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The importance of transition probabilities in atomic collision experiments

ABSTRACT

The role of transition probabilities in Photon Emission Spectroscopy of charge changing collisions is discussed on the basis of collisions, like He^{2+}- and O^{3+} - H. For these systems an accurate knowledge of transition probabilities is essential to deduce state selective electron capture cross sections. In addition to these physical aspects, the practical aspect of calibrating the sensitivity of a vuv monochromator by the branching ratio method is discussed.

INTRODUCTION

Electron capture in collisions of multiply charged ions and neutral particles, especially atomic hydrogen is a subject of extensive theoretical and experimental studies (Janev and Winter, 1985). The interest in these charge transfer processes stems not only from fundamental aspects but also from their importance in fusion plasma research and astrophysics. We study these electron capture processes by means of Photon Emission Spectroscopy -PES- (Hoekstra et al, 1989a and Dijkkamp et al 1985). The process for single electron capture is schematically given by

$$A^{q+} + B \rightarrow \underline{A^{(q-1)+*}(nl)} + B^{+}$$
$$\hookrightarrow A^{(q-1)+}(n'l') + h\upsilon$$

In words: a multiply charged ion A^{q+} collides on a neutral target B and captures one of the target electrons into an excited state $A^{(q-1)+}(nl)$. This state will decay by emission of a photon, $h\upsilon$, and hence measurement of the photon emission gives direct information on the electron capture rate into $A^{(q-1)+}(nl)$.

The set-up used for this kind of measurements is shown schematically in fig. 1. Inside the collision chamber the multiply charged ions, produced by the Electron Cyclotron Resonance ion source installed at the KVI, cross a target beam. The photon emission is observed with two monochromators, one being sensitive in the "visible" spectral range (200 - 700 nm) and the other in the vuv range (10 - 80 nm). The monochromators can be positioned in such a way that there is no influence of polarization effects (Hoekstra et al 1989b). The absolute target beam density profiles are determined by electron impact induced radiation (Čirič et al, 1985). This radiation is measured with the spectrometer for "visible" light, which is equipped with an imaging lens system which enables measurements along the beam axis.

In this type of measurements there are three main applications of transition probabilities and the related quantities: branching ratio and lifetime, namely

I - Sensitivity calibration of the vuv monochromator

II - Identification of contributions from degenerate states in hydrogenic ions.

III - Determination of capture cross sections from complex emission spectra.

These three aspects will be discussed separately in the next sections on the basis of some collision systems of current interest.

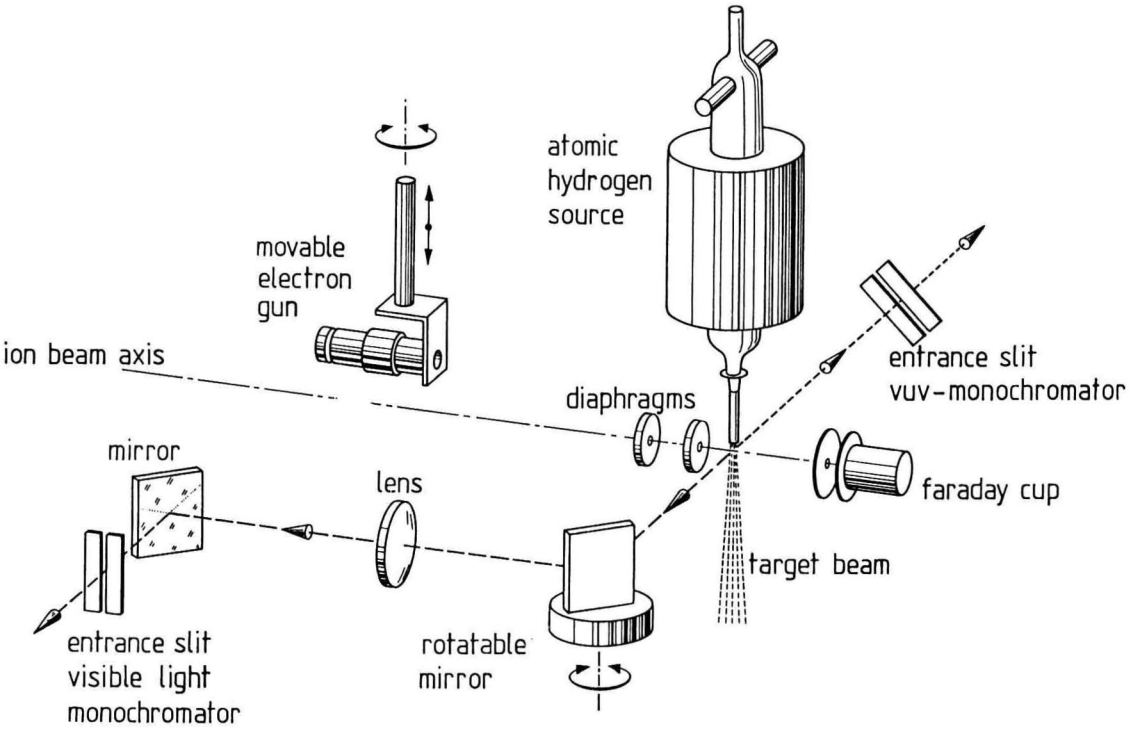

Figure 1. Schematical view of the experimental set-up.

I - SENSITIVITY CALIBRATION OF THE VUV MONOCHROMATOR

The vuv monochromator used is a grazing incidence vacuum spectrometer equipped with a position sensitive microchannelplate detector, enabling simultaneous detection of emission lines within ranges of about 20 nm. To determine the absolute sensitivity of this vuv monochromator, absolute emission cross sections for electron and ion impact processes are used. These cross sections are given in table 1. The wavelengths cover a range from 20 - 75 nm. If oscillator strengths are known, it is possible to get a few more calibration points in the range of 50 - 80 nm by measuring the intensity of resonance radiation after impact of electrons on noble gases (van Raan, 1973). In this range the sensitivity increases smoothly with decreasing wavelength (see fig. 2) and therefore an interpolation between the measured sensitivity points seems to be justified. However extrapolating to lower wavelengths is tricky since the sensitivity not only depends on the photon energy but also on the reflection coefficient of the grating. To extend the sensitivity calibration down to lower wavelengths we make use of branching ratios in Li-like ions (N^{4+}, O^{5+} and F^{6+}). For these ions the $4l \rightarrow 3l'$ transitions yield radiation in the range of 35 - 65 nm where the sensitivity is known, whereas the $4l \rightarrow 2l'$ transitions yield radiation in the range into which we want to extend the absolute

Table 1 Absolute emission cross sections (in $10^{-18}cm^2$) used for the sensitivity calibration of the vuv monochromator (Dijkkamp et al, 1985 and references therein). Typical error: 20-25%

	wavelength in nm		
	20.8 + 21.3		30.4
system	Ne^{4+} + He		e + He
energy (keV)	60		0.2
transition			
ion	NeIV		HeII
upper level	$3s\ ^4P$	$3s\ ^2D$	$2p\ ^2P^o$
lower level	$2p^3\ ^4S^o$	$2p^3\ ^2D^o$	$2s\ ^2S$
cross section	470		0.56

	wavelength in nm	
	46.1	71.8 - 73.1
system	e + Ne	e + Ar
energy (keV)	0.20	0.20
transition		
ion	NeII	ArII
upper level	$2s2p^6\ ^2S$	$3p^4 4s\ ^2P$
lower level	$2s^2 2p^5\ ^2P^o$	$3p^5\ ^2P^o$
cross section	4.80	1.71

sensitivity calibration, namely 9 - 20 nm.

As an example of the branching ratio method we will discuss the case of NV($1s^2 4p$), which is shown in fig. 3. The branching ratios have been deduced from the transition probabilities calculated by Lindgård and Nielsen, 1977. The sensitivity at 16.3 nm, K(16.3) is related to the known sensitivity at 62.9 nm, K(62.9) by

$$K(16.3) = \frac{0.19}{0.77}\frac{S(16.3)}{S(62.9)} K(62.9)$$

with S(16.3) and S(62.9) the measured signals at 16.3 and 62.9 nm. Unfortunately the signal at 62.9 nm includes the third order of the $3p \rightarrow 2s$ transition (3*20.93 = 62.8nm). Since the excited N^{4+*} ions are produced in charge

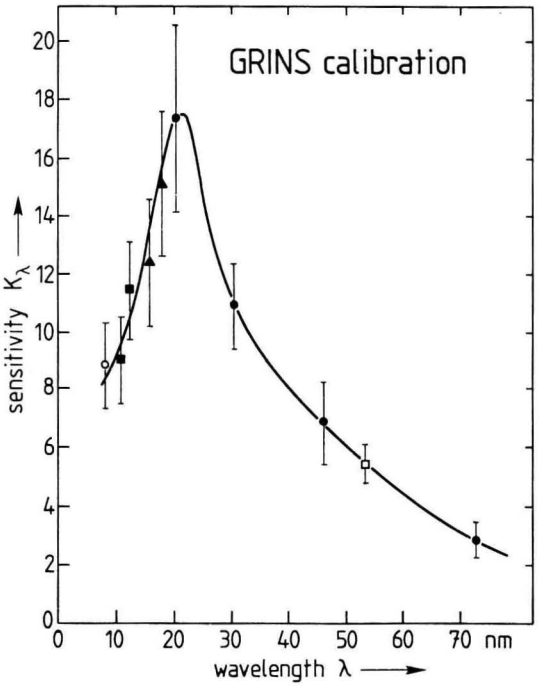

Figure 2. Sensitivity calibration curve of the vuv monochromator (GRINS). Branching ratio method: ○ - F^{6+}, ■ - O^{5+}, ▲ - N^{4+} and □ - He. ● - direct processes (table 1)

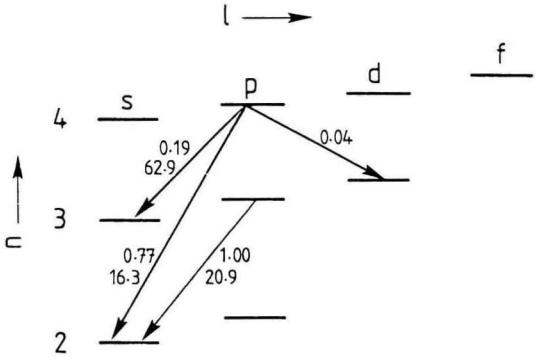

Figure 3. Schematic energy level diagram of NV. The relevant transitions have been indicated together with their branching ratios and wavelengths (in nm).

changing collisions of N^{5+} the excited state population can be steered by choosing an appropriate target. Charge transfer in collisions on H_2 populates $3l$ and $4l$ states, whereas collisions on He populate only $3l$ states (Dijkkamp et al, 1985). Hence collisions on He can be used to deduce the ratio between the first and third order of the $3p \rightarrow 2s$ line. Charge exchange between N^{5+} and H_2 is used to populate $N^{4+*}(1s^2 4p)$. It should be noted that at typical impact energies of 50 and 75 keV the contribution by the third order of the $3p \rightarrow 2s$ line to the signal at 62.9 nm is about 75 and 50%, respectively. Therefore the measurements have to be performed with optimal counting statistics. The results of this type of calibration procedures for Li-like ions are shown in fig. 2 together with the direct results of the processes given in table 1. Furthermore the figure includes the result of the branching ratio method for HeI($1s3p$) which has a branch in the visible spectral range (501.6 nm, $3p \rightarrow 3s$) and one in the vuv (53.7 nm, $3p \rightarrow 1s$), which links the sensitivity of the vuv monochromator to that of the spectrometer for visible light. The latter is calibrated on sensitivity (error 15%) by standard lamps and known electron impact emission cross sections.

Due to the accurate knowledge of branching ratios (ratio of transition probabilities) it has been possible to extend the sensitivity calibration of the vuv monochromator into the wavelength range of 9 - 20 nm.

II - IDENTIFICATION OF CONTRIBUTIONS FROM DEGENERATE STATES IN HYDROGENIC IONS

In hydrogenic ions the l levels are quasi-degenerate and therefore light emission from different l levels can not be resolved spectroscopically. So measurements of transitions in H-like ions have to be compared with the sum of the various theoretical contributions. Comparing in this way experiments for C^{6+} and O^{8+} - H collisions with the most elaborate calculations it was found that there is good agreement between theory and experiment for the dominant capture channels, whereas for the non-dominant high-n states there were considerable differences (Hoekstra et al, 1989a). However these transitions between high-n states, yielding light in the visible spectral range are particularly important for future plasma diagnostics (Boileau et al, 1989). Due to the strong fields in a tokamak the l states are mixed (Fonck et al, 1984) and hence it is essential to know all the l state electron capture cross sections separately. For the case of He^{2+} colliding on atomic hydrogen we have deduced the separate $4l$ cross sections from the measurement of the $4 \rightarrow 3$ transition (Hoekstra et al, 1989c). To that end we have exploited the fact that the lifetimes of the states are different. For these HeII($4l$) states the lifetimes and branching ratios for transitions to $n = 3$ are given in table 2. Radiation from shortlived states, e.g. $4p$ is mainly concentrated on the target area, whereas radiation from longlived states, like $4s$ is still emitted downstream the ion beam axis (fig. 1). Therefore the measurement of the emission profiles along the ion beam gives information

Table 2 Lifetimes, τ_{4l}, branching ratios for decay to $n = 3$, $\beta(4l \rightarrow 3)$.

	state			
	$4s$	$4p$	$4d$	$4f$
τ_{4l}(nsec)	14.2	0.77	2.26	4.53
$\beta(4l \rightarrow 3)$	0.42	0.042	0.25	1.00

on the l state population. This method, often used in collision experiments on static targets and in beam foil experiments, has only once before been used in a beam experiment, namely by Aumayr et al 1984 for H^+ - Li collisions.

Neglecting cascades the emission profiles along the ion beam axis, P_{4l} are described by

$$P_{4l}(z) = \frac{1}{v\tau_{4l}} \int_0^z T(z') \, e^{-(z' - z)/v\tau_{4l}} \, dz'$$

with v the velocity of the ions and τ_{4l} the lifetime of state $4l$, z the position along the ion beam axis and T(z') the target density profile. The measured signals, S(z) are equal to

$$S(z) = K \sum_l \beta(4l \rightarrow 3) \, P_{4l}(z) \, \sigma_{4l}$$

with K an absolute calibration constant, $\beta(4l \rightarrow 3)$ the branching ratio for decay to $n = 3$ and σ_{4l} the electron capture cross sections. By measuring the signals at some 25-30 positions along the ion beam axis, it is possible to deduce the cross sections from a least squares fit. This is feasible since the emission profiles $P_{4l}(z)$ are well known, which also is due to the fact that the transition probabilities, lifetimes and branching ratios are accurately known. As a typical example of the experimental results obtained in this way fig. 4 shows the results for the $4f$ state, together with the theoretical predictions by Fritsch, 1988. It can be seen that the experimental results increase smoothly, whereas the theory shows a structure around 4 keV/amu.

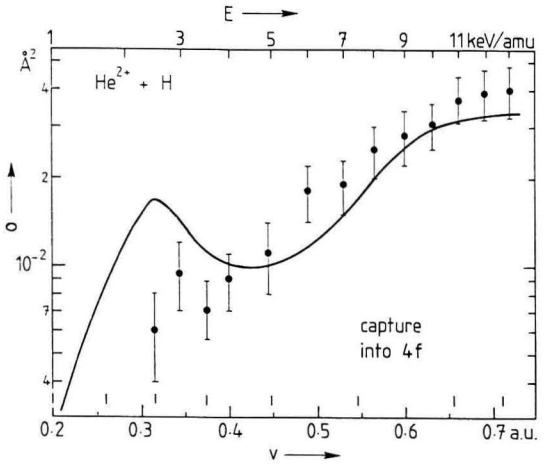

Figure 4. Electron capture into $He^+(4f)$ deduced from emission profile measurements. Solid curve - Atomic Orbital calculation by Fritsch, 1988

With knowledge of lifetimes and branching ratios of the HeII($4l$) states it has been possible to deduce for the first time high-n ($n = 4$ is a high-n level since the capture goes predominantly to the $n = 2$ level) state selective cross sections in He^{2+}-H collisions.

III - DETERMINATION OF CAPTURE CROSS SECTIONS FROM COMPLEX EMISSION SPECTRA

Photon emission following electron capture in O^{3+}- H ($O^{3+}(1s^2 2s^2 2p) \rightarrow O^{2+}(1s^2 2s^2 2pnl)$ plays an important role in astrophysical studies (Heil, 1987). Therefore fully quantal calculations have been performed (Heil et al, 1983 and Bienstock et al, 1983), which predicted that the $3p$ SL states are dominantly populated. However translational energy spectroscopy (Wilson et al, 1988) and PES (Hoekstra et al, 1989d) showed that the $3s$ SL are dominantly populated.

A useful evaluation of the PES measurements is only possible with a fair knowledge of transition probabilities, since a considerable number of emission lines falls outside the wavelength ranges covered by the spectrometers. Since a complete set of transition probabilities was not available, - especially two electron transitions of the type $2s^2 2p3p \rightarrow 2s2p^3$ were lacking - calcula-

tions have been performed (Hansen, 1989). The importance of these two electron transitions can be shown from measurements on the $3p\ ^1P$ and $3p\ ^3D$ states. Fig. 5 shows the emission profile for the $3p\ ^1P$ state. The solid curve is a least squares fit with a lifetime of 10 nsec, the dashed curve is a profile with a lifetime of 27 nsec, which is the lifetime deduced from the transition probability given by Wiese et al, 1966 for one-electron transition to $2s^2 2p3s\ ^1P^o$. The lifetime calculated (Hansen, 1989) is 11.8 nsec, which is in fair agreement with the measurement. His

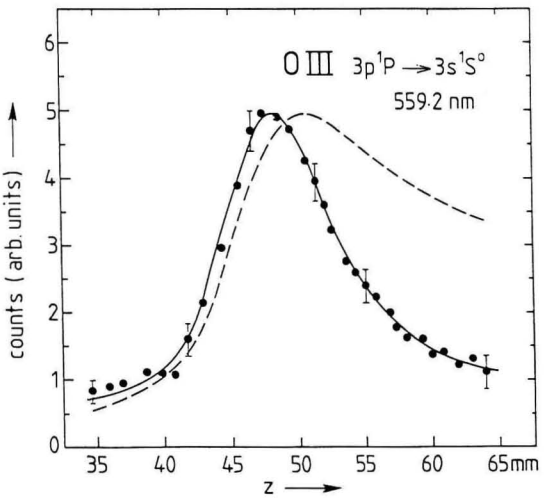

Figure 5. Emission profile along the ion beam axis of the $2s^2 2p3p\ ^1P \rightarrow 2s^2 2p3s\ ^1P^o$ transition. Solid curve least squares fit and dashed curve profile calculated with the lifetime deduced from Wiese et al, 1966 see text.

calculations show that for all the 6 $2s^2 2p3p$ states some 25-45% of the population decays via two-electron transitions to $2s2p^3$ states. We have measured the ratio between one- and two- electron transitions for $3p\ ^3D$ and found it to be 1.8 ± 0.4 which is in agreement with the calculated value of 2.1 (Hansen, 1989). More details will be given in a forthcoming article. Knowledge about these two-electron transitions is essential for determining level populations and interpreting the measured emission spectra.

CONCLUSION

It has been shown that an accurate knowledge of transition probabilities is important for photon emission spectroscopy of charge transferring collisions. With this knowledge it has been possible to extend the sensitivity calibration of a vuv monochromator. Furthermore it has been possible to resolve contributions from degenerate states in hydrogenic ions and to determine capture cross sections from complex emission spectra.

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