Determination of Hyperfine-Induced Transition Rates from Observations of a Planetary Nebula

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Observations of the planetary nebula NGC3918 made with the STIS instrument on the Hubble Space Telescope reveal the first unambiguous detection of a hyperfine-induced transition $2s2p\,^3P_0^o \rightarrow 2s^2\,^1S_0$ in the berylliumlike emission line spectrum of N IV at 1487.89 Å. A nebular model allows us to confirm a transition rate of 4×10^{-4} sec$^{-1} \pm 33\%$ for this line. The measurement represents the first independent confirmation of the transition rate of hyperfine-induced lines in low ionization stages, and it provides support for the techniques used to compute these transitions for the determination of very low densities and isotope ratios.

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Line ratios of the magnetic quadrupole (M2: $2s2p\,^3P_2^o \rightarrow 2s^2\,^1S_0$) and intercombination (IC: $2s2p\,^3P_1^0 \rightarrow 2s^2\,^1S_0$) transitions within multiplet UV0.01 of the berylliumlike ions have served as important tools for density measurements in many different sources (e.g., [1]). In spectra of doubly or triply charged ions, such as C III ($\lambda\lambda$1906, 1908), N IV ($\lambda\lambda$1483, 1486), and Si III ($\lambda\lambda$1882, 1892) the ratio of the two lines is a sensitive measure of electron densities near 10^4 cm^{-3}. It is less widely known that these multiplets have, in certain ions and isotopes, a third ("HPF") component, arising from the hyperfine nuclear interaction, such that the $2s2p\,^3P_0^o(F = I)$ hyperfine level decays to the $2s^2\,^1S_0(F = I)$ level. The HPF transition is of interest since its radiative decay rate is about an order of magnitude smaller than the weakest of the two "normal" lines, and it is therefore sensitive to electron densities substantially smaller than the ratio of the two other lines (e.g., [2,3]). The HPF line occurs only in spectra generated from isotopes that have nonzero nuclear spins. For example, it exists in the spectra of ^{13}C (which has a nuclear spin of 1/2) but not in ^{12}C (with a zero-spin nucleus). These lines can therefore potentially be used to determine relative isotope abundances in low-density sources.

The possibility of observing hyperfine-induced transitions was first suggested by Bowen (as stated in [4]), and was later confirmed by observation of the $6s6p\,^3P_0^o \rightarrow 6s^2\,^1S_0^e$ transition in the heavy system of Hg I ([5]). The corresponding transition was observed in the homologous system of Cd I ([6]). For these systems the hyperfine-induced transition has a rate several orders of magnitude larger than for the cases we considered here. After some confusion about the relative size of the hyperfine-induced and M2 transitions, which was resolved by Garstang and Mizushima ([7–9]), it was clear that it would be impossible to observe the hyperfine-induced transitions in lighter alkaline earth metals in the laboratory.

More recently, observations of hyperfine-induced transitions have been dealing with fluorescence in He-like ions, invoked by laser excitations ([10,11]), highly ionized species ([12–14]), and rare-earth elements ([15]). In the He I-like ions there are two different possibilities of HPF-induced transitions: a $\Delta n = 0$ transition $1s2s\,^1S_0^e \rightarrow 1s2p\,^3P_0^o$, where the $^1S_0$ is the upper level, or a $\Delta n = 1$ transition $1s2p\,^3P_o^o \rightarrow 1s^2\,^1S_o^e$. The former competes with the intercombination line $1s2s\,^1S_0^e - 1s2p\,^3P_1^o$ to depopulate the upper and metastable $1s2s\,^1S_0^e$ level. By using laser-induced transitions it is possible to force the $J = 0 \rightarrow J' = 0$ transition, in isotopes with nuclear spins. The primary goal of these studies has been to accurately determine the fine structure of the $1s2p\,^3P^o$ level. The $\Delta n = 1$ transition competes with the allowed $1s2p\,^3P_0^o - 1s2s\,^3S_1^e$ transition, dominating it for high Z owing to the very large transition energy. The $\Delta n = 1$ transition has therefore been observed in He-like Gd ([14]) and Ag ([16]). None of these studies has been concerned with spontaneous transitions in light elements. The sole lifetime measurement involving a resolved line in He-like systems was in a regime with lifetimes on the order of 10^{-11} s, whereas the lifetime of the $^3P_0$ level in N IV is on the order of an hour.

It is important to note that, while atomic calculations have reached a large degree of maturity for the berylliumlike systems, it is difficult to find "experimental" tests of the calculations used to model the hyperfine-induced transitions. A large-scale calculation of the transition probability for astrophysically interesting lines was published quite recently ([2]). The calculations involve extensive representation of correlation in the form of large multiconfiguration expansion. The effect of valence, core valence, and core-core correlation is included.

The present method uniquely verifies the validity of the complex methods that are required to model the hyperfine-induced transitions. These lines can only be observed in low-density, large-scale astrophysical plasmas, which have emission measures large enough to produce an observable line. Here we examine spectra of N IV in a planetary nebula treated as an atomic laboratory. Both stable isotopes of N have nuclear spin (^{14}N with spin 1, ^{15}N with spin 1/2), so that HPF-induced transitions are always present. Our purpose here is to report the first convincing detection of a $2s2p\,^3P^o_0 \rightarrow 2s^2\,^1S_0$ HPF transition in a bright, low-density astrophysical source, the high excitation planetary nebula NGC 3198, and to deduce a transition rate from this observation.

We obtained observations of NGC3918 with the Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope (HST). This object was chosen because it is a low-density object, with both a high surface brightness and a large angular size ($\approx$ 12 arc sec diameter). It has been observed extensively and a model of the nebular emission is available ([17]). Spectral data were acquired on 12 and 13 April 1999 using the G140M grating at the 1470 Å wavelength setting with the 52×0.2 arc sec slit. Target acquisition was done using images obtained in the O III line with the STIS "F28X50OIII" aperture. The spectrograph slit was centered on a bright knot of O III emission along the northern rim of the nebula. The O III image and WFPC2 F555W images (U2SA1803 and U2SA1804, taken by H. Bond through HST Guest Observer program 6119) was used to verify the exact placement of the STIS slit, as shown in Fig. 1. The slit intersects both the knot centered by the target acquisition as well as another bright O III knot on the southern edge of the nebula.

Care was taken to deal with corrections due to variable dark currents in the detector. The nebular lines were placed in the lower right part of the STIS detector, where the dark current glow observed at high detector temperatures is lowest. The glow intensity increased from exposure to exposure as the detector temperature increased during the observations. While the glow does not strongly affect the N IV lines, it contaminates the faint continuum flux. A smoothed, coadded image of the FUV glow taken from the STScI/STIS web site was scaled to the glow intensity in the upper left portion of each image and subtracted. These glow subtracted images were then added and processed through the STIS "iraf calstis" tasks to produce a flat fielded, spatially rectified, and flux calibrated "$\times 2d$ image."

The resulting spectrum shows three emission line components clearly visible at very high S/N ratio (Fig. 2), and

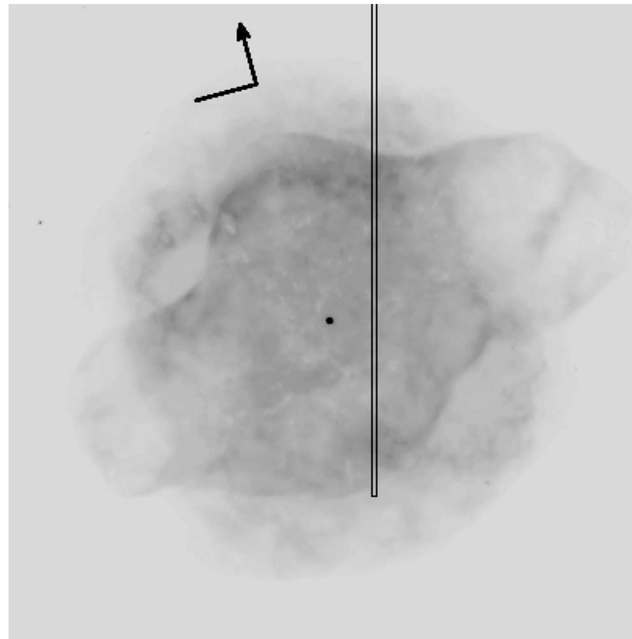

FIG. 1. The image shows the combined WFPC2 F555W data rotated to match the orientation of the STIS detector. The position of the STIS slit is marked. Except for the central star itself, most of the flux in the F555W image is due to O III 5008 Å emission.

a featureless continuum with a mean surface brightness of 2.72×10^{-15} erg arc sec^{-2} cm^{-2} Å^{-1} s^{-1}, extending about 10 arc sec along the slit. The three lines are all at the expected wavelengths of the N IV M2, IC, and HPF lines. Given the match of the previously observed and computed properties of the M2 and IC lines in the extensive modeling efforts of [17], the shorter wavelength lines must be due entirely to the M2 and IC components of N IV.

Several pieces of evidence indicate that the third component is indeed due to the HPF-induced transition in N

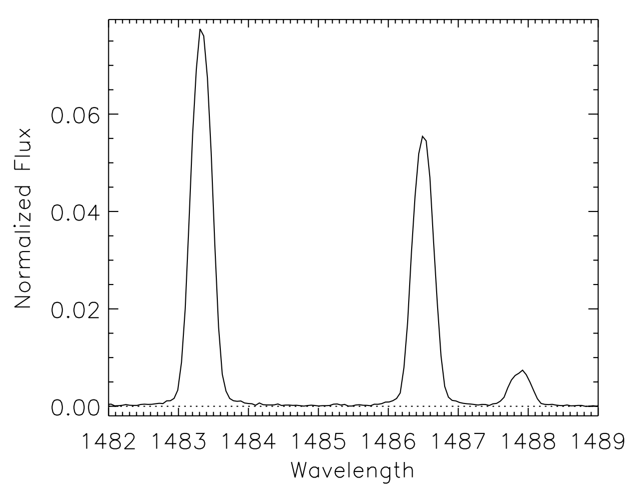

FIG. 2. The normalized, background subtracted line profile integrated over the length of the slit.

IV. First, the shapes of all three features are very similar. The apparent slight asymmetry of the proposed HPF line is simply due to random noise fluctuations. Second, a search for lines from known nebular ions yields nothing else that would lead to emission only at this wavelength. Third, Fig. 3 shows that the spatial distribution of surface brightness of the three emission components, as a function of position along the slit, are very similar. Furthermore, all three features differ dramatically from the O III surface brightness distribution. Fourth, despite a factor of 2 variation in the individual N IV M2 and IC line intensities along the slit, the ratio of the M2/IC lines is remarkably constant, with a mean ratio of 1.38 ± 0.01 (Fig. 4). The ratio of the brightness of the M2 to the proposed HPF line varies between 10 and 12, with a mean of 11.0, and an rms variation of 0.75. The higher variations in the HPF/M2 ratio, probably result from density fluctuations in the nebula (see below), but the ratio itself is nevertheless remarkably constant.

To dispel any remaining doubts as to the HPF identification of the 1487 Å component, we compare these observations with calculations of the three components using the nebular model of [17]. The nebular emission is obviously not uniform (see Fig. 1). The model of Clegg and co-workers [17], based upon much lower angular resolution data than discussed here, captures only some of the inhomogeneity by finding the least structured model compatible with the data then available. In their model, emission lines originate from two distinct volumes within a spherical nebula, separated by a cone whose axis is fortuitously oriented along the observed line of sight (see Fig. 10 of [17]), thus the model is rotationally symmetric along the observed line of sight. Within this cone there is a region of high electron density, roughly 6×10^3 cm^{-3}. Exterior to the cone the density is 3 times smaller. Using the nitrogen abundance listed in Table 20 of [17], the density distributions given by their Eq. (1) and accompanying parameters, we have adopted their ionization fractions listed in the two components (their Table 18) to integrate the N IV emission along representative lines of sight intercepted by the STIS slit. The level populations were computed using atomic data listed by [2]. For the N IV spectrum, 55% of the emission from the entire nebula arises from the more tenuous region (this can be contrasted below with the value of 9% for the C III lines observed by [3]). The relative contribution to the total brightness from the tenuous region increases with distance from the central star. Using Fig. 1, we have estimated the lines of sight at each position along the projected STIS slit and have computed the N IV intensities along the slit positions. As shown in Figs. 3 and 4, both the computed absolute intensities and ratios between the lines are remarkably similar to the observations, considering that the nebula is much more highly structured than the model. The variations in the M2/HPF ratio are probably dominated by line-of-sight nebular density fluctuations in plasma at densities below 10^4 cm^{-3}, to which the HPF/M2 or HPF/IC ratios are sensitive, but the M2/IC ratio is not.

Our observations should be regarded as the first *definitive* detection of an HPF-induced transition, even though [3] claimed that the equivalent transition in C III was detected in NGC 3918 at a 5σ level using the Goddard High Resolution Spectrograph on the HST. The data of [3] differ in several ways from ours. In spite of the factor 0.6

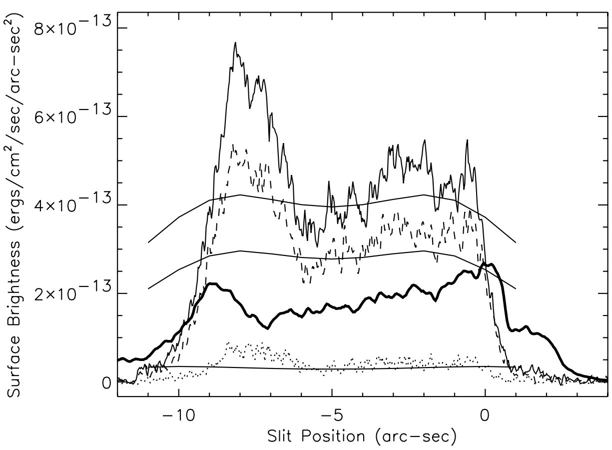

FIG. 3. Observed surface brightness as a function of position along the slit. The thin solid line gives the surface brightness of the M2 component, the long dashed line shows the IC line, and the dotted line the HPF line. The thick solid line shows the O III surface brightness along the slit as inferred from the WFPC2 F555W image. Slit positions are measured from the position centered on by the STIS target acquisition. Also shown (smoother curves) are the computations discussed in the text.

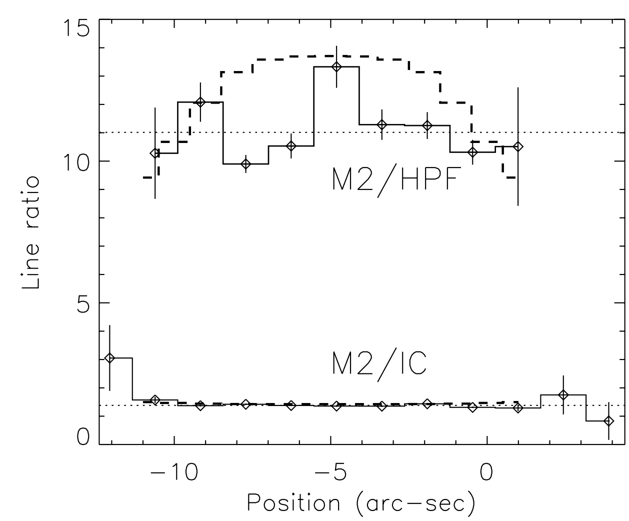

FIG. 4. Observed (histograms) and computed (simple curves) line ratios and error bars are plotted as a function of position along the slit. The line ratios calculated using flux summed over the whole slit are shown by the dotted lines. Model calculations are shown as dashed lines.

lower abundance of nitrogen, both stable nitrogen isotopes have nuclear spin, increasing the predicted relative strength (relative to the IC line) by 2 orders of magnitude, in comparison with carbon. Their signal-to-noise ratios are therefore much lower than ours; furthermore there are other, unidentified, features in their spectrum (see their Fig. 4) of similar strength to those claimed to be the HPF transition. Thus blending and systematic errors may be important. Second, our list of arguments concerning the reality of the new emission feature and its identification with the HPF-induced transition lends additional credence to our detection, and last, because both the ^{15}N and ^{14}N isotopes have nuclear spin, leading to similar transition rates in both cases, the strength of the HPF-induced transition is almost independent of the isotope ratios. Thus we can use the N IV nebular spectra as an independent check of atomic data and/or the thermodynamic structure of the nebula, in particular, to probe lower densities than have previously been inferred (for example, from [17]). A perturbation analysis reveals that the ratio of the HPF to either the IP or M2 transition is, for fixed values of the electron densities characteristic of the nebula ($\approx 5000\ \mathrm{cm}^{-3}$), sensitive primarily to the radiative transition rates, provided that the collision cross sections between the $2s^2\,{}^1S_0$ and $2s2p\,{}^3P^o_{0,1,2}$ levels are fixed according to LS coupling rules (that is not taking into account relativistic corrections nondiagonal in L and S). The model ratios averaged over the slit are $\mathrm{M2/HPF} = 12.1 \pm 1.4$ and $\mathrm{IC/HPF} = 8.4 \pm 1.1$ (the uncertainties are rms values). The sensitivity analysis shows that any systematic error in the transition rates would have been detected if its amplitude were greater than 33% of the computed values. The agreement between the observed and computed ratios thus provides the first independent support for the computations of the HPF transition rates by [2], where $A(^{14}\mathrm{N}) = 4.92 \times 10^{-4}\ \mathrm{s}^{-1}$ and $A(^{15}\mathrm{N}) = 3.62 \times 10^{-4}\ \mathrm{s}^{-1}$.

In conclusion, our analysis validates with 33% accuracy the transition rates computed for the HPF-induced transition of N IV, arguably the slowest atomic rate ever determined. This gives us greater confidence in using the atomic data of [2] for further analyses of the similar ions C III and Si III. In these cases, only the minority isotope has a nuclear spin, and opening up possibilities for testing isotopic abundances in planetary nebulae. The $^{13}\mathrm{C}/^{12}\mathrm{C}$ ratio may vary widely in stellar ejecta, depending on the nucleosynthesis history of the material. Substantial variations in different parts of the same nebula are possible. This would open a new window into the study of the late stages of stellar evolution. Furthermore, the ratio between the HPF and other lines will provide a sensitive and reliable density diagnostic for densities near $10^3\ \mathrm{cm}^{-1}$, lower by an order of magnitude than was possible using the M2/IC ratios ([2]). Variations in electron density correlated with radial line-of-sight velocity variations might contribute to the slight asymmetry in the HPF line opening up the kind of analysis discussed by [18].

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