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TESTING THE CREATION OF THE UNIVERSE: THE PRIMORDIAL HELIUM ABUNDANCE

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RESUMEN

Las mediciones de alta precisión de la abundancia primordial de elementos ligeros es una de las pruebas fundamentales del Big Bang. La abundancia primordial de helio, $Y_{\rm p}$, el cociente de He a H por masa, se determina por las lineas de emisión que se forman durante el proceso de recombinación-decaimiento, $\mathrm{He}^{+}+e^{-} \rightarrow \mathrm{He}^{0}(nL) + h\nu$, seguido de la cascada radiativa. Una prueba definitiva del Big Bang requiere una precisión del 1% o mejor. $Y_{\rm p}$ se mide de los cocientes de intensidades de lineas de recombinación de He I y H I en regiones H II. El cociente de densidad $n(\mathrm{He}^{+})/n(\mathrm{H}^{+})$ es proporcional a la intensidad de las lineas observadas y al cociente inverso de los coeficientes de recombinación. Los estudios previos de coeficientes de recombinación de He I suponen que los tripletes y singuletes son diferentes sistemas de cascadas radiativas que se comunican unicamente por colisiones con intercambio de electrones. De hecho, algunos niveles de alto momento angular tienen multiplicidades de espin mixto, lo que lleva a decaiminetos convencionales de dipolo electrico que mezclan a los tripletes y singuletes. Presentamos calculos tentativos de los coeficientes de recombinacion de He I a una temperatura de 10,000 K en el “caso B”. Se anticipan diferencias de 1% o mayor que pueden afectar la $Y_{\rm p}$ en cantidades cosmologicamente significativas.

ABSTRACT

Precision measurement of the primordial abundance of the light elements is one of the fundamental tests of the Big Bang. The primordial abundance of helium, $Y_{\rm p}$, the ratio of He to H by mass, is measured from emission lines that form during the recombination-decay process, $\mathrm{He}^{+} + e^{-} \rightarrow \mathrm{He}^{0}(nL) + h\nu$ followed by radiative cascade. A definitive test of the Big Bang requires an accuracy of 1% or better. $Y_{\rm p}$ is measured from ratios of intensities of He I and H I recombination lines in H II regions. The density ratio $n(\mathrm{He}^{+})/n(\mathrm{H}^{+})$ is proportional to the observed line intensities and the inverse ratio of recombination coefficients. All previous studies of He I recombination coefficients have assumed that the triplets and singlets are distinct radiative cascade systems that communicate only through electron exchange collisions. Actually, certain large-angular-momentum levels have strongly mixed spin multiplicities, leading to conventional electric-dipole decays that act to mix the singlets and triplets. We present tentative calculations of He I recombination coefficients at a temperature 10,000 K in ”Case B”. Changes 1% or greater are anticipated, and changes of this magnitude may affect the deduced $Y_{\rm p}$ by cosmologically significant amounts.

Key Words: **H II REGIONS — ISM: ABUNDANCES — RADIATION MECHANISMS**

The measurement of the primordial abundances of ^{4}He is one of the decisive tests of the Big Bang (Olive *et al.* 2000, Peimbert and Torres-Peimbert 1974). Models of Big Bang nucleosynthesis predict the ^{4}He/H abundance ratio to an accuracy of about 1 part in 10^{4} (Olive *et al.* 2000). For instance Izotov and Thuan(1998) find the ^{4}He/H ratio (by mass fraction), $Y_p = 0.244 \pm 0.002$.

Y_p is measured by considering ratios of the intensities of He I and H I recombination lines in recorded spectra. A decisive test of the Big Bang can only be made if the rate coefficients describing how these lines form are known to an accuracy that is substantially better than the 1% accuracy that is possible with large samples of objects. All previous calculations of He I recombination efficiencies have assumed LS coupling (Benjamin *et al.* 1999,Brocklehurst 1972), in which the He^{0} singlets and triplets are considered as separate cascade-decay systems. Here we present tentative calculations that go beyond the LS-coupling approximation and predict He I effective recombination coefficients (Osterbrock 1989, p. 78) that include the effects of singlet-triplet inter-combination lines. These may change the re-

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combination coefficients to a cosmologically significant extent.

LS coupling provides the most familiar description of the levels and spectra of simple atoms. It is tempting to suppose that in helium LS coupling would be essentially perfect, but on the contrary in He I configurations $(1sn\ell)nL$ where $L \leq 3$, LS coupling breaks down via singlet-triplet mixing. For F-states ($L = 3$) the breakdown is already serious (MacAdam and Wing 1975), and beyond $L = 4$ it becomes maximal, certain fine-structure levels being nearly equal mixtures of singlet and triplet character.

The accuracy of the radiative recombination model presented here is determined by the atomic data used. The high precision calculations of Drake(1996a) are used extensively in the calculation of level energies, quantum-defects, oscillator strengths and matrix elements for the lowest lying levels. The level energies for states of helium are the high precision results of Drake(1996a).

The method used to calculate the spontaneous radiative transition rates (Einstein A coefficients) depends on the initial and final states. Rates for the non-permitted transitions are from the literature Hata and Grant(1981), Lin *et al.* (1977), Drake(1979). For the dipole-allowed transitions the oscillator strengths are from Drake(1996a), Van Regemorter *et al.* (1979), and Kono and Hattori(1984).

The largest relativistic correction comes from singlet-triplet mixing between states with the same n, L, and J (*e.g.* $3^1D_2 - 3^3D_2$, due to $H_{\rm fs}$ Drake 1996a). Oscillator strengths representing the rediagonalization of the 2×2 matrices $H_0 + H_{\rm nfs} + H_{\rm fs}$ can be obtained from the unmixed oscillator strengths and direct and exchange integrals (Drake(1996a), MacAdam and Wing 1975). For low-lying transitions we use mixing-angle data from Drake(1996a), and we extrapolate for higher-lying transitions.

Radiative recombination rates (α) are the least-well-known quantities in the model calculation. These are obtained by detailed balancing (Peach 1967) from He I photoionization cross sections.

The novel aspect of our calculation is the inclusion of singlet-triplet mixing and its effects on the resulting emission spectra. The effects of including singlet-triplet mixing are seen by contrasting the LS-restricted (LS) and singlet-triplet-included (ST) cases. The differences presented here between the LS and ST cases should have very high accuracy since they are determined chiefly by the transition probabilities, which themselves are accurate

Tentative Results: DO NOT CITE			
Transition	Wavelength	Intensity(LS)	LS:ST
	Å	Ergs/sec/cm^2	Ratio
		* 10^{27}	
$3^3P_0 - 2^3S_1$	3888.63	1.043207	1.00016
$3^3P_1 - 2^3S_1$	3888.67	3.433175	1.00062
$3^3P_2 - 2^3S_1$	3888.67	7.456810	1.00371
$4^1D_2 - 2^3P_2$	4471.07	0.0	0.00000
$4^1D_2 - 2^3P_1$	4471.09	0.0	0.00000
$4^3D_1 - 2^3P_2$	4471.46	0.402216	1.00241
$4^3D_2 - 2^3P_2$	4471.47	0.879947	0.99329
$4^3D_3 - 2^3P_2$	4471.47	3.521416	0.99342
$4^3D_1 - 2^3P_1$	4471.48	0.241328	1.00241
$4^3D_2 - 2^3P_1$	4471.48	0.527963	0.99328
$4^3D_1 - 2^3P_0$	4471.68	0.080432	1.00241
$3^3D_1 - 2^3P_2$	5875.59	0.618366	1.00852
$3^3D_2 - 2^3P_2$	5875.60	1.601593	0.95800
$3^3D_3 - 2^3P_2$	5875.60	11.12744	0.97793
$3^3D_1 - 2^3P_1$	5875.61	0.371015	1.00852
$3^3D_2 - 2^3P_1$	5875.63	0.960943	0.95799
$3^3D_1 - 2^3P_0$	5875.96	0.123650	1.00852
$3^3S_1 - 2^3P_2$	7065.14	1.529243	1.00191
$3^3S_1 - 2^3P_1$	7065.18	0.917531	1.00191
$3^3S_1 - 2^3P_0$	7065.68	0.305780	1.00191
$3^1D_2 - 2^1P_1$	6678.16	4.244204	1.04793
$3^3D_1 - 2^1P_1$	6679.66	0.0	0.00000
$3^3D_2 - 2^1P_1$	6679.68	0.0	0.00000

to 5 significant figures Drake(1996a), Hummer and Storey(1998). The absolute accuracy of the calculation is set by the accuracy of photoionization cross sections used to generate the recombination coefficients, but the methodology we follow is standard, so whatever errors are introduced will also be present in previous calculations. A final uncertainty is due to the finite size of our model atom.

The density ratio $n({\rm He}^+)/n({\rm H}^+)$ is proportional to the observed line intensities. *Tentative* LS case intensities for helium are given in table as well as the ratio of the LS to ST intensities.

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