Creation and Measurement of a Coherent Superposition of Quantum States

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The creation and control of a coherent superposition of two quantum states is a crucial ingredient in many quantum information algorithms. In this work, we demonstrate experimental techniques for creating and measuring a well-defined coherent superposition of two degenerate atomic states with equal amplitudes in metastable neon. Starting from state $^3P_0$, we create adiabatically a coherent superposition of the magnetic sublevels $M = \pm 1$ of state $^3P_2$ using a tripod-STIRAP scheme [1, 2], which is a variation of the well-known technique of stimulated Raman adiabatic passage (STIRAP) [3]. In a second step, we demonstrate an independent technique for measuring the phase of the created superposition. It is based upon coupling level $^3P_2$ to $^3P_1$ by a linearly polarized laser, followed by detection of the population in the $^3P_2(M = \pm 2)$-states as a function of the polarization angle of that laser. This scheme is suitable to prove the reliability of the present or other creation techniques.

The coupling scheme of tripod-STIRAP is shown in Fig. 1. The initially populated state $(2p^5 3s)$ $^3P_0$ is coupled by a π-polarized pump laser P to the intermediate state $(2p^5 3s)$ $^3P_1(M = 0)$, which in turn is coupled to the final states $(2p^5 3s)$ $^3P_2(M = \pm 1)$ by σ^+ and σ^- polarized Stokes lasers S_+ and S_-). The two Stokes fields are produced by a linearly polarized laser beam (which can be viewed as an equal superposition of σ^+ and σ^- polarizations). The pump field is spatially offset downstream but overlapped with the Stokes fields, as shown in Fig. 2, thus producing a STIRAP-type interaction sequence.

The Hamiltonian of a resonant tripod system (Fig. 1(a)) has four adiabatic states [1] that are parametrized by two mixing angles $\vartheta(t)$ and $\varphi(t)$, defined by

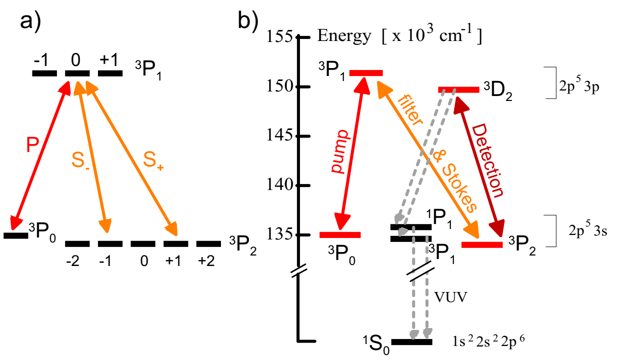

FIG. 1: a) Coupling scheme for the creation of the coherent superposition using tripod-STIRAP. b) Level Scheme of ^{20}Ne including the levels involved in the experiment. Dashed lines represent spontaneous emission used in the detection.

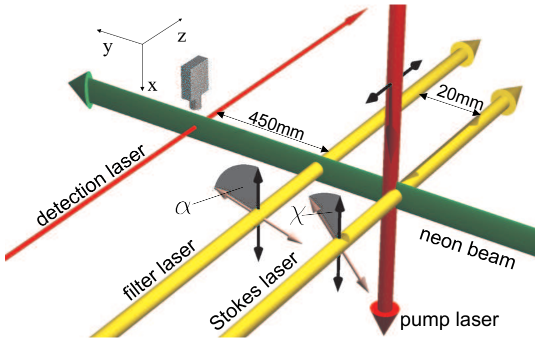

FIG. 2: Geometry of the experiment. The direction of polarization $\hat{e}_P$ (indicated by the small arrows) for the pump laser ($\lambda = 616$nm) is chosen to be the z-axis, its direction of propagation defines the x-axis, while the neon beam propagates in y-direction. The two circularly polarized Stokes lasers are generated by a linearly polarized laser ($\lambda = 588$ nm) propagating in z-direction, whose direction of polarization forms an angle χ with the x-axis. The propagation of the so called filter laser ($\lambda = 588$ nm) is parallel to the Stokes laser and its direction of polarization $\hat{e}_F$ forms an angle α with the x-axis. The detection laser ($\lambda = 633$ nm) is unpolarized.

$\tan\vartheta(t) = \Omega_P(t)/\Omega_S(t)$ and $\tan\varphi(t) = \Omega_{S_-}(t)/\Omega_{S_+}(t)$, where Ω_x ($x = P, S_+, S_-$) are the Rabi frequencies of the coupling lasers and $\Omega_S(t) = \sqrt{\Omega^2_{S_+}(t) + \Omega^2_{S_-}(t)}$. Two of the adiabatic states are degenerate dark states, without components of the intermediate state $^3P_1$,

$$\begin{aligned} |\Phi_1(t)\rangle &= \cos\vartheta(t)|0,0\rangle - \sin\vartheta(t)\cos\varphi(t)e^{-i\chi}|2,-1\rangle \\ &\quad - \sin\vartheta(t)\sin\varphi(t)e^{+i\chi}|2,+1\rangle \qquad (1a) \\ |\Phi_2(t)\rangle &= \sin\varphi(t)e^{-i\chi}|2,-1\rangle - \cos\varphi(t)e^{+i\chi}|2,+1\rangle, \quad (1b) \end{aligned}$$

where the states are labelled in the $|J, M\rangle$ notation and the angle χ is defined in Fig. 2. The coupling between these dark states, $\langle\Phi_1(t)|\dot{\Phi}_2(t)\rangle = \dot{\varphi}(t)\sin\vartheta(t)$, induces a (resonant) transition between them, which has been used by Theuer *et al* [2] to build a variable atomic beam splitter. In the present experiment, there is only one linearly polarized Stokes laser, which produces two coincident and copropagating σ^+ and σ^- fields with the same intensity; hence $\Omega_{S_-}(t) = \Omega_{S_+}(t)$ and $\varphi \equiv \pi/4$, and the nonadiabatic coupling between the dark states vanishes identically. Moreover, because the pump field is delayed with respect to the Stokes field, we have $\vartheta(-\infty) = 0$ and $\vartheta(+\infty) = \pi/2$. Hence, in the adiabatic limit, the atom evolves along the adiabatic path $|\Phi_1(t)\rangle$ from the initial state $|0,0\rangle$ to the final state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|2,-1\rangle e^{-i(\chi+\phi)} + |2,+1\rangle e^{+i(\chi+\phi)}], \qquad (2)$$

where ϕ is an arbitrary phase, e.g. from an external magnetic field. Thus the use of a linearly polarized Stokes field guarantees equal amplitudes of the two states.

Adiabatic evolution ensures robustness of the created state against small-to-moderate variations in the interaction parameters. Because the population transfer vehicle is a dark state, this technique is immune to loss of coherence and population due to spontaneous emission from the intermediate state $^3P_1$. Because the superposition involves Zeeman sublevels of the metastable $^3P_2$ state it is not subjected to spontaneous emission on a timescale < 1 s from this state either. Decoherence occurs only via external magnetic fields or collisions within the beam.

The measurement of the superposition is based upon mapping the superposition parameters onto the populations of a subset of the M-states. This is done by exposing the atoms to a linearly polarized "filter" laser, which couples the M'-sublevels of the $^3P_2 \leftrightarrow {^3P_1}$ transition with $\Delta M' = 0$, where the quantum number M' is defined with respect to the direction of polarization $\hat{e}_F$ of the filter laser. The resulting state vector $|\Psi'\rangle$ in the basis of the M'-sublevels (ordered from $M' = -2$ to $M' = +2$) of level $^3P_2$ reads

$$|\Psi'\rangle = \frac{1}{\sqrt{2}}[-\cos(\xi/2-\alpha), i\sin(\xi/2-\alpha), 0, -i\sin(\xi/2-\alpha), \cos(\xi/2-\alpha)], \quad (3)$$

with the relative phase $\xi = 2(\chi + \phi)$. The filter laser optically pumps the populations out of states $M' = \pm 1$. The population remaining in states $M' = \pm 2$ serves to measure the phase ξ.

In order to measure the population in states $M' = \pm 2$ the atoms travel through a magnetic field, which causes a uniform distribution of the population over the M'-states An unpolarized detection laser transfers the population of the $^3P_2$ level into the level $^3D_2$, from where light-induced fluorescence (LIF) to the ground state is detected. The measured signal $S(\alpha)$ is proportional to the total population in states $M' = \pm 2$ (see Eq. (3)),

$$S(\alpha) = p\cos^2(\xi/2-\alpha), \quad (4)$$

where p is the detection probability. For an incoherent superposition the modulation vanishes, as can be seen from Eq. (4) by averaging over the phase ξ.

In Fig. 3 a typical LIF signal $S(\alpha)$ is shown. The observation of a modulation is a direct proof of the coherence between the states $|2,-1\rangle$ and $|2,+1\rangle$.

The phase of the superposition is controlled by the angle χ of the Stokes polarization (see Fig. 2), which provides a simple and robust tool for manipulating the superposition. Figure 4 confirms a linear dependence, with a slope of unity, between the preset phase and the measured phase. Hence our technique allows one to write in and read out any given phase of the superposition (2).

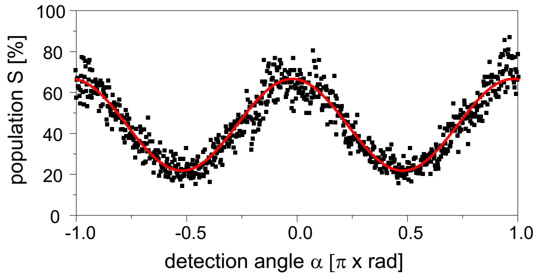

FIG. 3: Population S(α) as a function of the polarization angle α of the filter laser (see Fig. 2). The line is a $\cos^2$-fit to obtain the phase of the superposition.

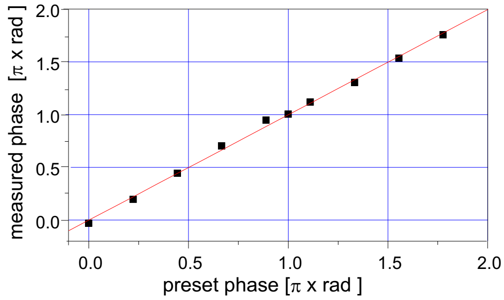

FIG. 4: Measured phase versus preset phase. The preset phase is controlled by the polarization angle χ of the Stokes laser. The line is a linear fit with a slope of unity.

We also measured the influence of magnetic fields $\mathbf{B}$ on the created superposition and the introduced decoherence. A magnetic field parallel to the pump polarization causes a spread in the superposition phase because of the velocity spread of the neon atoms. A perpendicular magnetic field leads to a redistribution of population between the magnetic sublevels of level $^3P_2$.

In conclusion, the accuracy of both the creation and the measurement techniques, and the elimination of decoherence, suggest a significant potential for the use of these techniques in quantum information algorithms, where high fidelity is crucial.

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