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A METHOD FOR DETERMINING THE PHOTOSPHERIC ^{4}He ABUNDANCE

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ABSTRACT

The photospheric ^{4}He/H ratio is not measured directly but is inferred from stellar evolution models, helioseismology, and coronal observations. We suggest a procedure for determining the photospheric ratio on the basis of solar wind isotopic He abundances and γ-ray line measurements. Recent *Ulysses* measurements of the ^{4}He/^{3}He isotopic ratio in the solar wind indicate that it is constant over a large range of velocities; long-term averages in the ratio from different experiments are also consistent with one another, with values ranging from 2050 to 2350 and uncertainties ranging from 120 to 200. This constancy supports models indicating that substantial fractionation of these isotopes does not occur as they are transported from the photosphere to the solar wind. Comparison of the time histories of the 2.223 MeV neutron capture line and prompt de-excitation lines from solar flares provides the only direct measurement of the ^{3}He/H ratio in the photosphere. This ratio has been determined for only a few flares. The most reliable ratio determined to date is $2.3 \pm 1.2 \times 10^{-5}$, where the uncertainty is statistical at the 90% confidence level. By multiplying these solar wind ^{4}He/^{3}He and γ-ray–derived ^{3}He/H ratios, we obtain estimates of the photospheric ^{4}He/H ratio ranging from $\sim$0.02 to 0.10. Improved observations of the solar wind ^{4}He/^{3}He ratio and modeling of its origin can confirm that it measures the photospheric ratio. Recent improvements in our understanding of flare-accelerated particles, based on γ-ray line data, can be applied to models of 2.223 MeV line production. Application of these corrected models to high-quality γ-ray line data obtained from instruments on the *Compton Gamma Ray Observatory* and the *Solar Maximum Mission* will result in a more accurate measurement of the photospheric ^{3}He/H ratio and thus the ^{4}He/H ratio.

Subject headings: solar wind — Sun: abundances — Sun: flares — Sun: photosphere — Sun: X-rays, gamma rays

1. INTRODUCTION

The present helium abundance of the Sun has significant consequences for stellar evolution models (Christensen-Dalsgaard et al. 1996) and impacts solar neutrino production (see, e.g., Bahcall & Pinsonneault 1995). Our knowledge of the relative abundances of helium and hydrogen in the Sun is uncertain, however (see, e.g., Grevesse, Noels, & Sauval 1996). This is true because He is not detectable in the photospheric spectrum or in meteorites. The ^{4}He/H number ratio is measurable in the solar wind at an average value between about 0.03 and 0.05, but it is also highly variable on short timescales ranging from 0.001 to over 0.3 (Gloeckler & Geiss 1989); this raises questions about fractionation of these different charge species in their transport from the photosphere to the corona and finally into the solar wind. UV spectroscopy over a sunspot provided a broad range of acceptable values for this ratio, from 0.078 to 0.22 (Laming & Feldman 1994). A more precise abundance ratio, 0.07 ± 0.011, for the solar corona was recently reported by Gabriel et al. (1995), but this ratio may not reflect the photospheric abundance.

The solar helium abundance has typically been derived from application of stellar evolution models to the Sun (see, e.g., Bahcall & Pinsonneault 1995). This yields a ^{4}He/H ratio of about 0.084. Helioseismology provides a means of measuring the helium abundance in the convective zone (see, e.g., Dziembowski, Pamyatnykh, & Sienkiewicz 1991; Hernández & Christensen-Dalsgaard 1994). These measurements yield a ^{4}He/H ratio, 0.082, consistent with the stellar models, but the value is sensitive to uncertainties in the equation of state (see, e.g., Kosovichev et al. 1992; Christensen-Dalsgaard et al. 1996).

In this Letter we suggest a method for measuring the ^{4}He/H ratio in the photosphere on the basis of γ-ray line measurements and observations of the ^{4}He/^{3}He isotopic ratio in the solar wind. We obtain an estimate of ^{4}He/H ratio based on existing observations and current models. We then discuss how improvements both in the line measurements and in models for γ-ray production and transport can provide a more accurate method for measuring the ^{4}He abundance in the photosphere.

2. NEW METHOD FOR DETERMINING THE PHOTOSPHERIC ^{4}He/H RATIO

Measurement of the photospheric ^{4}He/H ratio is possible with solar wind ^{4}He/^{3}He and solar flare γ-ray line observations. This is based on the premise that the solar wind ^{4}He/^{3}He ratio measures the photospheric ratio. Temporal measurements of the 2.223 MeV neutron capture line in solar flares and calculations of the line production provide an excellent means of measuring the photospheric ^{3}He/H ratio. Multiplying these two ratios gives the desired photospheric ^{4}He/H ratio.

2.1. *Solar Wind Measurement of the* ^{4}He/^{3}He *Isotopic Ratio*

Measurements of ^{3}He in the solar wind have been made since the late 1960s with foil samples returned from the lunar surface (see, e.g., Geiss & Reeves 1972) and instruments on spacecraft such as *ISEE 3* (Coplan et al. 1984) and *Ulysses* (Bodmer et al. 1995). Although there was some early evidence for variability in the observed ^{4}He/^{3}He ratio based on the *ISEE 3* observations, recent measurements by *Ulysses* indicate

that the daily averaged ratio is constant over a broad range of wind speeds from 350 km s^{-1} to 950 km s^{-1}. The average ratios derived from the foil, *ISEE 3*, and *Ulysses* observations also are in good agreement: 2350 ± 120, 2050 ± 200, and 2290 ± 200, respectively. It is important to confirm that this ratio is constant in order to be confident that the solar wind isotopic ratio of He measures the photospheric ratio. Additional measurements with the *Ulysses* data are in progress (G. Gloeckler 1997, private communication).

In principal, one would expect the ^{4}He/^{3}He ratio to be the same in the solar wind and in the photosphere because the primary fractionation effect for elements appears to depend on first ionization potential (see, e.g., Meyer 1996 and references therein). As the first ionization potentials of the two isotopes of He are virtually identical, one would not expect to find a significant amount of fractionation. Bodmer et al. (1995) indicate that none of the models for fractionation effects due to ionization and acceleration of particles to solar wind speeds can account for significant changes in the ratio. More detailed calculations are required, however (see note added in proof).

2.2. *Photospheric* ^{3}He/H *Ratio from* γ*-Ray Line Measurements*

Determination of the photospheric ^{3}He/H ratio has significant impact on our understanding of stellar evolution and big bang nucleosynthesis (see, e.g., Schramm 1996). The most direct way of measuring the ^{3}He abundance in the photosphere is by observing the time dependence of 2.223 MeV γ-rays produced when solar-flare neutrons are captured on ambient hydrogen (Wang & Ramaty 1974). Neutrons of ~1–10 MeV in energy are primarily produced when flare-accelerated protons interact with ambient ^{4}He ($p\alpha$) leading to np^3He, $n2p^2$H, and $2n3p$ (Hua & Lingenfelter 1987b). Flare-accelerated α-particles interacting with ambient hydrogen (αp) produce higher energy neutrons (~10–50 MeV) through the same reactions. When both the accelerated α/proton and the ambient ^{4}He/H ratios have values of 0.1, roughly comparable numbers of low- and high-energy neutrons are produced. The time history of the neutron capture line is dependent on the interaction time profile, spectrum, and directionality of flare-accelerated particles, the solar density and composition, and the abundance of ^{3}He. The last dependence occurs because the radiationless ^{3}He(n, p)^{3}H interaction has a cross section 1.6×10^4 that of ^{1}H(n, γ)^{2}H and absorbs the neutrons without emission of the 2.223 MeV photon. The density of photospheric ^{3}He is thus a critical parameter in determining the time profiles of the neutron capture line.

Kanbach et al. (1981) performed Monte Carlo calculations that demonstrated that the 2.223 MeV emission should generally follow an exponential decay with a time constant of about 100 s. Prince et al. (1983) applied such an exponential approximation to four flares observed by the *Solar Maximum Mission (SMM)* γ-ray spectrometer; they obtained a time constant of ~90 s for the intense flare on 1982 June 3, which they used to set an upper limit of 3.8×10^{-5} on the ^{3}He/H ratio in the photosphere. Murphy et al. (1997) used the same approximation and have set a 2 σ limit of 2.3×10^{-5} on this ratio for the immense flare of 1991 June 4 using data from the OSSE experiment on the *Compton Gamma Ray Observatory (GRO)*. These methods only are approximations, however, and depend on a single assumed density in the interaction region.

Hua & Lingenfelter (1987a, 1987b) have performed Monte Carlo calculations of neutron capture line emission using a model for the density distribution of the solar atmosphere. They used various accelerated-particle spectra and angular distributions, assuming photospheric abundance for both the accelerated particles and ambient material. They obtained a ^{3}He/H ratio of $(2.3 \pm 1.2) \times 10^{-5}$ (90% confidence level) for the 1982 June 3 flare, consistent with the upper limit derived by Prince et al. (1983). There are uncertainties in the ratio because of the choice of photospheric model and accelerated-particle composition and spectrum. Thus, current values for the photospheric ^{3}He/H ratio are in the range ~ 1–4×10^{-5}.

2.3. *Implications for the Photospheric* ^{4}He/H *Ratio*

The product of the solar wind ^{4}He/^{3}He ratio and the photospheric ^{3}He/H ratio derived from γ-ray line measurements in flares can provide an estimate of the photospheric ^{4}He/H abundance ratio. This is based on the premise that the solar wind ratio accurately reflects the abundance in the photosphere. The estimated ^{4}He/H ratio falls in the range ~0.02–0.10 on the basis of the currently available experimental values. This range is consistent with values obtained from stellar modeling, helioseismology, and UV observations of the corona. We discuss below how an improved ^{4}He/H ratio can be obtained from the γ-ray line observations.

Since the publication of the work of Hua & Lingenfelter (1987a), there have been new developments in our understanding of the accelerated-particle spectra based on γ-ray line measurements that impact the derived ^{3}He/H line ratio. First, a power-law spectrum for the accelerated particles appears to provide a better fit to the γ-ray line data (Share & Murphy 1995; Ramaty et al. 1995) than the Bessel function used by Hua & Lingenfelter. Second, the accelerated-particle abundances are enhanced in heavy elements over the photospheric abundances used by Hua and Lingenfelter. This includes an accelerated α/proton ratio that is closer to 0.5 than to 0.1 (Murphy et al. 1991; Share & Murphy 1997; Murphy et al. 1997). A larger α/proton ratio produces more high-energy neutrons that reach higher densities, slow down, and are captured faster. This results in an effectively shorter 2.223 MeV line decay time (see Fig. 8 in Hua & Lingenfelter 1987a). These changes in the model can have a significant impact on the derived concentration of ^{3}He and thus on the ^{4}He/H ratio in the photosphere.

There are several flares in the *SMM* (Share & Murphy 1995) and *GRO* OSSE (Murphy et al. 1997), COMPTEL (Rank 1995), and EGRET (Bertsch et al. 1997) databases with high-quality γ-ray line data that can be analyzed with these improved models. At least four flares during Cycle 22 have produced time histories of 2.223 MeV line emission with excellent statistics. Several more can be expected in Cycle 23. Combining these high-quality γ-ray observations, modified models for production of γ-ray lines, and new analysis of the solar wind observations will result in an improved measurement of the photospheric helium abundance.

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Note added in proof.—Recent calculations by Bodmer & Bochsler (Eos: Trans. AGU, 78 [17], S254 [1997]) indicate that solar wind ^{4}He may be depleted by up to 30% relative to ^{3}He for certain coronal magnetic field configurations.