ABSOLUTE CHARGE STATE YIELDS OF 20 MeV I IONS SCATTERED FROM ARGON AND XENON*

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Summary

Absolute yields of charge states resulting from the scattering of 20 MeV Fe and I ions were determined over the range of scattering angles 0° to 1.5°. Measurements were made over the pressure range of 10^{-3} to 1 Torr as measured in a 2 cm long differentially pumped cell, corresponding to the transition region for non-equilibrium to equilibrium final charge state distributions. The final charge state yields were found to be independent of the initial charge state of the ion species. The relatively large integrated yields make the technique attractive for possible use as a terminal stripper in large tandem accelerators.

Introduction

Electron capture and loss processes occur with high probabilities during interactions between high energy ions and atoms or molecules. According to experimental evidence, the loss of several electrons during a single collision is a high probability process whereas the capture of more than one electron during an encounter is less likely. This disparity is the physical basis on which many high-energy heavy-ion accelerators are constructed. Since the final energy of an ion is directly proportional to the charge state of the ion during acceleration, the technique of employing a stripping medium (either solid or gaseous) is often used between acceleration stages to produce highly ionized particles. During traversal of the stripping medium, the charge state of a particular ion may fluctuate many times with the average charge state of a beam of particles reaching an equilibrium value after traversal of a certain thickness of the stripping medium. Not only is the information gained from the study of the stripping process of great practical importance to accelerator users who need to predict the yield of a particular charge state in advance of an experiment, but it also provides useful information to atomic physicists who are interested in electron capture and loss phenomena.

According to a recent comprehensive survey of the literature, extensive information is presently available concerning ionic charge state distributions and average equilibrium charge states of heavy ions passing through gases and solids.[1] Most of the charge state information has been obtained from experiments in which the highly charged ion species were produced in large impact parameter collisions between the projectile and equilibrium thicknesses of a low atomic number stripper such as carbon, oxygen or nitrogen. A few measurements have been reported using heavy stripping media which are relevant to the present work. Kessel measured relative charge state fractions for 1.5 through 12 MeV I ions scattered by xenon through angles between 2.5° and 8° at target densities sufficiently low so that single scattering events were observed with no subsequent electron capture.[2] The results of these measurements indicate that highly ionized states are produced in violent, low impact parameter collisions between the projectile and target. Ryding, Wittkower and Rose made similar measurements using energetic iodine, selenium and bromine beams and oxygen, argon, krypton, xenon, carbon and gold targets.[3] They observed an increasing yield of very high charge states with increasing atomic number of the target. In addition, they found that the angular distribution of high charge state ions produced by high atomic number strippers were peaked at non-zero angles. The present measurements differ from those previously reported [2,3] in that we have measured, quantitatively, the yields of highly charge ions as a function of angle and pressure.

The present work concerns the scattering of 20 MeV I and Fe ions from argon and xenon over a pressure range from 10^{-3} to 1 Torr as measured in a 2 cm. long differentially pumped cell. The present set of experiments were undertaken to determine whether the absolute yields of highly charged ions obtained from high atomic number stripping gases are sufficiently high to merit consideration for use in the terminal of high energy tandem accelerator (provided of course, that such a stripper can be practically designed).

Description of Experimental Procedures and Apparatus

The experimental arrangement used in the investigations is shown schematically in fig. 1. A momentum analyzed, 20 MeV ion beam produced in the ORNL tandem accelerator, was collimated prior to entering the target chamber by two apertures, separated by 154 cm, having diameters of 3 mm and .5 mm, respectively. A beam monitor, consisting of a surface barrier detector, was used to detect particles scattered at 60° from a

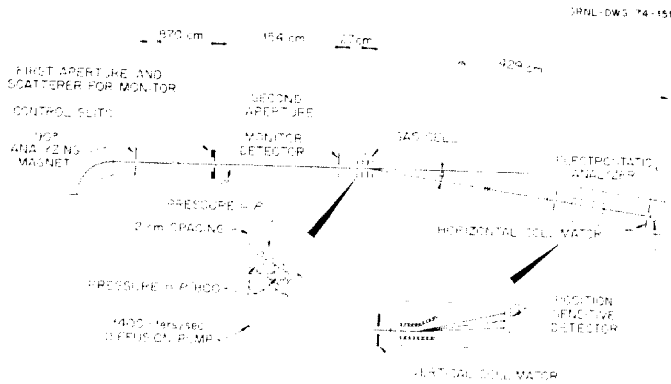

Fig. 1. The experimental arrangement.

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chemically etched annular film surrounding the first aperture. The details of the monitoring system have been previously reported by Appleton *et al.*[4]

A differentially pumped target cell was positioned 27 cm after the second aperture and mounted directly above a 1400 ℓ/sec diffusion pump. The target cell consisted of two circular entrance apertures, each 1 mm in diameter separated by 2 cm. Two exit apertures 1 x 2.5 mm and 1 x 4 mm respectively, and spaced 2 cm apart, permitted measurements at scattering angles through 3°. Target gases were introduced in the central portion of the cell where the pressure was measured with a capacitance manometer. The cell was mounted over a freely rotating axis which served as the pivot point for determining the angle through which the particles were scattered.

The distributions of charge states, present at a particular scattering angle, were analyzed according to their charge with a charge state analyzer, consisting of a vertical electrostatic analyzer and a position sensitive detector. The charge state analyses system has been described previously.[5] The charge state analyzer was mounted on the table of a milling machine and the table position used to determine the scattering angle. The charge state resolution was determined by a vertical collimator, .83 mm high, positioned at the entrance to the analyzer, and the angular resolution was defined by a mask 4.1 mm wide immediately in front of the position sensitive detector. The mask was located 429 cm from the center of the gas cell so that the angular resolution was, $\Delta\theta$ = .054° and the accepted solid angle was, $\Delta\Omega = 2.4 \times 10^{-7}$ ster. The monitor efficiency was calibrated by measuring the beam intensity at 0°, with the cell evacuated, as a function of monitor counts. In this way, an absolute monitor efficiency of 1 monitor count per 5000 ± 500 particles in the beam was determined. Vacuum levels in the flight tube preceeding and following the gas cell were approximately 2×10^{-6} Torr throughout the measurements.

Experimental Results

I^{6+} Scattered from Xenon

Absolute yields of I^{m+} ions per incident I^{6+} ion were measured at scattering angles between 0° and 1.5° for a number of cell pressures. A range of pressures from 10^{-3} to 1 Torr, corresponding to an atomic density range of 3.5×10^{13} to 3.5×10^{16} atoms/cm^3 was used during the experiment. Thus, the range of densities extended from nearly single event pressures to nearly equilibrium pressures. An isometric plot of the charge state yields of I^{m+} ion per incident I^{6+} ion, scattered from xenon at 1.5°, are given in fig. 2 as a function of pressure. Qualitatively, the charge state yields at 3×10^{-3}, 6×10^{-3} and 11×10^{-3} Torr are similar having charge states present between 12 and 26. From 0.3 Torr to 0.7 Torr, the yield data are also very similiar with charge states between 4 and 16 in the respective distributions. The constancy of the data at the lower and at the higher pressures points out respectively the regimes where capture after the scattering event is not very probable, and the density range where the charge state distribution is quantitatively similar to an equilibrium distribution. The average charge state, $\bar{Q}$, of the previous data versus pressure is shown in fig. 3. We note that the average charge state, $\bar{Q}$, increases with decreasing pressure. Apparently, electron transfer processes are still important even at the lowest pressures. The yields per incident particle per degree as a function of angle measured at .051 Torr for several charge states are shown in fig. 4. As expected, the angle of maximum yield increases with increasing charge.

I^{6+} Scattered from Argon

Angular distributions of the yield per incident particle per degree were measured for I^{6+} scattered from argon at pressures of .02, .05 and 0.1 Torr. Figure 5 shows the results of the .05 Torr measure-

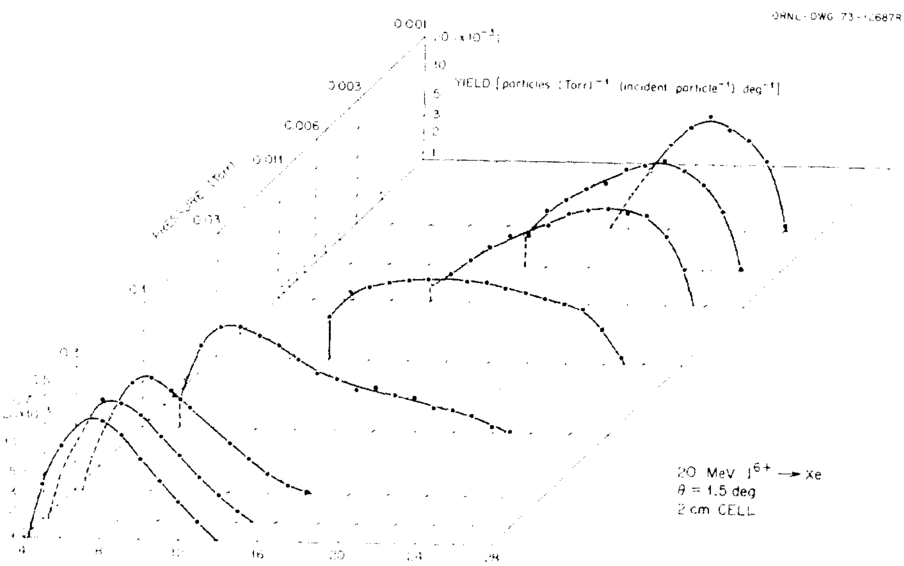

Fig. 2. The charge state yields [particles Torr^{-1} (incident particles)$^{-1}$ deg^{-1}] versus pressure for 20 MeV I^{6+} ions scattered from xenon at 1.5°.

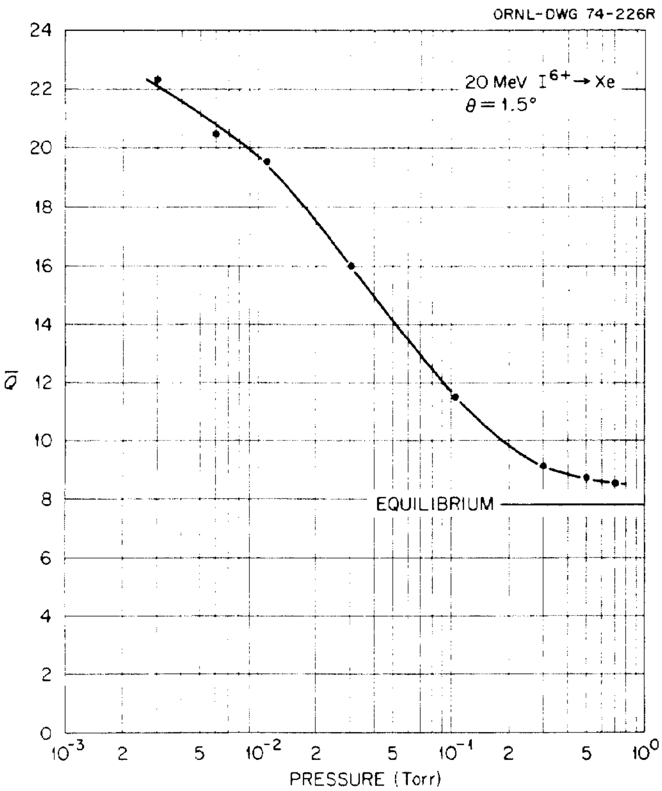

Fig. 3. The average charge states resulting from the scattering of 20 MeV I^{6+} ions from xenon at 1.5° as a function of pressure.

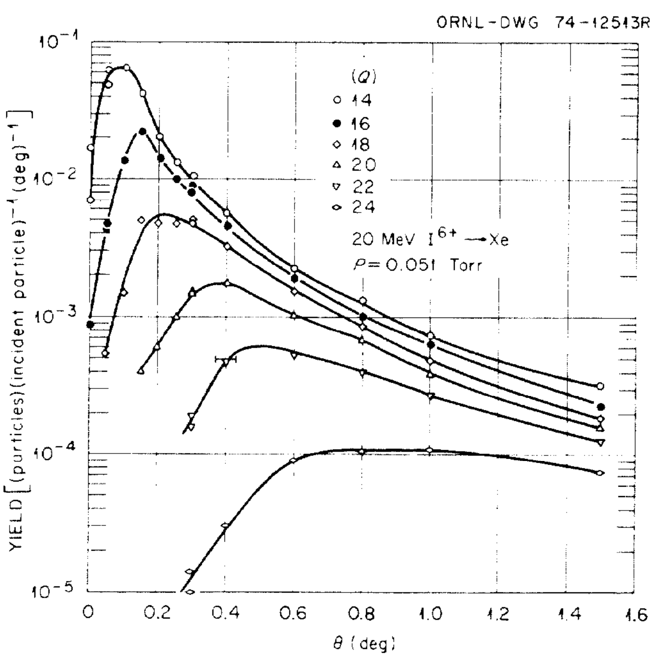

Fig. 4. The yields [particles (incident particle)$^{-1}$ deg^{-1}] of various charge states as a function of scattering angle for 20 MeV I^{6+} ions scattered from xenon at .051 Torr pressure.

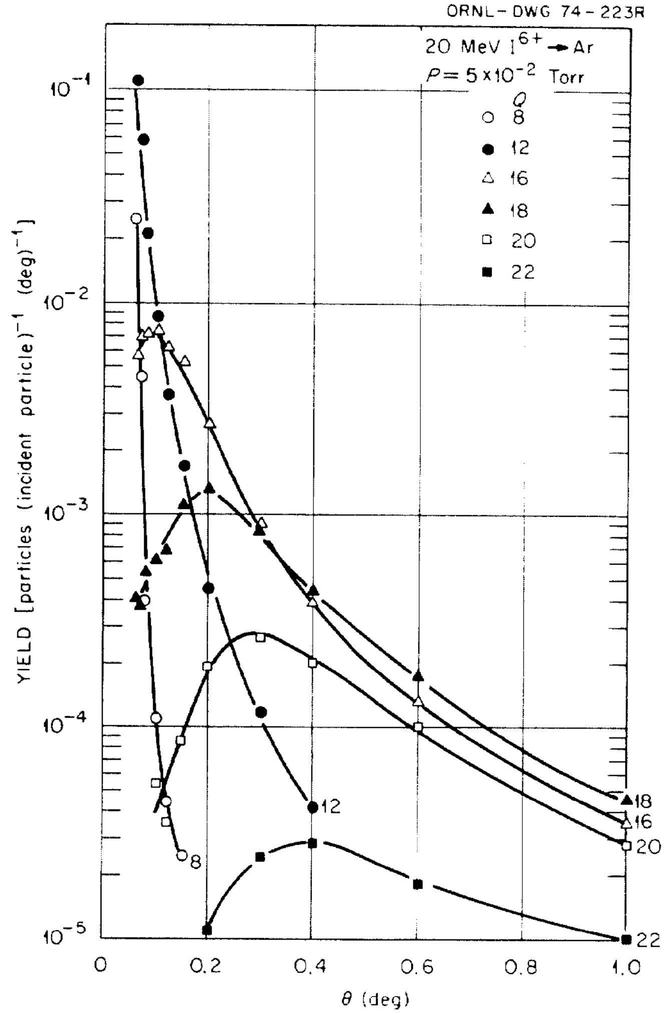

Fig. 5. The yields [particles (incident particle)$^{-1}$ deg^{-1}] of various charge states as a function of scattering angle for 20 MeV I^{6+} ions scattered from argon at .05 Torr pressure.

ments. We note again an increase in angle of maximum yield with increasing charge state. A direct comparison of the yields of a few high charge states from measurements made with argon and xenon stripping gases at 0.3° as a function of pressure are shown in Fig. 6. The charge state yields for xenon are seen to be 2 or 3 times higher than those from argon at the same pressure and scattering angle.

Effect of Varying the Incident Charge State

Figure 7 illustrates the independency of final charge state on the initial charge state of the ion. The data were taken at a pressure of 5 x 10^{-2} Torr for I ions of various charge states scattered from xenon at 0.3°. Both the average and individual charge state fraction are seen to be independent of the initial charge of the incident ion.

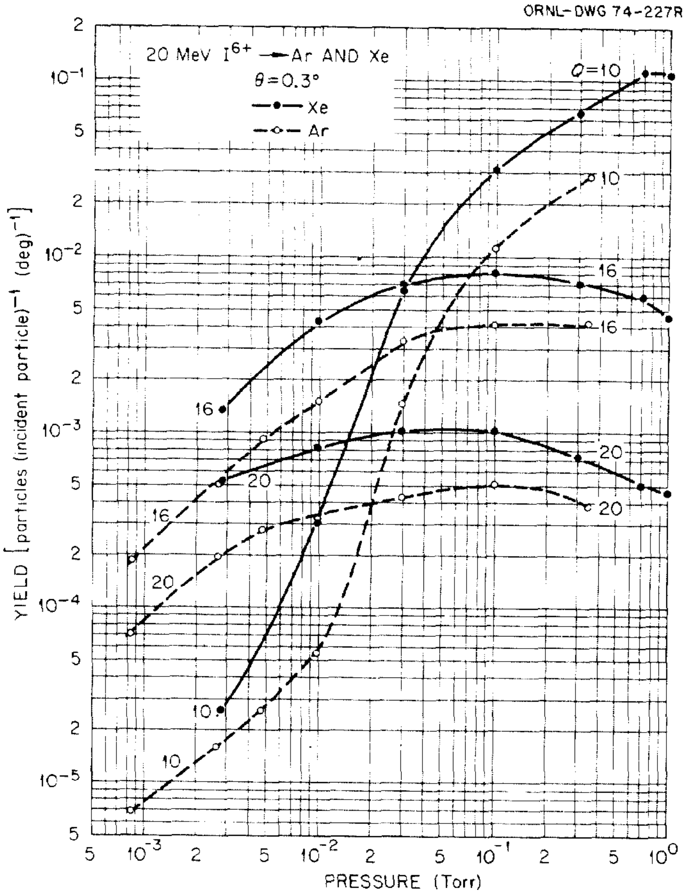

Fig. 6. Comparison of the yields [particles (incident particle)$^{-1}$deg^{-1}] of various charge states from 20 MeV I^{6+} scattered from argon and xenon at 0.3° as a function of pressure.

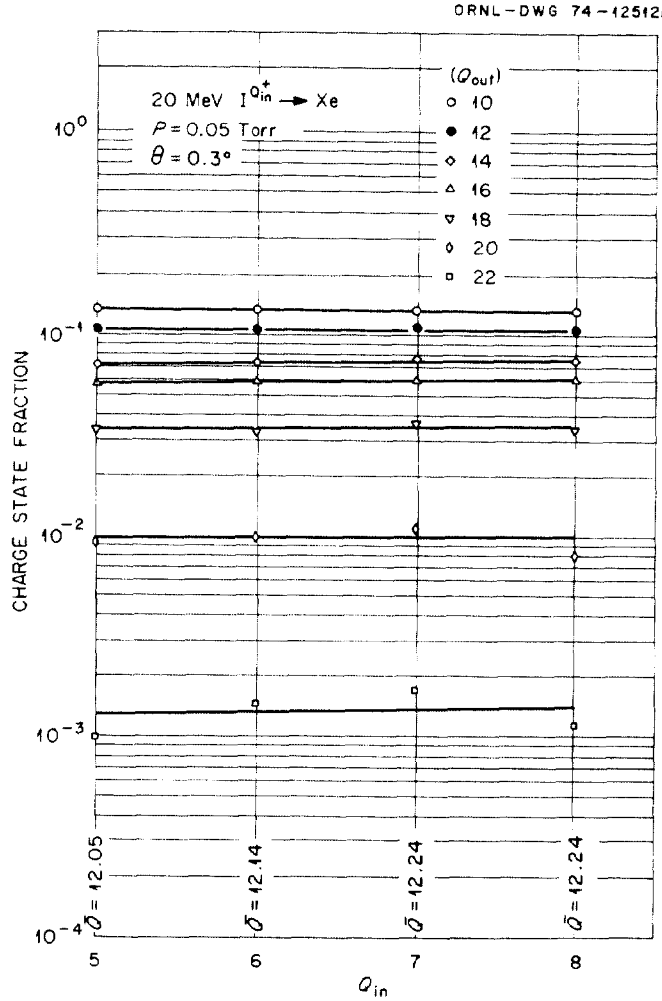

Fig. 7. Charge state fractions produced by scattering 20 MeV I ions from xenon at 0.3° and .05 Torr pressure as a function of initial charge state.

Fe^{4+} Scattered from Carbon and Xenon

A comparison of the total integrated yield versus charge state for 20 MeV Fe^{4+} scattered from xenon at 5.1×10^{-2} Torr (7.1 μg/cm²) and a carbon foil of 3 μg/cm² are shown in fig. 8. The contribution from the wide angle scattered particles to the total yields of the various charge states is readily seen. The yield per particle per degree as a function of laboratory scattering angle for Fe^{4+} scattered from the same materials is shown in fig. 9.

Conclusions

The present set of experiments were initially designed to provide information on the yields of high charge state ions obtained from high atomic number stripping gases from possible use in the terminal of a high energy tandem accelerator. As evidenced by these data, the prospects of the concept appear promising. For example, an intensity of 4×10^{-4} particles per incident particle of I^{16+} may be obtained for 20 MeV incident ions scattered from xenon if the acceptance angle is 10 mrad. An ion current of 4 pna could then be obtained for a beam of 10 μA of 20 MeV I^- incident on the stripper. This is comparable to the current expected from a carbon foil stripper, where the incident beam current would have to be held to a low value in order to preserve reasonable foil life.

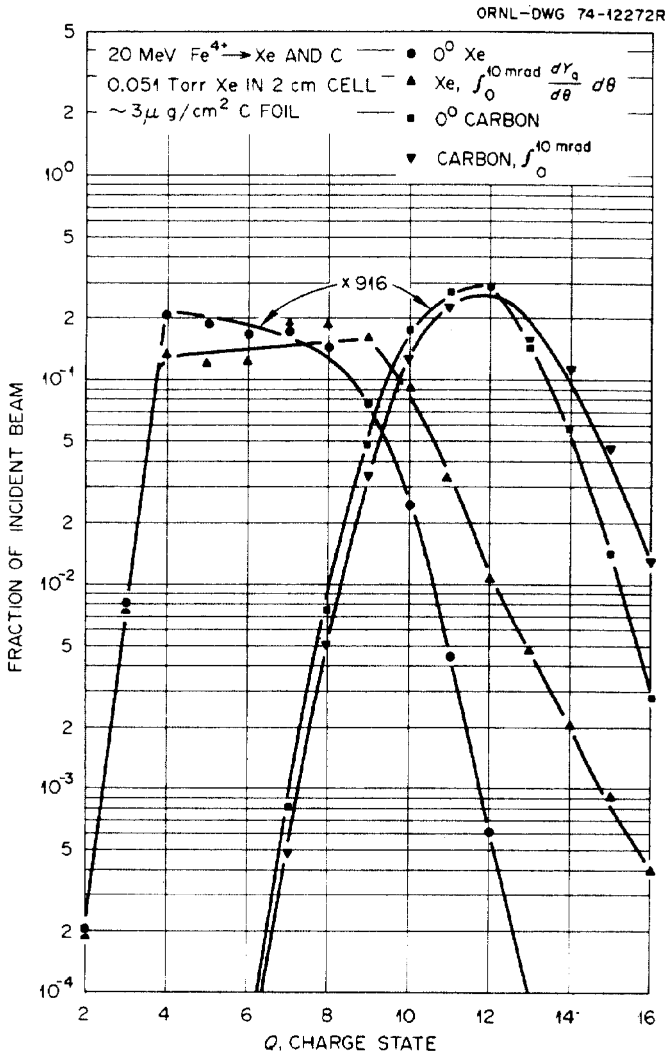

Fig. 8. Fraction of incident beam versus charge state for 20 MeV Fe^{4+} scattered from carbon and xenon.

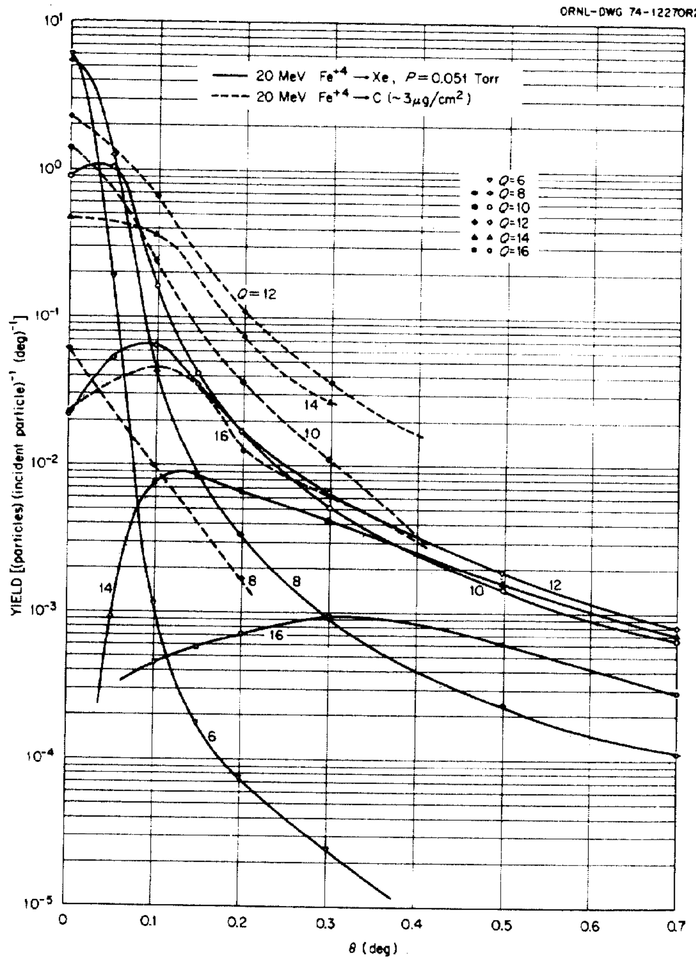

Fig 9. The charge state yields [particle (incident particle)$^{-1}$deg^{-1}] as a function of scattering angle of 20 MeV Fe^{4+} scattered from carbon and xenon.

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