Rydberg Atoms as Gravitational-wave Antennas†

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We show that highly excited Rydberg atoms nearby astrophysical gravitational wave sources are expected to emit significant electromagnetic radiation in the radio through a process of gravitationally induced resonance fluorescence. Semiclassical arguments are discussed and a quantum-mechanical expression for the differential cross section is obtained. This process could provide a new observational tool for the remote detection and study of gravitational waves.

1. INTRODUCTION

Recent studies have rekindled interest in the effects of gravitation on atomic systems [1]. These studies have shown that such effects, typically considered negligible under most astrophysical circumstances, may play a role in perturbing atoms if other processes are sufficiently depressed. In particular, it has been shown that the gravitational tidal energy shifts of freely falling Rydberg atoms of principal quantum number \( n \sim 900 \) or larger at the surface of neutron stars could in principle be resolved by means of radiotelescopic observations [1]. (Parker et al. first suggested this possibility; Ref. 2.)

Rydberg atoms are very fragile and thus lend themselves to being used as probes of external fields. Rydberg atoms with \( n \) up to \( \sim 700 \) are currently studied in the laboratory; atoms with \( n \) up to \( \sim 350 \) have been detected in the interstellar medium [3].

However, such highly excited atoms are extremely sensitive to other

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perturbations due to external magnetic fields and to atom-ion and atom-electron interactions. Therefore, the constraints on the temperature, density, and magnetic field of environments where observations could be successful are very strict and difficult to satisfy in the magnetosphere of a neutron star.

From this point of view, observations of Rydberg systems in the interstellar medium are more likely candidates for measuring the effects of gravitation on atoms. Of course in this case the difficulty is that the gravitational fields involved are hopelessly weak. Leen et al. have analyzed the possibility of detecting gravitational waves by directly measuring the periodic energy shifts caused on Rydberg atoms at distances $r_s \sim 10^9$ cm from the source. These studies imply that such effects are beyond the reach of present technologies.

In this essay we discuss the possibility of using Rydberg atoms as resonant quantum mechanical antennas for the detection of gravitational waves. In this case, the action of gravitational fields is not treated as quasi-time-independent as in all previous work on the subject. Instead, it is shown that the very high values of the quality factor $Q$ cause the time-dependent dynamical response of atoms acted upon by periodic gravitational waves to be quite dramatic even at distances $r_s$ from the source $\sim 1$ A.U.

2. SEMICLASSICAL ARGUMENTS

The foundations of the study of atoms in curved space-time were laid by Parker [2]. He expanded the Dirac equation to first order in the Riemann tensor and wrote a fully covariant perturbative Hamiltonian in Fermi normal coordinates. In the case of low electron speeds ($v/c \ll 1$), the most important correction corresponds to the tidal gravitational force stretching and squeezing the freely-falling atom.

In order to evaluate the importance of time-dependent gravitational perturbations on atoms, we shall consider the effects of a plane gravitational wave travelling toward the positive $z$ axis on an electron harmonically bound to a freely falling massive particle in the presence of radiation damping. The electron-particle system is in the $(x, y)$ plane at the initial time. The equation of motion then reads

$$\ddot{x}_i + \gamma \frac{\omega_0^2}{m} \dot{x}_i + \omega_0^2 x_i = c^2 R_{0i0j}(t)X^j(t), \quad (1)$$

where $\gamma$ is the friction coefficient related to the lifetime of the state $\tau$ as $\gamma/m = 1/\tau$, $\omega_0^2$ is the natural frequency, $R_{0i0j}$ is the Riemann tensor, $x_i$ is