captured[14]. Since channeled ions never approach closer than ~ 10^{-9} cm to atoms on normal lattice sites their probability of interacting with bound electrons is reduced over that for ions interacting in a random fashion with the atoms of a solid. This tends to suppress non-radiative capture and certainly contributes in part to the greatly reduced charge exchange cross-sections observed for channeled ions. Although the cross-sections for radiative capture are in general smaller than those for non-radiative capture because of the coupling of the electron with the electromagnetic field of the emitted photon, the REC process can proceed by capture of free as well as bound electrons since the photon emission allows for energy and momentum conservation. Furthermore, channeled ions interact freely with the weakly bound or conduction electrons by virtue of their trajectories in the single crystal. At sufficiently high ion velocities radiative charge transfer can become the dominant mechanism even for bound electrons[28].

The energetics of the REC process for a projectile ion of mass M_1, atomic number Z_1, and incident energy E_1, bombarding a solid target (M_2, Z_2) are shown schematically in Fig. 2 as viewed from the rest frame of the projectile ion. The energy of the emitted REC photon ($E_{REC} = Z_1^2 Ry + \frac{m_e}{M_1} E_1$ where Ry = 13.6 eV) is seen to depend on the charge state of the ion, Z_1, and the incident ion energy E_1. The width of the REC line should be determined by the velocity distribution of the electrons in the solid captured by the ion. This, in fact, was the motivation for the initial REC studies in single crystals[18].

3. Basis of Experimental Technique

The basis of the experimental simulation technique being considered derives from the restricted interactions experienced by channeled heavy ions. As an example, when 27.78 MeV O^{7+} ions are incident parallel to the [011] axial direction of a 0.62 μm Ag single crystal, approximately 97% of the incident ions are channeled between the symmetrically arranged rows of lattice atoms and consequently do not approach closer than ≈ 0.2Å to any target atoms while passing through the crystal. The other ≈ 3% of the ions have close encounters with the ends of the atom rows on entering the crystal, are deflected through angles too large to be channeled, and interact with the atoms of the single crystal in a normal fashion. (This 3% is referred to as the minimum yield fraction.) The consequences of the channeling effect on the observed photon spectrum for the case being discussed are illustrated in Fig. 3. When the single crystal is purposely misoriented so that the ions encounter the lattice atoms at random as they would in an amorphous or polycrystalline Ag sample one obtains the spectrum labeled random (solid circles) in Fig. 3. The prominent features above 2.5 KeV are characteristic Ag L x-rays excited by the incident oxygen ions. When the beam is incident along the [011] (open circles Fig. 3) the yield of Ag L x-rays is reduced to ≈ 3% of that observed for the random orientation, i.e., only those ions <u>not</u> channeled, the minimum yield fraction, excite Ag L x-rays. The two spectra in Fig. 3 have been normalized by the minimum yield fraction for comparison purposes and corrected for x-ray absorption effects. More strikingly, however, is the prominant peak evident in the channeling spectrum between 1.5 KeV and 2.0 KeV. This peak results from radiative electron capture of target conduction electrons as illustrated in Fig. 2. As we shall see later, the energy of this peak is consistent with capture of a free electron by a fully stripped O ion into its innermost shell and the width, which is determined by the velocity distribution of the electrons in the [011] channel which are captured, shows reasonable agreement with expectations. The spectrum labeled [001] in Fig. 2 represents another aspect of the present study and will not be discussed here.

Radiative electron capture by highly stripped heavy ions was first observed by Schnopper et al. [13] for energetic heavy ion bombardment of polycrystalline targets. The advantages of the present technique of measuring REC in single crystal targets are: 1) channeled ions are predominately of one charge state for the reasons discussed earlier in connection with Fig. 1. In contrast, heavy ions incident in polycrystalline solids, have a distribution of charge states[14] and the energies and widths of the observed REC photons will interfere and complicate interpretation. Close scrutiny of the random spectrum in Fig. 3 shows evidence for a poorly resolved broad peak at about 1.3 KeV. This is likely due to REC to various oxygen charge states. 2) The channeling effect greatly reduces close encounters between the ions and bound target electrons without diminishing the ion interactions with the free or conduction electrons. This renders the REC of free electrons a much more prominent feature relative to the characteristic target x-ray background (as Fig. 3 shows) and thus more amenable to direct investigation. 3) In the channeling configuration most of the incident ions appear to be in a single charge state interacting primarily with conduction electrons. Therefore, viewed from the rest frame of the projectile, a 40 MeV O^{8+} ion interacting with the electrons in the [011] channel is the experimental analogue of a fully stripped oxygen impurity ion bombarded by a 1.4 KeV electron gas with a density the order of 10^{22} to 10^{23} electrons/cm^3. This situation should approximate the interactions experienced by an impurity ion with the dense energetic electrons in a CTR-type plasma sufficiently to make the channeling technique a viable simulation method for investigating the functional dependence of the REC phenomenon.

IV. RESULTS

Measurements were made for oxygen ions with energies from 17.8 to 40 MeV transmitted parallel to the [001] and [011] axes of Ag single crystals ranging in thickness from 0.4 to 0.8 µm and the [011] axis of a 2.8 µm thick Si single crystal. Various selected input charge states were used.

a) REC Peak Energy

The energetics of the REC process, Fig. 2, indicate that the REC peak energy should vary with incident ion energy, E_1 and charge Z_1 as $E_{REC} = Z_1^2 Ry + \frac{m_e}{M_1} E_1$. Results for a variety of measurements using O^{6+}, O^{7+} and O^{8+} ions in Ag [011], (100) and random directions and in Si[011] are summarized in Fig. 4. Regardless of the input charge state of the ion, it appears that, excepting the random case, the REC peak energy is most nearly that expected for capture into a fully stripped O^{8+} ion. This is in agreement with earlier charge state measurements which indicate that the ions rapidly go to 8+ in the crystal channel[22-25].

b) REC Cross-Sections

It is also possible to extract REC cross sections and line widths from the measurements. The yield of REC relative to Ag L x-rays for a channeling situation can be obtained from the areas under the respective peaks in a corrected spectrum such as Fig. 3. The reduction in the Ag L x-ray yield in going from a randomly oriented to a channeling target configuration (i.e., the minimum yield fraction) can be accurately measured using the beam monitoring arrangement. Since the absolute Ag L cross-section has been measured[29], it is then possible to obtain cross sections for REC by comparison. Results from our measurements on Ag and Si are compared in Fig. 5 to two separate theoretical calculations and to measurements by Schnopper et al.[17] for REC by oxygen ions in N_2 and O_2 gasses. The ion charge state at each incident energy is indicated on the left hand figure and one can see that there are no strong input charge effects. Measured REC cross-sections for planar channeling, (100), appear to be lower than axial results at the same energy, and the one Si point appears considerably lower than the comparable Ag result. The Si measurement is, however, somewhat speculative because of the difficulty in extracting the REC peak from the tail of an intense Si K x-ray line. The data corrections for absorption and angular dependence listed on the figure were applied to the present results only while charge state corrections were applied to the results of Schnopper et al. as well. The charge state corrections were made on the assumption that only the fraction of oxygen ions which are 8+ contribute substantially to the REC cross-sections. These charge state corrections are not exact and represent an upper limit. However, the corrections are in the right direction since theoretical calculations[12,14] indicate that free electrons are most likely to be captured into the innermost shell, and O^{7+} capture is less probable than O^{8+} capture because of the density of states.

The line labeled σ_{BS} is the calculated REC cross-sections for capture to O^{8+} based on the Bethe and Salpeter[12] formalism. The curve labeled σ_{RN} is a calculation made specifically for the channeling conditions of the present experiments. The calculation uses standard radiation theory together with a statistical model of the electron states in a single crystal. The space varying electron density is averaged over impact parameters appropriate for channeled ions. A detailed account of these calculations will be forthcoming[30].

c) REC Line Widths

Radiative electron capture line widths extracted from measurements such as those in Fig. 3 and corrected for detector resolution are shown in Fig. 6 as solid bars. Measurements were made for various input charge states, energies and crystal thicknesses. The vertical extent of the bars encompass all such effects at each incident energy. The solid line labeled RN are the line widths calculated specifically for REC by O ions channeled in Ag single crystal channels[30]. The dashed line was calculated from a free electron formalism presented by Schnopper et al.[17].

V. DISCUSSION OF RESULTS

The phenomena of electron capture are not well understood. Only the very simplest cases for capture of a bound electron by hydrogen or helium ions have been treated[14]. There are essentially no treatments applicable to bound electron capture by heavy ions, particularly partially stripped heavy ions. Radiative electron capture, is by comparison, based on a more reliable theoretical framework[12] and one would expect REC cross section calculations to show the proper dependence on ion energy and charge, and line width calculations to give a good account of the measured photon distributions. However, the cross-section measurements reported here (Fig. 5) show substantial differences in magnitude and shape from the Bethe and Salpeter theory (σ_{BS}), and although there is good magnitude agreement with the more pertinent calculations (σ_{RN}) there is still a significant difference in functional dependence. The source of this disagreement is now known at the present time. It appears from previous measurements of the energy loss and charge states of channeled oxygen ions[18,23-25], and from the incident ion energy dependence of the REC peaks (Fig. 4) that the channeling measurements reported here deal primarily with O^{8+} ions interacting in a free electron gas environment. This is an experimental situation that should be most amenable to the theory (i.e., hydrogen-like ions in a free electron gas). At energies less than 10 MeV the channeled O ions begin to populate the lower charge states but if this were a serious source of disagreement then the charge state correction made to the data should have brought the measured cross sections in Fig. 5 into agreement with the calculations. Obviously more detailed experimental investigations as well as correlated theoretical calculations are required.

The measured widths (Fig. 6) are in reasonable agreement with the calculations which take account of the electron states actually sampled by the channeled ions. These results are very encouraging since they indicate that REC experiments in the channeling configuration may be a viable new tool for measuring the velocity distributions of electrons in single crystal channels.

Resolution of these apparent discrepancies is also important for evaluating the usefulness of this heavy ion channeling technique as a means of simulating a plasma-like environment for studying pertinent impurity ion interactions such as REC and bremsstrahlung. There are obviously differences between this simulated environment and an actual CTR plasma, but whether these differences seriously affect the direct applicability of such measurements is not at all clear. The proposed technique has several attractive features. The unique environment provided by the channeling effect allows one to study an ion of a single charge state interacting with a dense electron gas bounded by positively charged nuclei. The interactions experienced by the heavy ion should be similar to those experienced by an impurity ion as a result of electron bombardment in a plasma and this technique provides a means of studying these interactions in a controlled laboratory environment. The species of heavy ion can be easily varied by changing heavy ion beams from the accelerator and the relative energy of the electron gas $(\frac{m_e}{M_1} E_1)$ by varying the ion energy E_1. As a result of the channeling effect, other specific processes associated with free electron interactions and pertinent to impurity ions in a plasma can also be investigated; besides REC these include inverse bremsstrahlung, ion energy loss, excitation ionization and electron multiple scattering.

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FIGURE CAPTIONS

Fig. 1. Measured emergent charge state distributions for oxygen ions transmitted in a random direction and [011] axial channel of a 0.8 µm Ag single crystal[24].

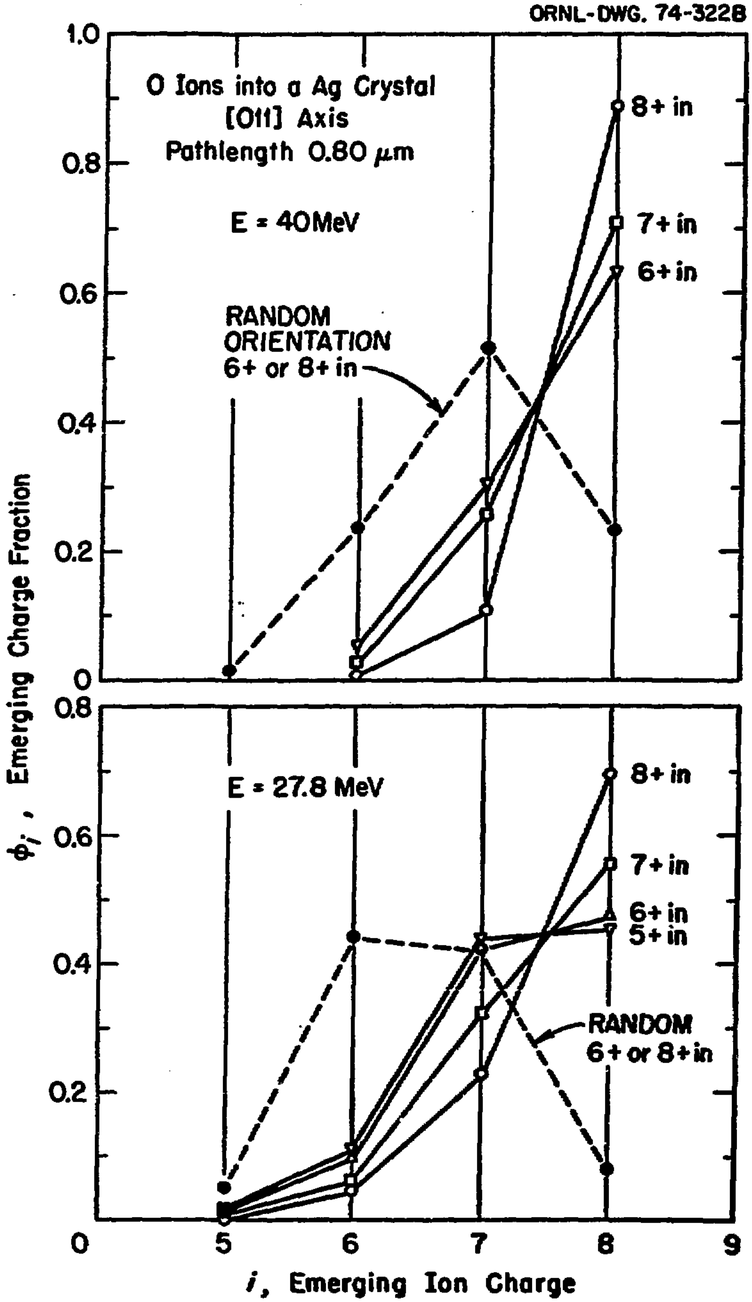
Fig. 2. Schematic representation of the radiative electron capture effect viewed from the rest frame of the projectile ion.

Fig. 3. Normalized photon spectra for 27.78 MeV O^{7+} ions transmitted in a random and [011] axial direction of a 0.64 µm Ag single crystal.

Fig. 4. Measured REC peak energies versus incident ion energies compared to calculations.

Fig. 5. Corrected REC cross sections measured for various input charge states, energies, and targets, and compared to theoretical calculations (see text).

Fig. 6. Measured widths of REC peaks compared to theoretical calculations.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O Ions into a Ag Crystal
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Pathlength 0.80 μm
E = 40MeV
RANDOM ORIENTATION 6+ or 8+ in
8+ in
7+ in
6+ in
E = 27.8 MeV
8+ in
7+ in
6+ in
5+ in
RANDOM 6+ or 8+ in
φᵢ , Emerging Charge Fraction
1.0
0.8
0.6
0.4
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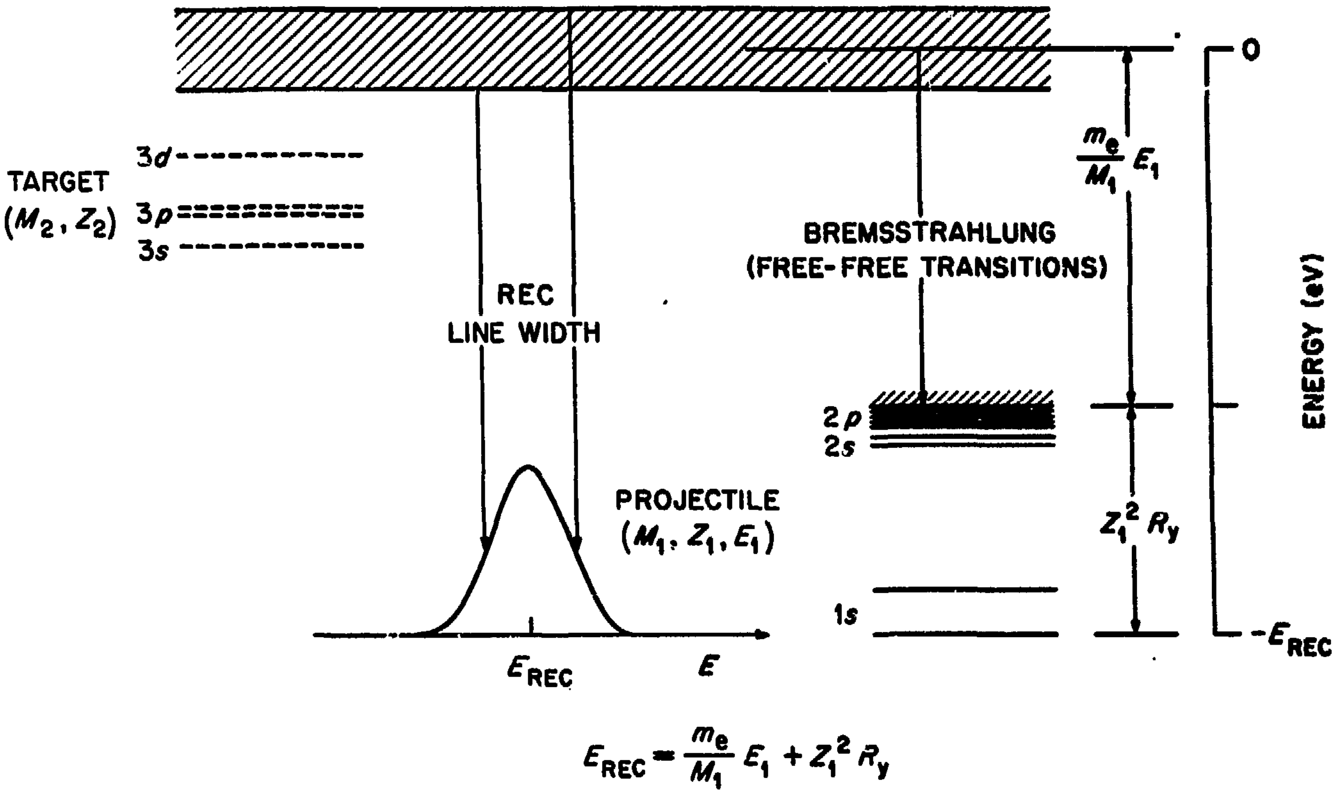

Radiative Electron Capture Schematic.

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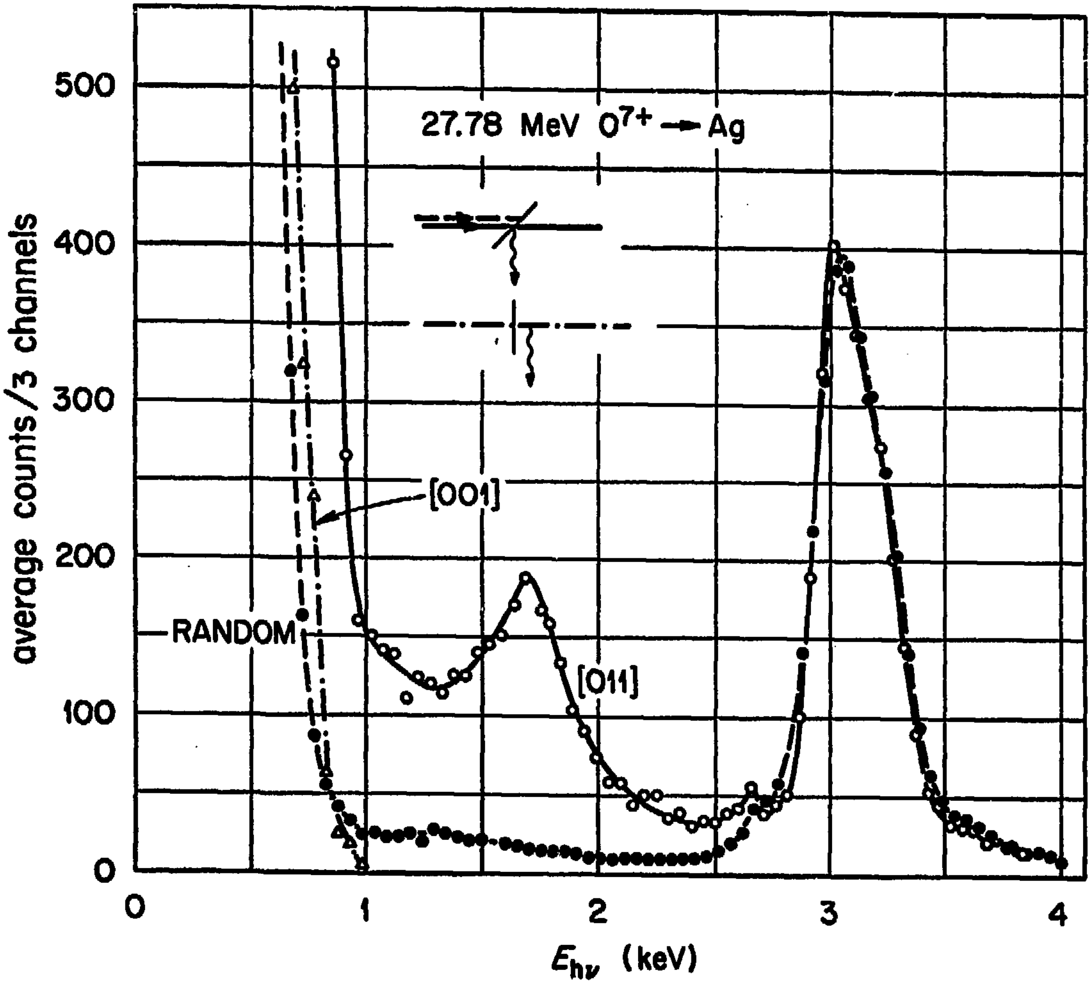

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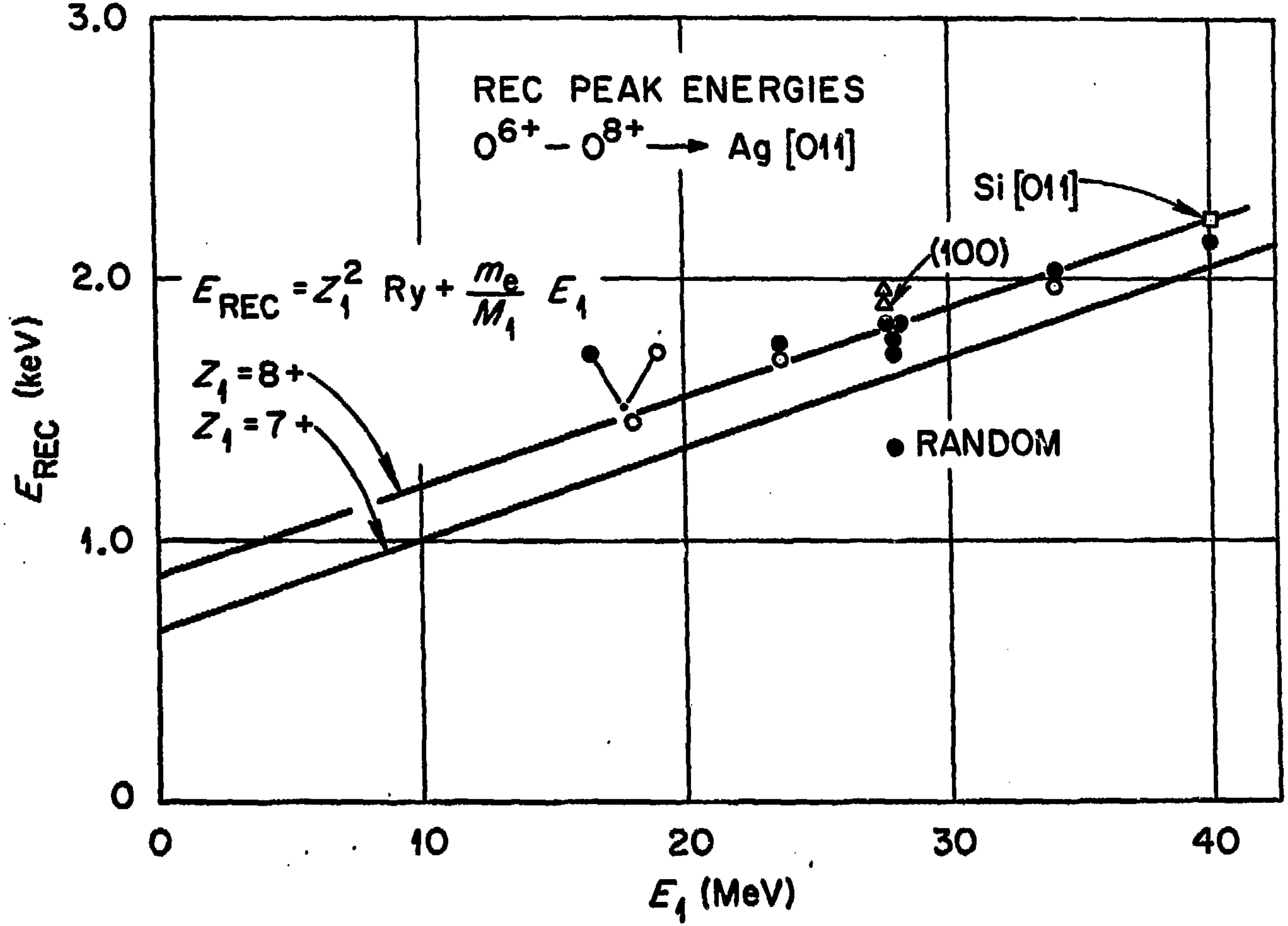

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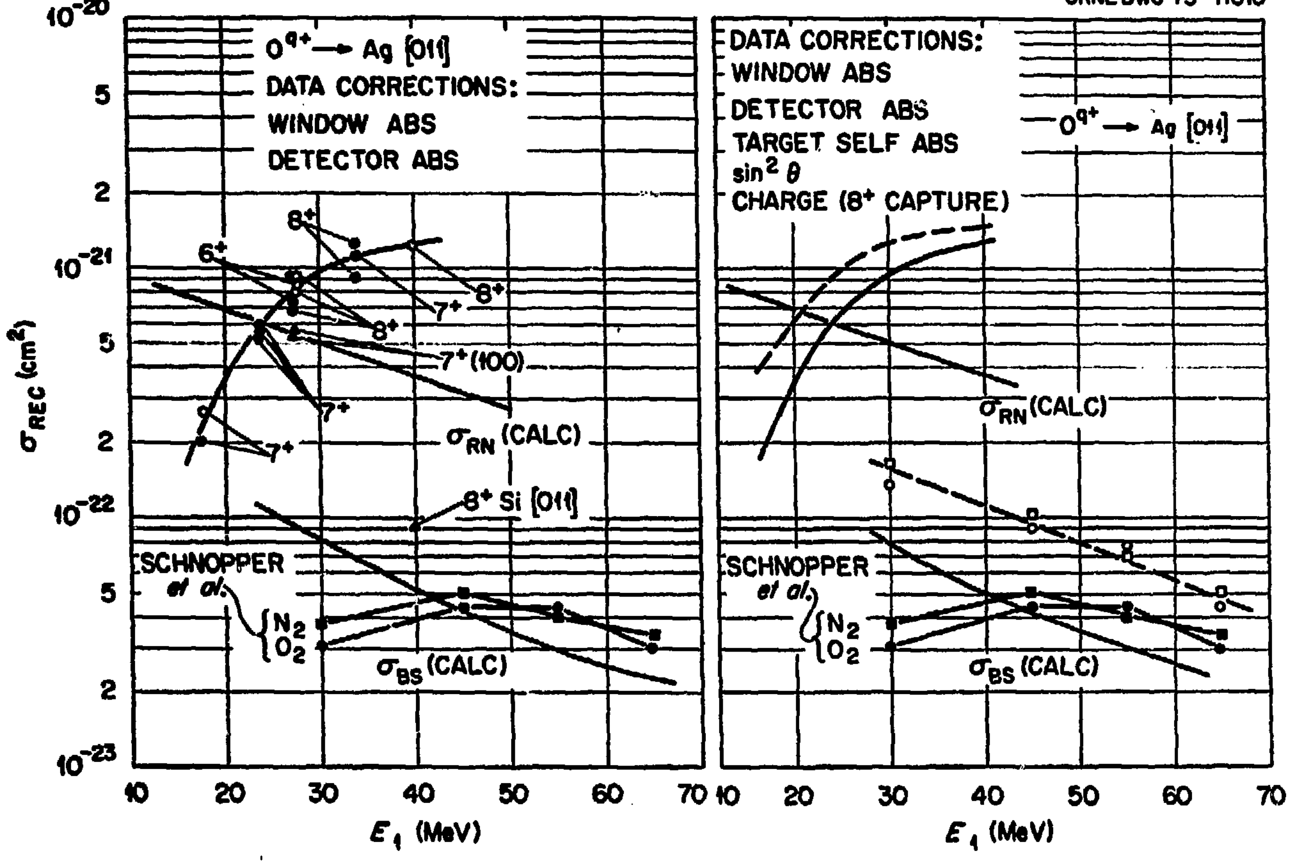

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