There exist in the literature no calculated numerical data for the total cross section Q_0, including relativistic effects, for a Thomas-Fermi field, to be compared with our results for Q_0. The previous paper indicates that the total cross section ${}_1Q_0$ is a good[2] approximation to the exact ${}_1Q_0$ because $|f(\vartheta)|^2$ agrees well with the numerical data, which suggests that the relativistic total cross section Q_0 should yield a good approximation also.

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K-Series Fluorescence Yields of Vanadium, Manganese, and Neon*

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K-series fluorescence yield (w_K) measurements have been made for vanadium, manganese, and neon using the proportional counter method. The values obtained are the following: vanadium, 0.304±0.013; manganese, 0.308±0.015; and neon, 0.043±0.004. A discussion of method and errors is given and a comparison of these values with other computed and experimental values is made.

INTRODUCTION

When a vacancy in the K shell of an atom is filled by an electron from an outer shell, the electron rearrangement is accompanied by the emission of an x-ray or an Auger electron of the K series of that atom. The fraction of the number of K-shell vacancies for a large number of atoms of the same atomic number leading to the emission of x-rays is called the K-series fluorescence yield (w_K) for that element, and in the same way the remaining fraction leading to the emission of Auger electrons is called the K-series Auger yield. It is evident that measurements of the intensity of the K x-rays or K Auger electrons or both can give information as to the number of K-shell vacancies produced in a source. This information is of special interest when the vacancy has been produced by electron capture or internal conversion in radioactive atoms. Other applications of these measurements have been discussed by Bergström.[1]

Many summaries of K-series fluorescence yield measurements have appeared in recent years[2–5] indicating better agreement of results for various experiments and methods. The magnetic spectrometer method measures the Auger electrons directly; hence w_K values have been determined for elements of high atomic numbers (greater than 46) with an accuracy of 1 to 8%. The solid angle difference method utilizing the NaI-Tl scintillation counter as the detector is described by Roos[5] and has been used to measure w_K for elements of low and intermediate atomic numbers with an accuracy of 1.5 to 5%. The proportional counter method described previously[6] possesses good accuracy and a certain uniqueness for determining w_K for noble gases and radioactive nuclei which have undergone electron capture or internal conversion. The proportional counter is well adapted for determining w_K for elements of low atomic number in that it has a high detection efficiency for low-energy x-rays and electrons. This method has been used to determine the fluorescence yields of vanadium, manganese, and neon.

EXPERIMENTAL

The proportional counter used in this experiment was similar to the one described previously[6] except that it was made of aluminum. There were two source positions available. The previous source position was an opening in the wall of the counter which was covered by a cylindrical aluminum cup in which the gas pressure was the same as the counter pressure. The other source position was a brass tube extending about 6 inches into the counter and parallel to the central wire. The source ring was fastened to the end of this probe thus positioning the source at a distance of 0.8 inch from the central wire. In order to avoid field distortion, a potential divider between the central wire and the counter wall was used to supply a potential to the source tube which corresponded to the potential of the counter field at that point. The counter details are shown in Fig. 1. The counting gas used in the measurements on vanadium and manganese was a mixture of 90% argon and 10% methane, of 99.9% purity. The electronic components of the spectrometer are essentially the same as used in

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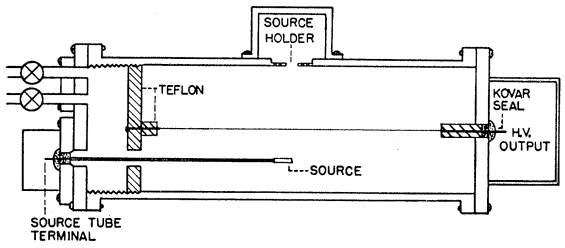

FIG. 1. Proportional counter.

previous measurements except that a nonoverloading linear amplifier has been used.

SOURCES AND PREPARATION

The isotopes used in this work were Cr^{51} and Fe^{55} and were obtained from the Isotopes Division of the Oak Ridge National Laboratory. Cr^{51} decays 97% of the time by electron capture to the ground state of V^{51}, and approximately 3% of the time to an excited state which decays to the ground state with the emission of a 320-kev gamma ray. The source had the chemical form of $CrCl_3$ in an HCl solution with a purity greater than 99%. Fe^{55} decays only by electron capture to the ground state of Mn^{55}.

Considerable effort has been devoted to the preparation of thin conducting source backings and thin sources. Some backings of 5–10 $\mu g/cm^2$ Formvar film coated with aluminum were attached to thin aluminum rings. The outer diameter of the rings mounted at the chamber wall and on the probe were $\frac{3}{4}$ inch and $\frac{7}{16}$ inch, respectively. Although the vacuum volatilization method was used, the electroplating method proved most successful for obtaining thin uniform sources. The electrolytic cell in each case consisted of a drop of radioactive electrolyte placed between a cathode of conducting source backing and a small anode of silver. The $CrCl_3$ and $FeCl_3$ in HCl solutions were neutralized by adding 0.1N $NH_4(OH)$ and electroplated with 60 and 3 microamperes of current, respectively. The remaining electrolyte in each case was drawn off with an eye dropper and the cathode carefully rinsed with distilled water before drying. The best sources were estimated to have a total backing thickness of 40 $\mu g/cm^2$ and a source thickness of 4×10^{-3} $\mu g/cm^2$.

EXPERIMENTAL RESULTS

The spectra shown in Fig. 2 were obtained by placing the Cr^{51} source on the source probe with the counter filled to three-fourths of one atmosphere of pressure. Spectrum A was obtained without an absorber over the source and spectrum B was obtained with a 1.54 mg/cm^2 aluminum absorber over the source to remove the Auger electrons. The spectrum has been corrected for the absorption of the incident x-rays in the aluminum foil. Spectrum C was obtained by subtracting curve B from curve A. The higher energy peak of curve A shown at a pulse height of 540 is principally the vanadium K-L x-ray and corresponds to an energy of 4.95 kev. The second peak shown at a pulse height of 430 is principally the vanadium K-LL Auger electrons and corresponds to an energy of 4.44 kev. Curve B represents the contribution of the vanadium K-shell flourescence to curve A, and curve C represents the contribution of vanadium K-shell Auger electrons to curve A. The dashed portion of curve C is an estimation of low-energy electron "tailing." Figure 3 shows a similar set of spectra obtained by placing the Fe^{55} source in the wall source position with the counter filled to one atmosphere of pressure. The higher energy peak of curve A shown at a pulse height of 545 is principally the manganese K-L x-ray and corresponds to an energy of 5.90 kev; the second peak shown at a pulse height of 490 is principally the manganese K-LL Auger electrons and corresponds to an energy of 5.17 kev. Curve B represents the contribution of the manganese K-shell fluorescence to curve A, and curve C represents the contribution of manganese K-shell Auger electrons to curve A. Again the dashed line is the estimated low-energy electron "tailing."

In each of the sets of spectra, a small contribution to the total x-ray intensity is made by the K-M and K-N x-rays. In like manner a small contribution to the total electron intensity is made by the K-LM and K-LN Auger electrons. The L-shell vacancies make no contribution to the spectra.

In an attempt to measure the fluorescence yield of neon, the manganese K x-ray spectrum shown in Fig. 4 was obtained by using the proportional counter filled to one-half of one atmosphere of pressure with a mixture

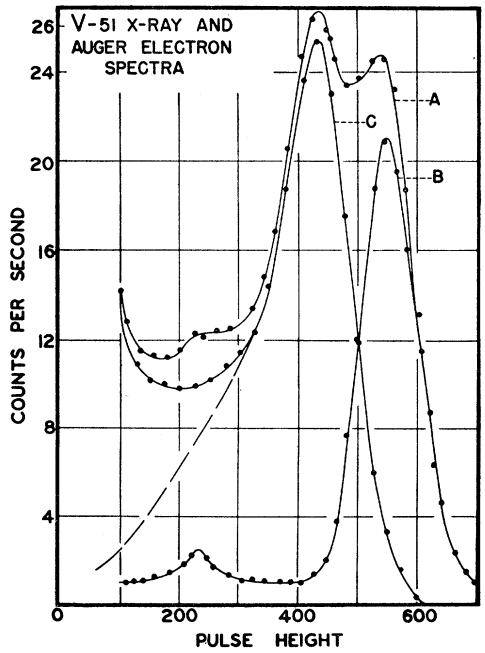

FIG. 2. Curve A is the total spectrum, curve B is the x-ray spectrum, and curve C is the Auger electron spectrum.

of 90% neon and 10% methane, of 99.9% purity. The spectrum was taken with a 1.53-mg/cm^2 aluminum absorber placed over the same source of Fe^{55} used to obtain the spectra of Fig. 3. With the exception of the aluminum wall fluorescence peak at 100 pulse-height units, there is only one peak which represents principally the contribution due to the 5.90-kev K-L x-ray of manganese. Neon x-rays are formed when the manganese x-rays ionize the gas atoms in the K, L, and M shells. If the atom reorganizes with the emission of a K Auger electron, the electron is immediately absorbed along with the primary ionization and a pulse corresponding to the full 5.9 kev is recorded. If the atom reorganizes with the emission of a K-L x-ray, the x-ray can escape from the counter and a pulse will be formed corresponding to the energy of the initial photoelectron plus Auger electrons and x-rays from the L and M shells. The escape peak for neon x-rays should occur at an energy corresponding to the difference in the incident photon energy (5.9 kev), and the binding energy (0.9 kev) for the K shell of the neon gas (5.0 kev). Thus since the x-ray yield for neon is small and because of the closeness of the escape energy to the K x-ray energy of iron, the peak is not resolved.

If one assumes a Gaussian distribution, for the total energy peak and subtracts it from the total peak, a small residual area corresponding to the escape peak is found at an energy of 5 kev. This curve B is shown in Fig. 4.

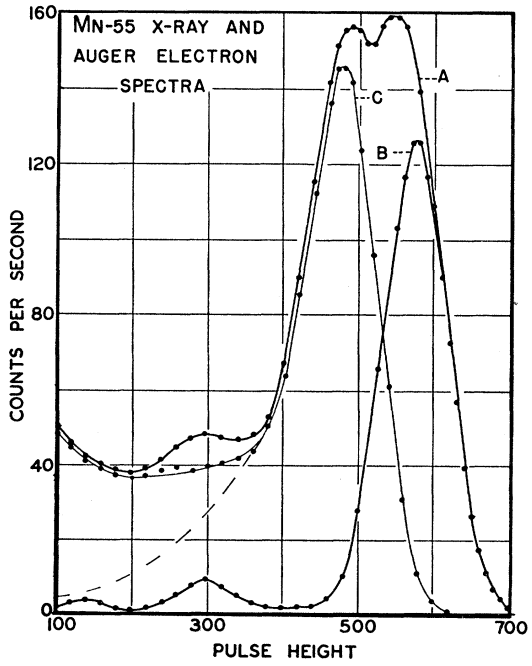

FIG. 3. Curve A is the total spectrum, curve B is the x-ray spectrum, and curve C is the Auger electron spectrum.

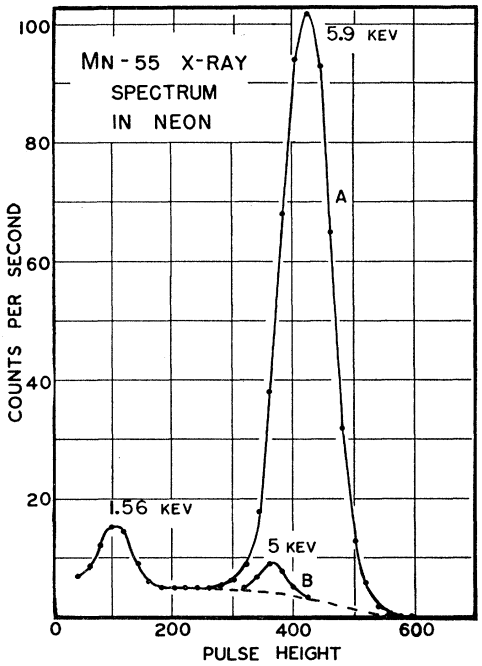

FIG. 4. Curve A is the total spectrum, and curve B is the escape peak.

DISCUSSION

In computing the K-series fluorescence yield of vanadium and manganese, the largest contribution to uncertainty in the final result was the estimation of the "tailing" effect of the Auger electrons. After a thorough study of this effect the chief contribution was found to be due to source thickness and source backing. Thus, in estimating the extrapolated electron curves, an attempt was made to evaluate that portion of the intensity due to source absorption which should be included in the measured intensity and that portion of the intensity due to backscattered electrons which whould not be included in the measured intensity, since the effective counting geometry was a 2π solid angle. For all spectra measured, 16 to 20% of the total electron intensity was attributed to backscattering. This seemed to indicate that all backing thicknesses used produce about the same backscattering. The 40 μg/cm^2 backing thickness was found to be approximately equal to the measured range 36.5 ± 6.5 μg/cm^2 for 4.4-kev electrons in Formvar. The low-energy tails drawn in Figs. 2 and 3 produce a maximum error of 7% in the measurement of spectrum C. The reproducibility in spectrum B was within 2 to 3% and the error in the measurement of counter efficiencies was 0.5%.

Even though there was an uncertainty of 6% in evaluating the fraction of neon x-rays escaping from the counter and an uncertainty of 4% in evaluating the ratio of J_K to J_K-1, the contribution of these errors to the fluorescence yield of neon was not quite so serious. The reproducibility for the total energy peak was within 2% and for the escape peak within 5%.

RESULTS

Cr^{51}-V^{51}

In order to determine the K-series fluorescence yield of V^{51}, the counter efficiency for 5.0-kev x-rays was measured by comparing the areas under the x-ray peaks when the counter is operated at two different pressures. The efficiency was found to be $(98.6\pm0.5)\%$. The efficiency for Auger electrons was assumed to be 100%. The most probable value obtained from measurements on three separate sets of spectra similar to those shown in Fig. 2 was $w_K=0.304\pm0.013$.

Fe^{55}-Mn^{55}

The K-series fluorescence yield of Mn^{55} was determined from two separate sets of spectra similar to those shown in Fig. 3. The measured counter efficiency for the 5.9-kev x-ray was $(94.1\pm1.0)\%$ and again the electron efficiency was taken as 100%. The most probable value obtained was $w_K=0.308\pm0.015$.

Neon

To determine the K-series fluorescence yield of neon, it was necessary to examine the spectrum of Fig. 4. As indicated previously, the Gaussian distribution fitted to the total energy peak includes neon K x-rays which did not escape from the counter but which were reabsorbed. A correction for this contribution to the total intensity was estimated from absorption data[7] and the mass of gas per cm^2 as seen by the x-rays. Also since it is not possible to distinguish between the amount of radiation absorbed in the K shell from that absorbed in the $L, M, N, \cdots$ shells, a correction was made for the fraction of incident radiation absorbed in shells other than the K shell. The "K jump" value used in making this correction was $J_K=15$ and was obtained from the extrapolation of a curve reported by Rindfleisch.[8] After corrections were made and errors considered, the most probable value for the K-series fluorescence yield of neon was found to be $w_K=0.043\pm0.004$. No allowance was made for systematic error.

There being no reliable experimental data available to the authors for the K-series fluorescence yields of vanadium and manganese, values of 0.286 ± 0.025 for vanadium and 0.290 ± 0.025 for manganese were computed from the semiempirical relationship of Burhop[9] and found to agree within the limits of error. Also our values fit the fluorescence yield *versus* atomic number curve reported by Roos.[10] The calculated value from the semiempirical relation for the K-series fluorescence yield of neon was 0.0080 ± 0.0018. Experimental values of 0.083[11] and 0.018 ± 0.004[12] have been obtained by Locher and Heintz, respectively. The wide variation in values gives an indication of the uncertainties involved.

Even though uncertainties exist in the above evaluations, the authors believe that a liberal allowance has been made in estimating the probable errors.

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Coulomb Corrections in the Theory of Internal Bremsstrahlung

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The internal bremsstrahlung associated with allowed β decay is calculated for the case for which the gamma-ray energy is less than $2mc^2$, the kinetic energy of the electron in its final state is small compared to mc^2, and $Ze^2/\hbar c$ is small compared to 1. It is not assumed that $(Ze^2/\hbar c)mc$ is small compared to the final momentum of the electron, or to the gamma-ray momentum. Results are obtained for the gamma-ray energy spectrum and for the angular correlation between the electrons and the gamma rays. For S^{35}, for which the above assumption would seem to be satisfied, the agreement between theory and experiment for the number of gamma rays per β disintegration per mc^2 is better than that previously obtained; because of uncertainties in the experimental results, the extent of the improvement is not clear. Under the additional assumption that the final kinetic energy of the electron is small compared to the gamma-ray energy, an expression is derived for the polarization of the gamma rays.

1. INTRODUCTION

THE probability of internal bremsstrahlung for allowed β decay was first calculated, in the Born approximation and for vector coupling, by Knipp and Uhlenbeck[1] and by Bloch[2]; their results are commonly referred to as the KUB theory. These Born approximation calculations were subsequently extended[3,4] to

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