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Experimental study of charge-state distributions and photon emissions from beam–tilted-foil interactions

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Relative spectral-line intensities of beam-foil-excited magnesium projectiles have been measured versus the projectile energy (100–900 keV) with carbon foils tilted 0°, 30°, and 45°. The photon intensities depend upon the foil tilt angle. Charge-state distributions measured for H^+, C^+, N^+, O^+, Na^+, Mg^+, S^+, and Kr^+ transmitted through carbon foils tilted 0°, 30°, and 45° (100–400 keV) were found not to be influenced by the tilt angle in contrast to the optical results. Charge-state distributions for C and S, which have not been reported earlier, are in agreement with a recently proposed independent-electron model for charge-state distributions and beam-foil populations.

I. INTRODUCTION AND EXPERIMENT

A series of measurements has recently indicated[1] that polarization of line radiation following beam-foil excitation depends upon the foil tilt angle, defined as the angle between the beam axis and the foil normal. This is understandable[2] from the fact that the axial symmetry present in the beam-foil excitation with untilted foil is reduced to reflection symmetry when the foil is tilted. The polarization measurements[1] clearly indicate the presence of surface effects in the beam-foil excitation mechanism. However, it is not only the symmetry that is changed when the foil is tilted. The time that the projectile interacts with the back of the foil increases with tilt angle (provided foil-surface irregularities do not destroy the surface orientation on an atomic scale). We have therefore carried out charge-state distribution measurements, as well as optical studies in which the tilt angle is changed, to observe a possible influence on charge fractions as well as on photon intensities caused by the tilt angle.

We have measured charge-state distributions for the elements H, N, O, Na, Mg, and Kr in the energy interval 100–400 keV. These elements have been studied earlier with untilted foils.[3-5] We have also studied distributions for carbon and sulfur which have not been reported earlier. The sulfur data supplement a recent optical beam-foil study of that element.[6]

The measurements were made at the 600-kV heavy-ion accelerator at the Institute of Physics, University of Århus, the experimental procedure being very similar to that used earlier by Hvelplund *et al.*[5] The ions of interest passed through a narrow aperture and then through a self-supporting carbon foil (5 $\mu g/cm^2$). A 0.1-mm-diam aperture downstream from the foil selected the central part of the beam, which in a transverse electric field approximately 20 cm from the foil was split into its charge-state components. The components were finally recorded by a position-sensitive detector.[7]

In addition to the charge-state distribution measurements we have also observed photon emissions from beam-foil-excited magnesium (100–900 keV). In the optical measurements, the region close behind the foil was viewed by a scanning monochromator (McPherson model 218) through a lens using a magnification of unity. The observation direction was perpendicular to the beam axis, and the carbon foils were tilted so that either the foil normal was in the same plane as the beam axis and the observation direction (i.e., the horizontal plane), or the plane defined by the beam axis and the foil normal (a vertical plane) was perpendicular to the observation direction. The two sets of data using the same tilt angle but different orientations of the foil normal agreed within the experimental uncertainties (<20%). Also, measurements with different beam-current intensities (below 500 nA in all cases) yielded the same results. These points are clearly of importance in a study like this.

It must here be said that whereas a quantitative data reduction is straightforward in the case of untilted foils, because the observation region can be chosen to be immediately after the foil, a proper data reduction is not so clear with tilted foils. This is partly because the observation time after excitation is somewhat ill defined, but also because it is projectile-velocity dependent.

The energy loss of the projectiles in the foil may be quite considerable, and it increases—as the foil thickness does—with the tilt angle. Thus energy-loss corrections are crucial in experiments such as these where the apparent foil thickness is changed. Corrections for energy losses in the foils were made by use of the experimental data of Fastrup *et al.*,[8] who in their measurements used a geometry very similar to ours.

II. RESULTS AND DISCUSSION

A. Dependence upon tilt angle

We found for all projectiles and energies used in this investigation (100–400 keV) that the charge-state distributions were not influenced by tilting the foil 30° or 45° (within our experimental uncertainties, which generally were around 5% or less) when proper corrections for energy losses were made. The aperture in front of the electrostatic analyzer could be displaced so that measurements could be done on particles scattered up to 2°. The absence of a tilt-angle dependence was noted for particles scattered up to this angle as well as for particles having passed the foil with essentially no deflection.

This result is in agreement with those of Tolk *et al.*[9] who observed oscillatory structures in ion yields in low-energy ion-surface scattering. They found no observable shifts in the positions of oscillation maxima as a function of the projectile velocity for different values of target orientation angles (corresponding to the tilt angle in this work). They found, however, that the ion yields changed with scattering angle, but that was at angles much larger than our maximum deflection angle of 2°.

We found, on the other hand, that in some cases the photon intensity of a spectral line depends rather much upon the tilt angle. This is illustrated in Fig. 1, in which we show the relative intensity of a Mg III transition as a function of the projectile energy. The three curves in Fig. 1, corresponding to tilt angles of 0°, 30°, and 45° are on the same relative scale, and we note that not only the relative intensity but also the shape of the curves depend on the tilt angle. Similar results were found for transitions in Mg II^a, Mg II^b, and Mg IV, in the sense that the shapes of the excitation curves vary with tilt angle. However, the relative change of intensity versus tilt angle, at fixed projectile energy, differed for different charge states. Mg I transitions showed no change of photon intensity with tilt angle. Use of Mg^{2+} incoming beam particles (the beam current of which was much weaker than that of singly charged magnesium) yielded the same results at the same energy.

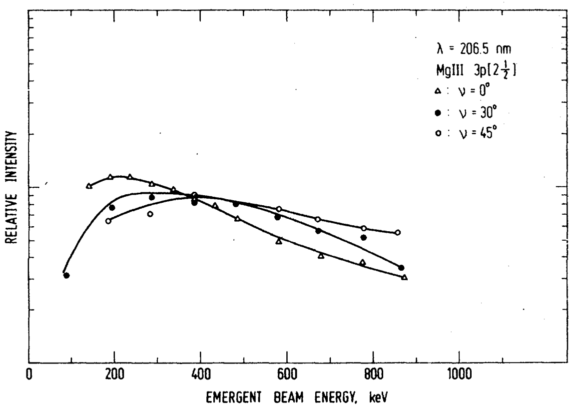

FIG. 1. Relative beam-foil photonyields for a Mg III transition vs the projectile energy, and with foils tilted 0°, 30°, or 40°.

Therefore we have reason to believe that the final excitation observed in beam-foil interaction may change with tilt angle. The change of shape with tilt angle cannot be accounted for merely because of the above-mentioned ambiguity in the data reduction together with an increased slowing down and scattering of beam particles with tilt angle. It indicates the presence of surface effects in the excitation process because the interior of an amorphous foil is not changed by tilting the foil.

There is presently a high interest in circular polarization observed from beam-foil excitations with tilted foils. Experiments[1] indicate clearly that orientation may result in addition to the alignment observed with untilted foils. Theoretical work is in progress.[2] We note here that the total level population depends in some cases on the foil tilt angle. This is most presumably because the interaction time between the back of the foil and the projectile increases with tilt angle, and there may well be a relation between the change of total level population with tilt angle and the induced orientation.

The absence of a charge-state distribution dependence upon the foil tilt angle is not in accordance with our observations that optical beam-foil excitation functions depend on the tilt angle; see Fig. 1. This diversity between charge-state distributions and optical beam-foil observations may be understood from the following two reasons. (i) In optical beam-foil observations taken immediately after the foil one observes light from particles having suffered all kinds of possible deflections, whereas the charge-state distributions reported here belong to those of almost undeflected particles. (ii) The foils will most presumably appear as having a rough surface on a scale comparable to the average value of the diameter of an atom or ion in its ground state or in a low-lying excited state. Thus the foil orientation loses its meaning for such species, and the major part of a charge-state component is made up of ground-state or low-lying excited species.

B. Charge-state distribution results

1. General remarks

The charge-state distributions obtained here are generally in good agreement with earlier measurements.[3-5] Our data for nitrogen confirm the data reported by Hvelplund *et al.*,[5] but not those of Wickholm and Bickel.[10] In passing we note that whereas those of Hvelplund *et al.*[5] fit well to the independent-electron model for charge-state distributions,[11] the results of Wickholm and Bickel do not, giving relatively too-large values for the higher-charge components.

2. Carbon

The charge-state distribution data measured for carbon are given in the table. We mention that there is a good agreement between our data at 380 keV and those of Smith and Whaling[4] at 369 keV.

In the following we shall discuss the results in terms of the independent-electron model.[11] Therefore we repeat here the basic definitions and concepts of the model. The reader is referred to Ref. 11 for a detailed discussion of the model.

The electronic structure of the projectile is regarded as made of two parts: (i) a core of inner shells of relatively small size, which can lose electrons only during rather violent collisions with a foil atom, and (ii) the valence shell together with outer shells, which are all ill-defined during the passage through the solid. The final arrangement of electrons outside the core is thus supposed to take place during the time that the particle interacts with the back of the foil. This final interaction is regarded as a multielectron transfer from the back of the foil to the projectile.

A parameter α is defined[11] as the total probability that an electron is transferred from the back of the foil to a bound state outside the core of the projectile. Following an independent-electron picture, it is then easy to show[11] that the charge-state fraction P_i is given by

$$P_i = [n!/i!(n-i)!]\alpha^{n-i}(1-\alpha)^i \qquad (1)$$

as long as the projectile core is unexcited (i.e., at relatively low projectile energies). P_i is the fraction of outgoing particles which carry the charge ie, e being the charge of a proton and $i = 0, 1, 2, \ldots, n$, where n is the maximum number of electrons which can be accommodated outside the closed core.

The ground-state configuration of neutral carbon is $1s^2 2s^2 2p^2$. It is clear that the two $1s$ electrons remain as an unexcited core at our projectile energies. It is not so clear whether the $2s$ electrons act as another core or as outer electrons, since their binding energies and also their mean radii are comparable to those for the $2p$ electrons.[12] The observed charge-state distributions for carbon (see Table I) are fairly well described as those of a two-electron system in the independent-electron picture,[11] except for the doubly charged component at 88 keV, where the deviation between experiment and model is approximately 20%. The numbers deduced from the model [Eq. (1)], together with the values of the parameter α used, are included in the table.

The experimental charge-state distributions are not reproduced as well from the model if treated as systems of three or four independent electrons. We thus conclude that the $2s$ electrons are best described as core electrons, and that the independent-electron model reproduces the experimental data rather well. We have found earlier[11] that the $2s$ electrons act as core electrons also in nitrogen, oxygen, and fluorine. Thus carbon follows the trends shown by N, O, and F.

The formation of C^{3+} at energies above approximately 300 keV indicates the beginning of $2s$ core excitations, indicating the need for optical beam-foil excitation functions to supplement charge-state distributions.

As can be seen from the data, the formation of C^- is not a very rare process at the lower projectile energies. The model ignores in its present version[11] formation of negative ions. This is clearly a shortcoming of the model. On the other hand, formation of negative ions is a process somewhat different from formation of positive ions or neutrals, since the binding of the last electron, which creates the negative ion, is determined from weak, polarization effects, whereas the binding of electrons in positive ions or neutrals is caused by much stronger, Coulombic attractions.

In passing we note that also oxygen and fluorine are known to form negative ions at these projectile energies,[5] whereas formation of negative nitrogen ions has neither been observed here nor earlier.[5] This is because C^-, O^-, and F^- form ground states which are stable against autoionization, whereas the lowest-lying level in N^- is slightly above the ionization limit.

3. Sulfur

The charge-state distributions for sulfur shown in Table I can be satisfactorily fitted by applying Eq. (1) to a six-electron system except for the

TABLE I. Charge-state distributions for carbon and sulfur having passed through carbon foils. For each projectile energy listed, the upper set of charge-state distribution data is the experimentally determined one whereas the lower set results from Eq. (1) using the listed values for α.

Projectile	Emergent beam energy (keV)	α	P_{-1}	P_0	P_1	P_2	P_3	P_4	P_5	P_6
^{12}C	88		0.044	0.58	0.34	0.038				
		0.78		0.60	0.34	0.048				
	185		0.020	0.38	0.47	0.12	0.002			
		0.63		0.40	0.47	0.14				
	280		0.009	0.24	0.51	0.22	0.016			
		0.51		0.26	0.50	0.24				
	380		0.006	0.18	0.50	0.28	0.027			
		0.44		0.19	0.49	0.31				
^{32}S	85		0.036	0.38	0.42	0.13	0.03			
		0.85		0.38	0.40	0.18	0.04			
	180		0.011	0.18	0.41	0.27	0.11	0.02		
		0.77		0.21	0.37	0.28	0.11	0.02		
	275		0.004	0.096	0.32	0.31	0.20	0.072		
		0.69		0.11	0.29	0.33	0.20	0.066		
	375		0.002	0.051	0.23	0.31	0.27	0.13		
		0.61		0.052	0.20	0.32	0.27	0.13		
	425		0.001	0.037	0.19	0.26	0.27	0.17	0.06	0.01
		0.58		0.038	0.17	0.30	0.29	0.16	0.05	0.005

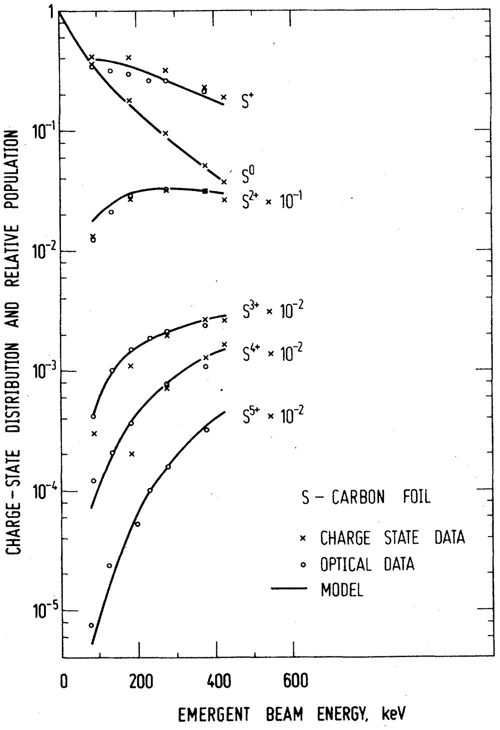

FIG. 2. Charge-state components and relative optical beam-foil populations (taken from Ref. 6) for sulfur having passed through carbon foils.

doubly and triply charged components at 85 keV and for S^{6+} at 425 keV. The fitted values are shown in Table I.

We have earlier[6] performed an optical beam-foil study of sulfur in this energy region and found that also the relative optical beam-foil population functions could be linked through applying Eq. (1) to a six-electron system. The values for α used for fitting the optical measurements deviate slightly from those deduced from the charge-state distribution data. The deviations are small and maybe are caused by differences between the foils used here and earlier. From the two sets of α we have formed an average value for α as a function of the projectile energy. By using these average values and Eq. (1), the full-drawn curves in Fig. 2 have been obtained. In that figure, we have, for comparison, plotted the charge-state distribution data from Table I. In addition, our earlier relative beam-foil population curves[6] are replotted in Fig. 2. We note from that figure that the two sets of experimental curves come close to each other; the deviations are generally within our experimental uncertainties, the only exception being S^{4+} at 180 keV. Also, the curves based upon the independent-electron model reproduces both sets of experimental data satisfactorily (we mention parenthetically that agreement between the model and either one of the data sets can be improved at the cost of a slightly larger disagreement between the model and the other data set). Thus the independent-electron model[11] for sulfur can reproduce ten experimental data sets by use of only one parameter. Five of the data sets are on an absolute scale (the charge-state distributions), whereas the other five sets are only relative numbers (the optical data).

Deviations between experiments and model are generally larger at the lowest projectile energies. This is where the experimental uncertainties generally are greatest. It is thus difficult to say whether these low-energy discrepancies reflect a limitation of the independent-electron model. One may speculate that for the low projectile energies the time of the interaction between the projectile and the back of the foil becomes so long that the electron-electron interactions may cause a partial breakdown of the independent-electron model.

For sulfur—as well as for carbon—we note the shortcoming of the model in that it does not account for negative-ion formation.

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[1] H. G. Berry, L. J. Curtis, D. G. Ellis, and R. M. Schectman, Phys. Rev. Lett. 32, 751 (1974); D. A. Church, in *Invited Papers, Review Papers, and Progress Reports of the Ninth International Conference on the Physics of Electronic and Atomic Collisions*, edited by J. S. Risley and R. Geballe (Univ. of Washington, Seattle, 1976), pp. 660–671.

[2] Y. B. Band, Phys. Rev. A 13, 2061 (1976).

[3] B. T. Meggitt, K. G. Harrison, and M. W. Lucas, J. Phys. B 6, L362 (1973).

[4] P. L. Smith and W. Whaling, Phys. Rev. 188, 36 (1969).

[5] P. Hvelplund, E. Laegsgård, J. Ø. Olsen, and E. H. Pedersen, Nucl. Instrum. Methods 90, 315 (1970); J. Heinemeier, P. Hvelplund, J. Østgård Olsen and F. R. Simpson, Phys. Scr. 10, 304 (1974).

[6] B. Dynefors, I. Martinson, and E. Veje, in *Beam-Foil Spectroscopy*, edited by I. A. Sellin and D. J. Pegg (Plenum, New York, 1976), Vol. 1, pp. 231–234.

[7] J. Ø. Olsen, Nucl. Instrum. and Methods 140, 29 (1977).

[8] B. Fastrup, P. Hvelplund, and C. A. Sautter, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 35, No. 10 (1966).

[9] N. H. Tolk, J. C. Tully, J. Kraus, C. W. White, and S. H. Neff, Phys. Rev. Lett. 36, 747 (1976).

[10] D. Wickholm and W. S. Bickel, J. Opt. Soc. Am. 66, 502 (1976).

[11] E. Veje, Phys. Rev. A 14, 2077 (1976).

[12] T. A. Carlson, C. C. Lu, T. C. Tucker, C. W. Nestor, and F. B. Malik, Report No. ORNL-4614 UC-34-Physics (Oak Ridge National Laboratory, 1970) (unpublished). S. Fraga, J. Karwowski, and K. M. S. Saxena, *Handbook of Atomic Data* (Elsevier, Amsterdam, 1976).