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MEASUREMENT OF INELASTICITIES FOR CHARGE CORRELATED MULTIPLE IONIZATION OF Ne BY FAST C^{6+} IONS*

R. SCHUCH, S. DATZ, P. F. DITTNER, H. F. KRAUSE, and P. D. MILLER

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377, U.S.A.

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Abstract

A description of measurements of inelasticities for multiple ionization in fast-single collisions is given for the example of 10 MeV C^{6+} ions with Ne atoms. The degree of multiple ionization was determined by time-of-flight of the recoil ions, extracted by an electric field in coincidence with the projectiles. Their energy loss for a given degree of multiple ionization was measured with a position-sensitive silicon detector in the focal plane of an Elbek magnetic spectrograph with an energy resolution of about 10^{-4}.

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1. Introduction

Translational energy spectroscopy has been shown to be a very useful tool in the study of slow ion-atom collision processes. The slow collision regime is defined here to mean that the ion velocity is not very different from the Bohr orbital velocity of the electrons involved in the reaction. The kinetic energy of the projectile, in this case, is only a few orders of magnitude higher than the inelasticity, i.e., the electronic excitation energy of the collisions investigated [1-3]. Therefore, even with low energy resolution of 10^{-3}, one could isolate certain reaction channels in the inelasticity. The small number of reaction channels and active electrons involved in slow collisions also contributed strongly to the success of these methods.

At higher collision energies (MeV/nucleon), translational energy spectroscopy has only been applied to cases of ionization and capture of inner-shell electrons [4,5]. Here, lack of interest in this technique is due to the facts that (1) the inelasticity becomes smaller than the energy resolution of the available spectrographs, and (2) the number of reaction channels and active electrons in an ion-multielectron target collision increases strongly with energy. If multielectron effects are of interest, translational energy spectroscopy might be very useful, even at high collision energies.

Here we report measurements of projectile energy loss involving multiple target ionization in single collisions using a magnetic spectrograph of the Elbek design [6]. The degree of multiple ionization is obtained by

projectile-recoil ion coincidences and time-of-flight. Some of these results are discussed in comparison with an independent particle model. We describe the energy calibration of the magnetic spectrograph and present data for the inelasticity in collisions of 20 MeV C^{6+} with Ne target atoms.

2. Experiment

A schematic view of the experimental setup is shown in fig. 1. The 10 MeV C^{3+} beam was obtained from the EN-tandem Van de Graaff accelerator at the Oak Ridge National Laboratory, and was post-stripped (PS) after the first 90° magnet. The regulation slits S(1) were closed to about 0.1 mm in order to define the beam energy with the second 90° magnet. After the second 90° magnet, the charge state and the beam energy spread were determined by S(1) together with slits S(2). The angular divergence was defined by another slit S(3) located in front of the gas cell. Slits S(2) and S(3) were closed to about 0.1 mm.

The gas cell (GC) was differentially pumped with three pumping stages. With the target at full pressure (1 mT) a pressure of 10^{-7} could be kept in the beam line. Two independent connections to the gas cell were used, one for gas inlet, the other for the pressure measurement with a capacitance manometer. The gas cell could be floated up to a potential of 5 kV for calibration measurements that are described later. Recoil ions produced by the beam-target interaction were accelerated and, after passing through a 4-cm drift region, detected with a double channelplate (CP) device. Coincidences between projectiles and the recoil-ion charge states were determined by time-of-flight (TOF) [7,8]. The total detection efficiency

of the recoil ions was determined in the following way: The number of projectiles undergoing capture N_{q-1} and the number of coincidences of these q-1 projectiles with recoil ions (n_Q) summed over all recoil-ion charge states (Q) were determined. The efficiency is then

$$e = (\sum_Q n_Q)/N_{q-1} \ .$$

We assumed equal efficiency for all recoil-ion charge states. An efficiency of 20% at an extraction voltage of 800 V was obtained.

About 50 cm after the gas target, the projectile ions entered the field of the Elbek spectrograph [6]. The spectrograph vacuum was in the low 10^{-6} Torr range with the gas target in operation. For optimum resolution, the maximum bending radius of about 1.2 m was chosen by positioning the position-sensitive detector (PSD) in the focal plane. In the first experiments reported here, a linear position-sensitive silicon detector of 15 mm length and .15 mm resolution was used. With the large dispersion of the magnet, of course, only one exit charge state of the projectile (for example q-1) could be detected in the PSD for a given setting of the magnetic field. The main beam was stopped in a Faraday Cup (FC). The count rate in the q-1 channel was less than 2000 Hz depending on the target pressure. In this projectile channel, as well as in the recoil-ion detector, a negligibly small background count rate was measured with no gas in the cell.

The study of coincidences between projectile and recoil ions not only allowed us to determine the recoil-ion charge state by time-of-flight, but also allowed us to relate it to the corresponding projectile energy loss. The energy pulse height, the position in the PSD, and the recoil-ion time-of-flight were analyzed on-line using a VAX-750 computer.

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3. Energy calibration

In order to obtain absolute values for the inelasticity, an energy calibration of the position in the PSD is necessary. This was achieved by detecting either the capture ($q \rightarrow q-1$) or loss ($q \rightarrow q+1$) channel in the PSD, and applying a known voltage to the gas cell. This voltage was typically 5 kV positive, so that, e.g., the q-1 ions which captured inside the cell lost energy in the amount of the potential applied to the cell compared to the primary beam energy. In fig. 2, a position spectrum for a potential of 4 kV is shown. The main peak in this spectrum is due to the projectile ions that captured an electron while in the cell and this peak is shifted from that observed with no voltage on the cell. The small peak observed at about channel 195 is therefore from ions which capture outside the cell in the gas flowing out the entrance and exit of the cell. The almost constant pressure dependence of the ratio of the intensity these two peaks and the low background count rate support the conclusion.

The potential applied to the cell was measured via a resistive voltage divider with a Keithley voltmeter. In a separate measurement, we determined the division factor of the resistor chain. The error in the absolute value of the potential is estimated to be of the order of 5%.

4. Charge state distribution and inelasticity

The charge state distribution of the Ne recoil ions measured in coincidence with electron capture of 10 MeV C^{6+} incident ions is shown in fig. 3 by open bars. The statistical errors vary from 12% at the lowest yield to 2% at the highest yield. Most probably two electrons are ionized simultaneously with the capture of an additional electron. For comparison

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with the binomial distribution, we assumed the ionization occurs only in the L shell of the Ne atom. This assumption was later confirmed by the inelasticity measurement. Assuming furthermore that the ionization probability per electron is independent of the number of L electrons ionized (most simple independent electron model), we compare this distribution with that generated by the binomial formula:

$$P_Q = \binom{N}{Q} \; P^Q \, (1-P)^{N-Q} \quad .$$

Where P is the L-shell single ionization probability and is obtained here by adjusting P at the measured Q=1 probability and taking N=8, the number of L electrons. The fact that the capture channel has a different impact parameter (b) dependence than the ionization channels can be seen by comparing the charge-state distributions for pure ionization and capture. The latter peaks at smaller impact parameter than for pure ionization. Therefore, in coincidence with capture, P can be taken as being localized in b.

The results of the binomial distribution are shown in fig. 3 as closed bars. The agreement with the data is surprisingly good which suggests that the independent electron model might be appropriate. However, one should be careful with conclusions from this agreement because very crude assumptions were made. Besides taking the ionization probability independent or the degree of ionization, it is also assumed here that it is equal to the capture probability for the important range of b. If we subtract the charge state from the distribution accounting for the capture from the L shell by taking N=7, the agreement of the binomial distribution becomes poorer.

Also included in fig. 3 is the comparison with the results of the classical Monte-Carlo model by Olson [9] shown as the full dots. His model includes screening by a Hartree-Fock potential, but it still represents an independent particle model. The agreement is reasonable considering the error bars in the experimental data and in the Monte-Carlo results.

In fig. 4, we show some inelasticities which were measured in coincidence with the recoil-ion charge states plotted above. These results show clearly the shift of the projectile energy loss with increasing degree of target ionization. Considering, for example, that the sum of the ionization potentials for making Ne^{5+} is 500 eV, one can see that the measured inelasticity exceeds this value by about the same amount.

5. Summary

We have presented a method for measuring the inelastic projectile energy loss for a given degree of target ionization after single collisions. The first results for 10 MeV C^{6+} single capture in Ne give inelasticities of about double the sum of the ionization potentials. A comparison of the measured multiple ionization probability accompanying capture with predictions of independent electron models show good agreement with both the binomial distribution and the results of the classical Monte-Carlo model by Olson.

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Figure captions

Fig. 1. Schematic view of the experiment setup. See text for abbreviations and slit widths. Dimensions shown are in meters.

Fig. 2. The position spectrum for capture of C^{6+} in Ne with 4 kV potential at the gas cell (further explanation, see text).

Fig. 3. Charge-state distribution for Ne recoil ion produced by electron capture of 10 MeV C^{6+}. The full bars show the binomial distribution, the dots represent the results of the classical Monte-Carlo calculation by Olson [9].

Fig. 4. Position spectrum for capture of C^{6+} in coincidence with different Ne recoil-ion charge states as marked in the figure.

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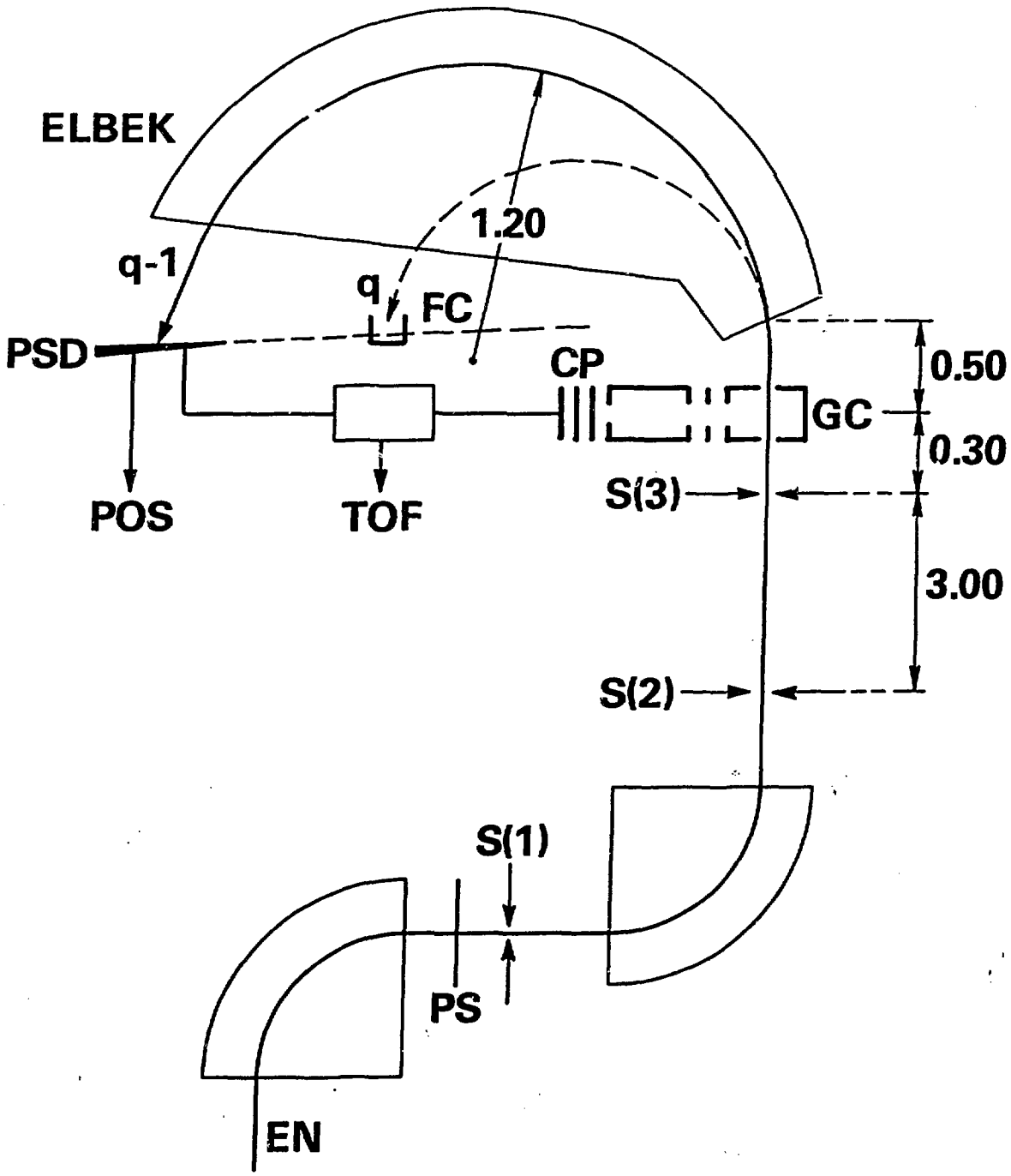
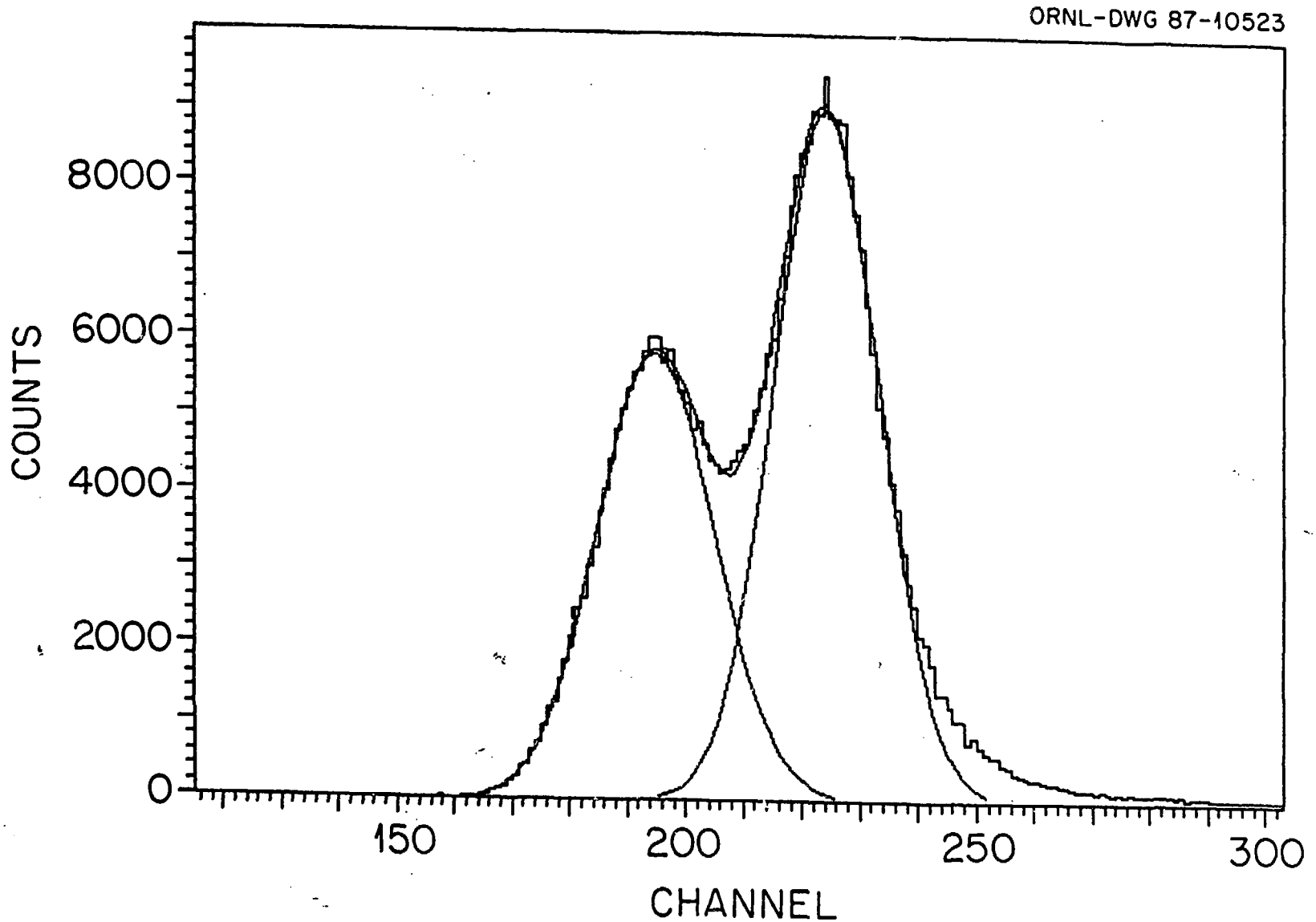


Fig. 1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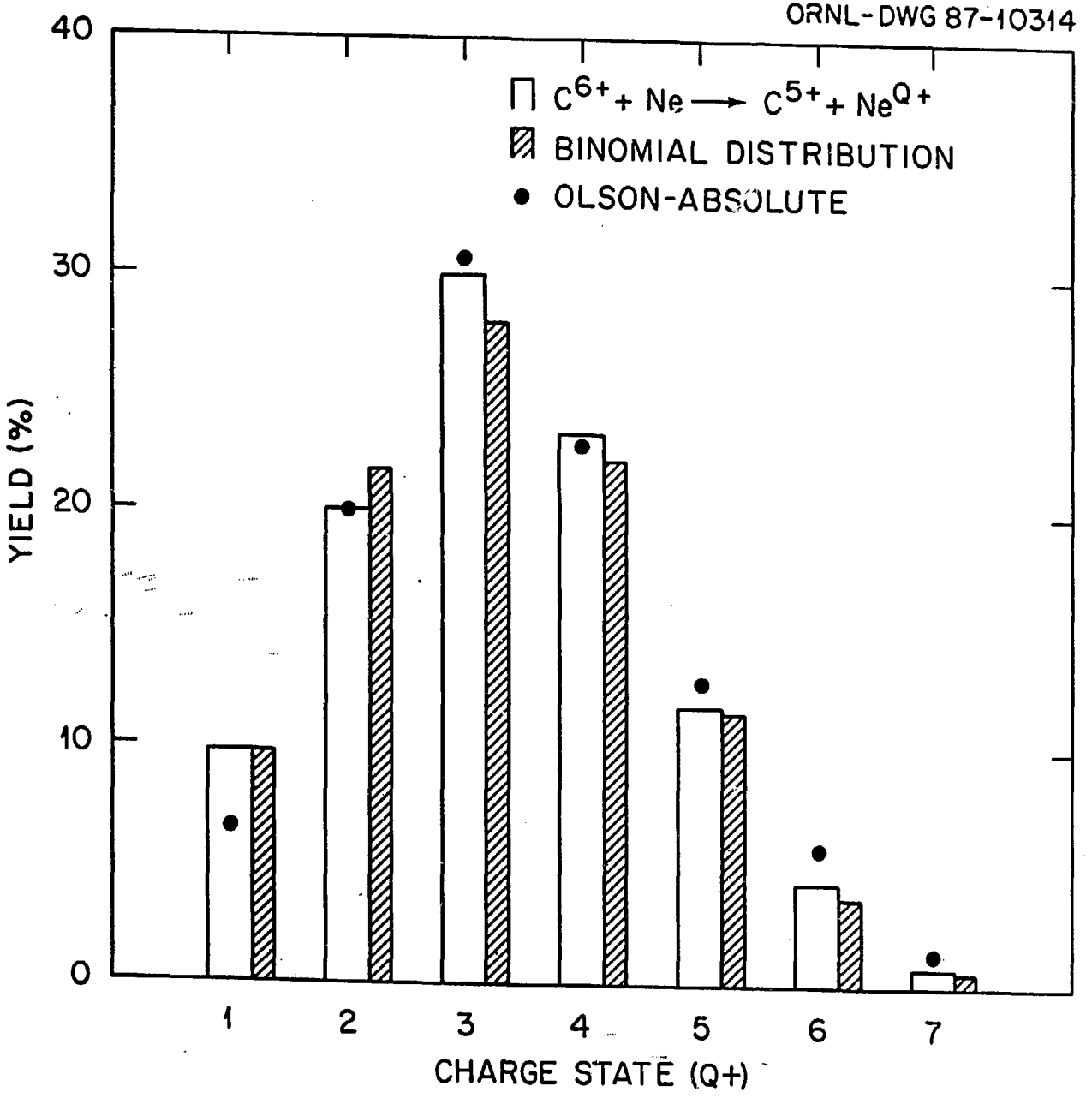
COUNTS
8000
6000
4000
2000
0
150
200
250
300
CHANNEL

Fig. 2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$C^{6+} + Ne \longrightarrow C^{5+} + Ne^{Q+}$
BINOMIAL DISTRIBUTION
OLSON-ABSOLUTE
YIELD (%)
40
30
20
10
0
1
2
3
4
5
6
7
CHARGE STATE (Q+)

Fig. 3

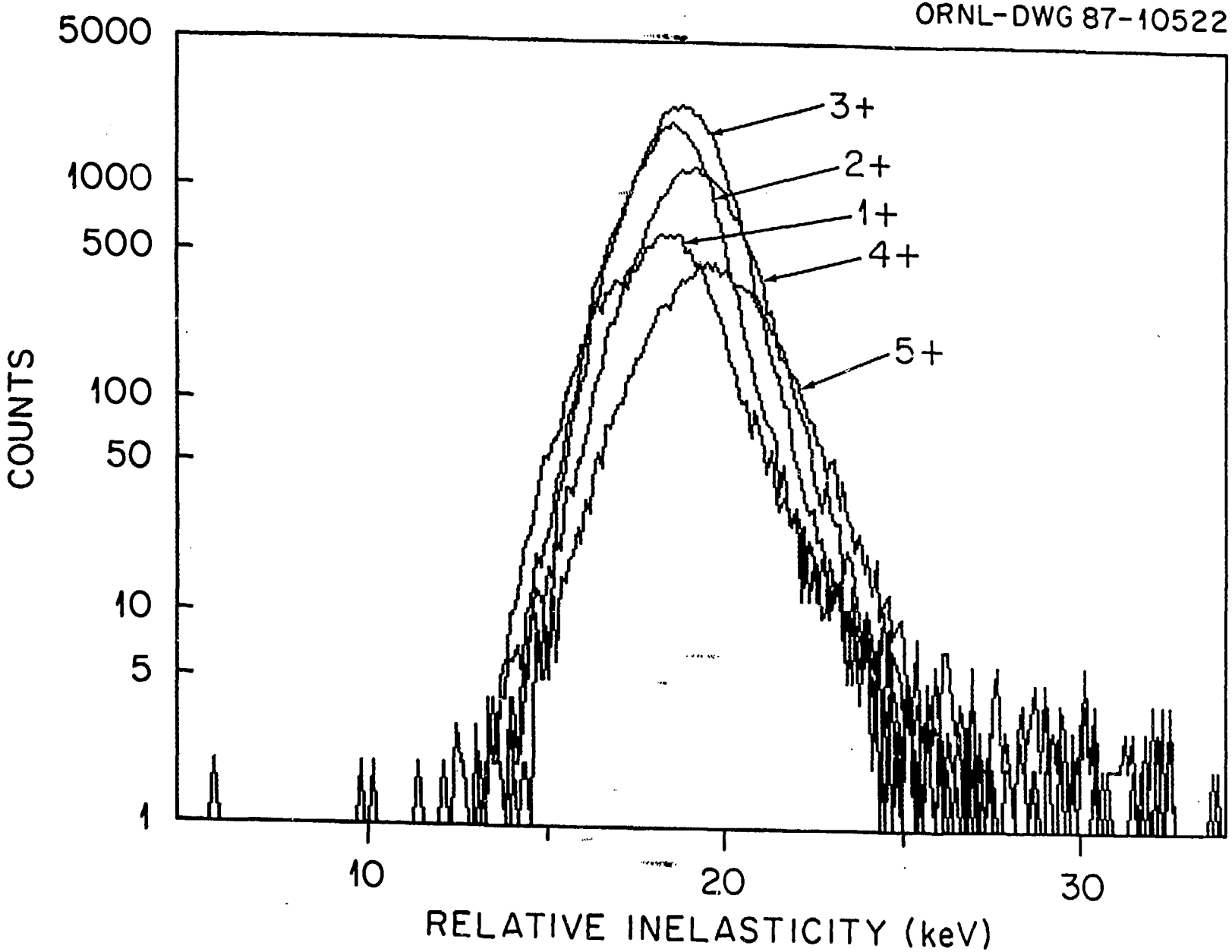
ORNL-DWG 87-10522
5000
1000
500
100
50
10
5
1
COUNTS
3+
2+
1+
4+
5+
10
20
30
RELATIVE INELASTICITY (keV)

Fig. 4