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Density Dependence and Dynamics of Dipole-Dipole Interactions Among Rydberg Atoms

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Density Dependence and Dynamics of Dipole-Dipole Interactions Among Rydberg Atoms

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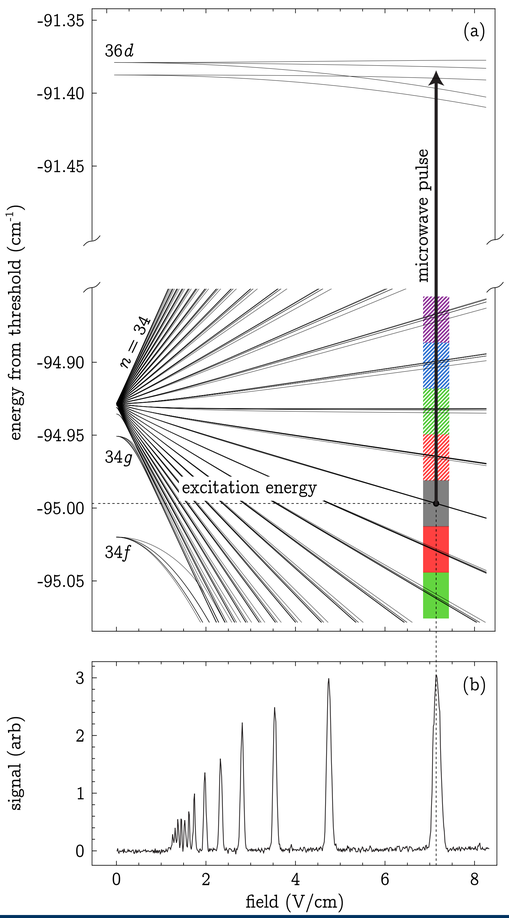
After trapping atoms, exciting them to an initial high-energy Rydberg state, and allowing them a brief time to exchange energy with each other through dipole-dipole interactions, we observe how their energies are redistributed among various energy levels. The measurements we make in this physical experiment do not give insight into how individual atoms interact or metrics like fidelity and entanglement entropy, which impact our results. For this reason, it is useful to compare our results from the physical experiment to those of our simulation on a supercomputer, in which we can track the final and initial energy of individual atoms and add parameters, to better explain what we observe in the physical experiment. We have refined our simulation by taking into account three body interactions, or dipole-dipole energy exchanges between three atoms at a time, in addition to the two-body interactions included in our previous model. In both our physical experiment and virtual model, we have varied the density, or number of atoms per volume within the trap, to observe its effect on the energy redistribution.

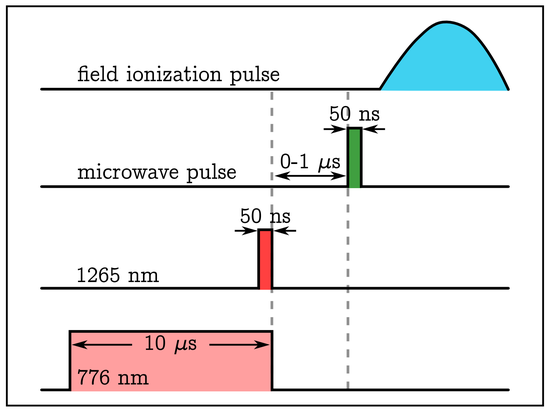
Experiment



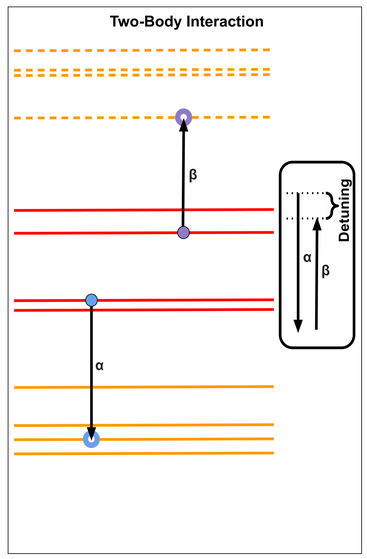
Ultracold Rydberg atoms, cooled to about 100 μK by a magneto-optical trap, interact via dipole-dipole interactions. By varying the intensity of the trapping lasers, we vary the density of the atoms, though we are unable to measure the exact density.

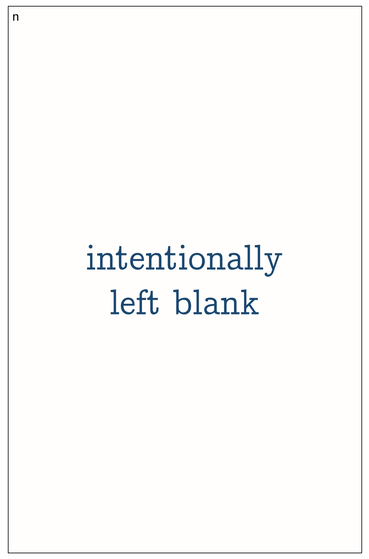
Fig. 1. A uniform electric field is applied throughout the experiment, splitting the energy levels into clusters corresponding to the orbital angular momentum of the outermost electron, as shown in (a) the Stark Map. The atoms in our experiment begin in the cluster highlighted in gray. Each cluster also has six discrete energy levels. Each spike in (b) indicates the population signal from a particular cluster detected using state-selective field ionization .

Fig. 2 The atoms are all excited to the same initial cluster by two laser pulses. Then, they are given a brief interaction period (≤ 1 μs) before a microwave pulse sends them to the 36d state where state-selective field ionization is used to detect the population of atoms in each cluster.



Model





Our simulation of the experiment models interactions within groups of four atoms at a time among 40 simulated atoms. We have varied the density by altering the spacing of the atoms. This summer, we have worked to integrate three-body interactions into our simulation of the experiment in addition to two-body. Two-body dipole-dipole interactions occur when one atom emits a photon which is absorbed by another atom. In many cases, as illustrated above, energy does not appear to be conserved in these interactions. One atom may go up further in energy than the other atom goes down; the magnitude of this difference is called the detuning of the interaction. Other sources of energy, like kinetic energy from the atoms, accounts for this detuning, however, the need for such added exchanges make the interaction less probable. Three-body interactions replace many two-body interactions in our previous model because they decrease the overall detuning of the interaction.

Results

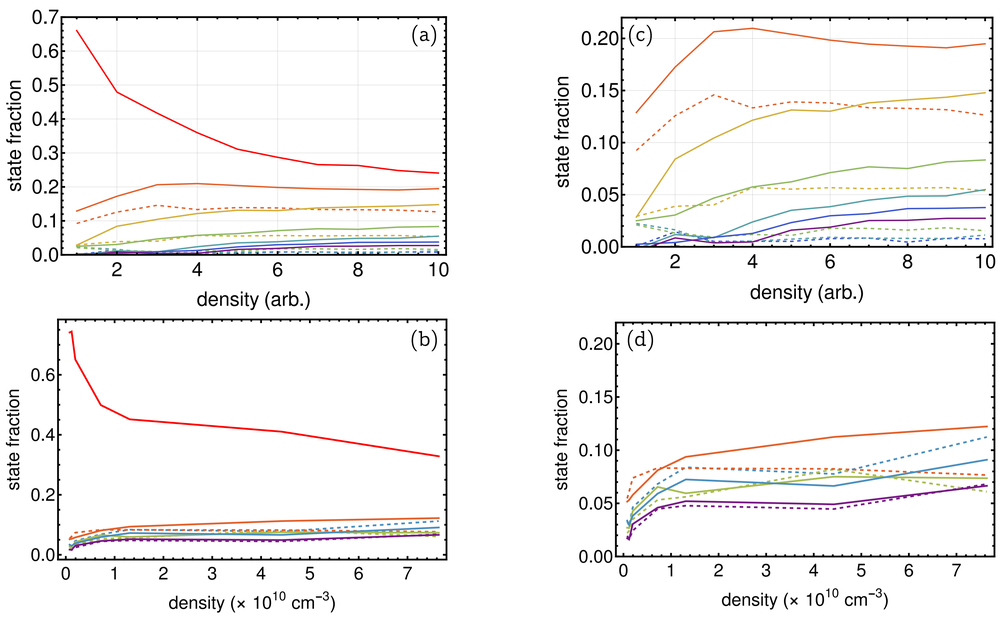


Fig. 2. Fraction of population in clusters as a function of density. Each colored line corresponds to a different cluster, with the initial cluster shown in red and the rest in rainbow order by degree from initial cluster. Data from clusters below the inital is graphed with a dashed line. (a) experimental data (b) model data (c) zoom in on experimental data (d) zoomed in on model data

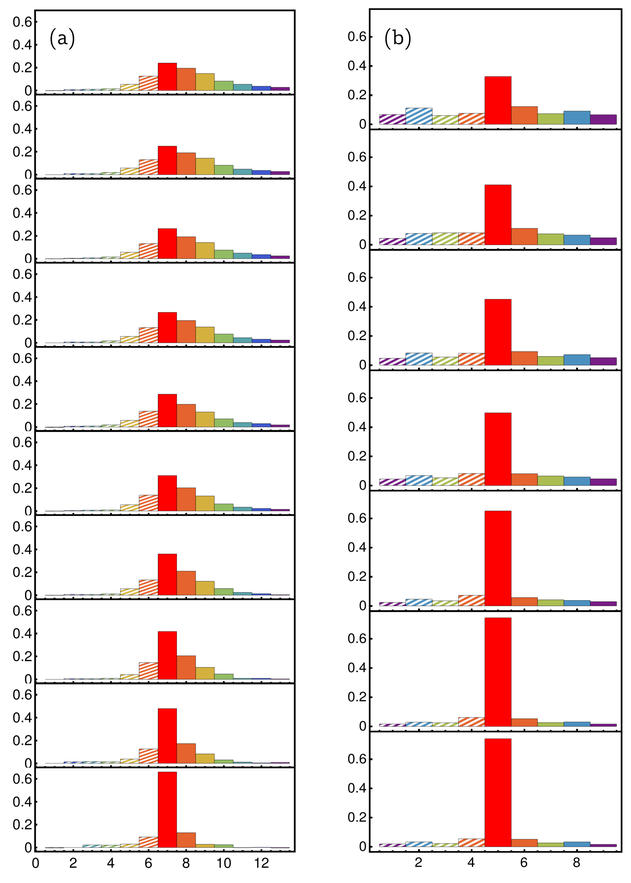


Fig. 3. Populations in Clusters at various densities, from top to bottom: higher density to lower density (a) experimental (b) model

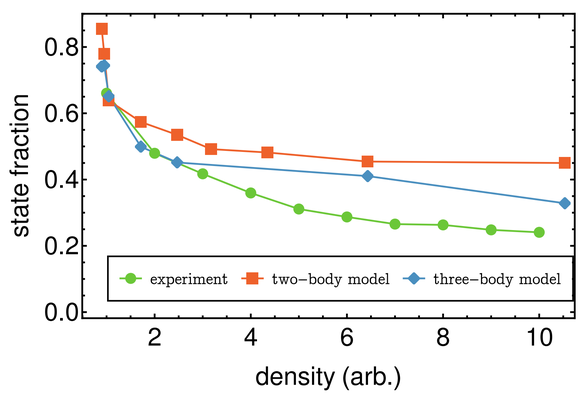


Fig. 4. Populations in inital cluster as a function of density for experimental (green), two-body model (red), and two- and three-body model (blue). Because we do not know the true densities in the experimental data, we have only matched the simulation data to experimental data by the shape of the curve. By adding the three-body interactions, our simulation data seems to have improved as the population decreases more quickly. In both models, at a high-density, our results do not match as nicely. This is understandable, as our simulation only models interactions within groups of four atoms at a time.

*This work was supported by the National Science Foundation (grant numbers 2011583 and 2011610).

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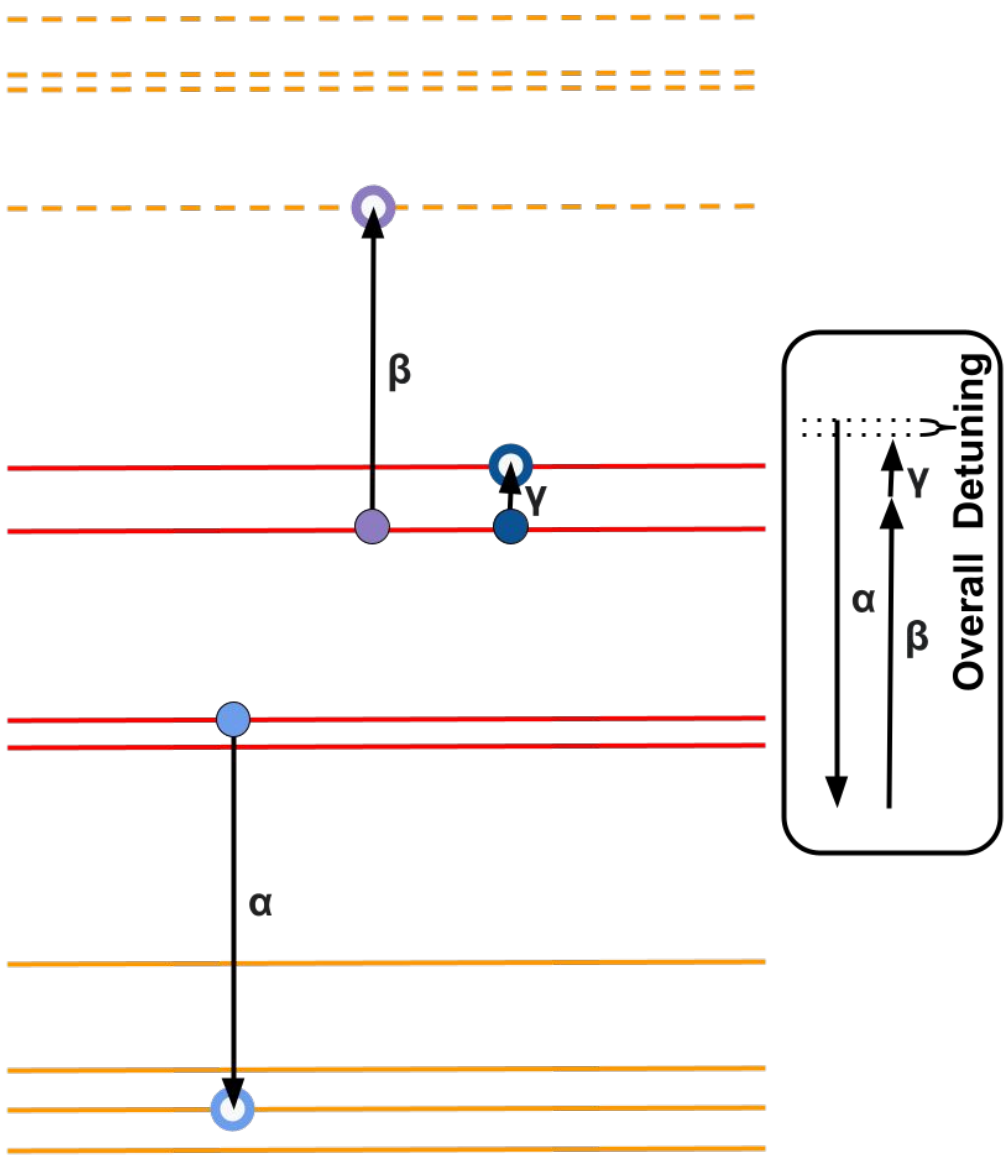
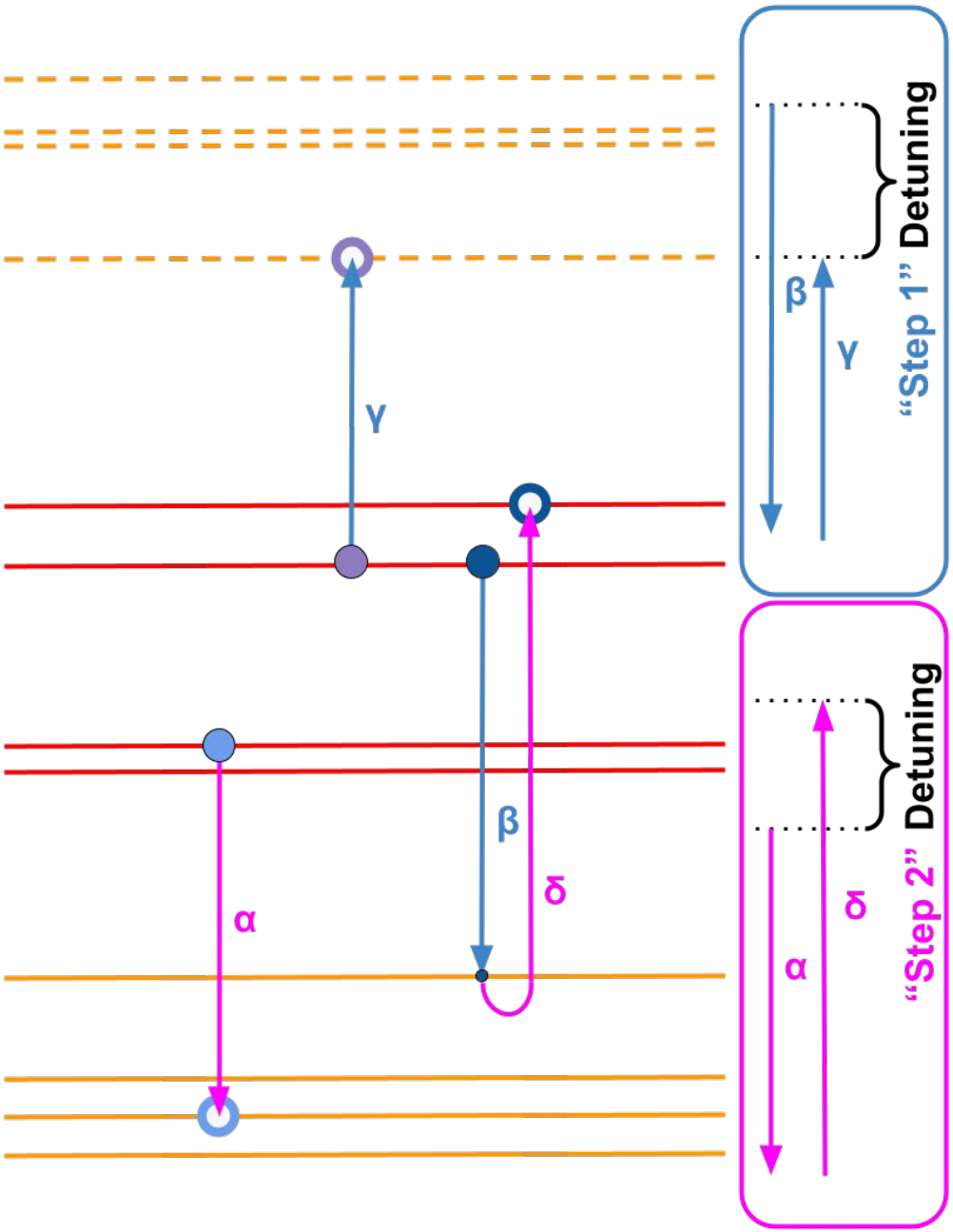
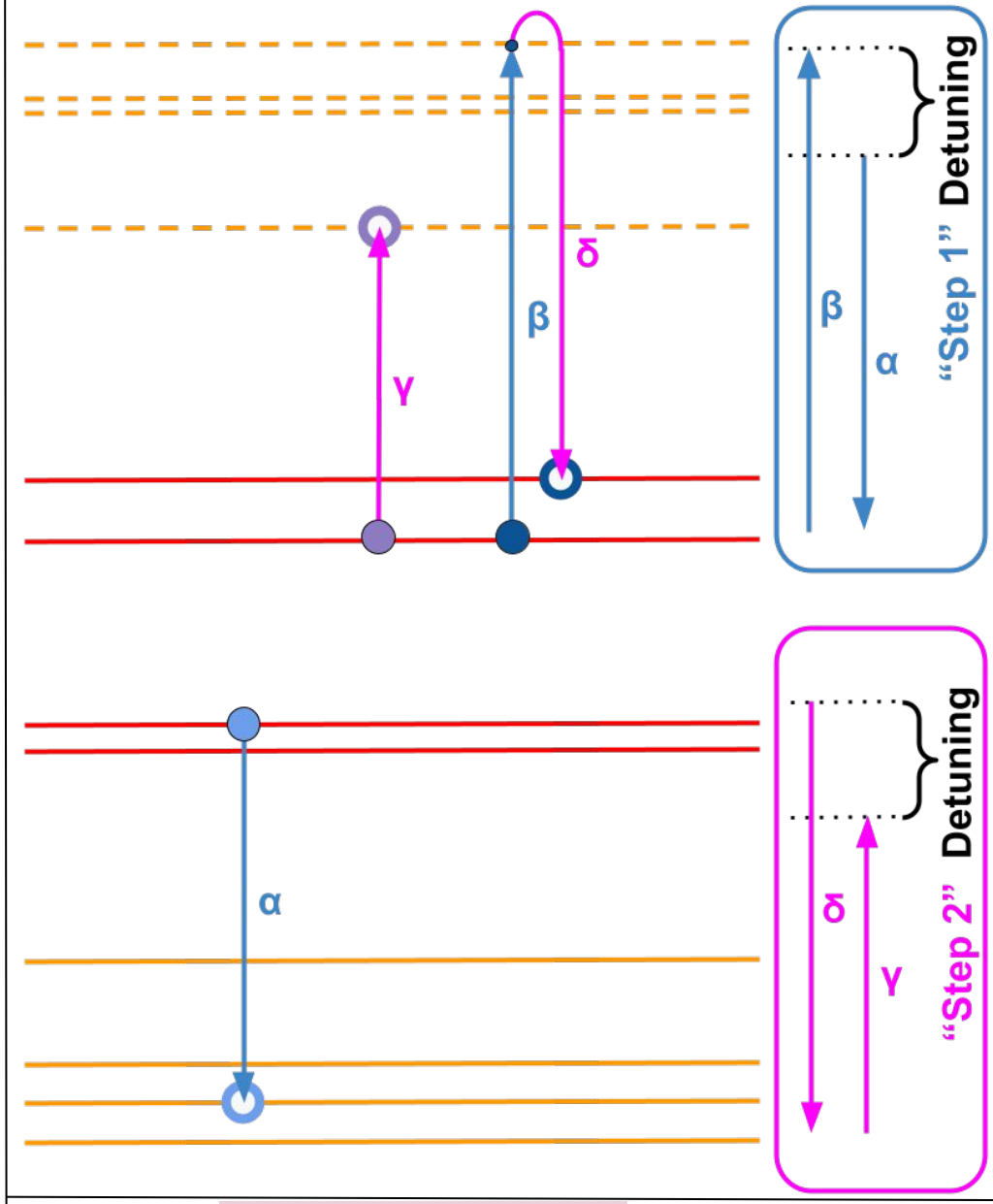
Initial and Final State in Three-Body Interaction



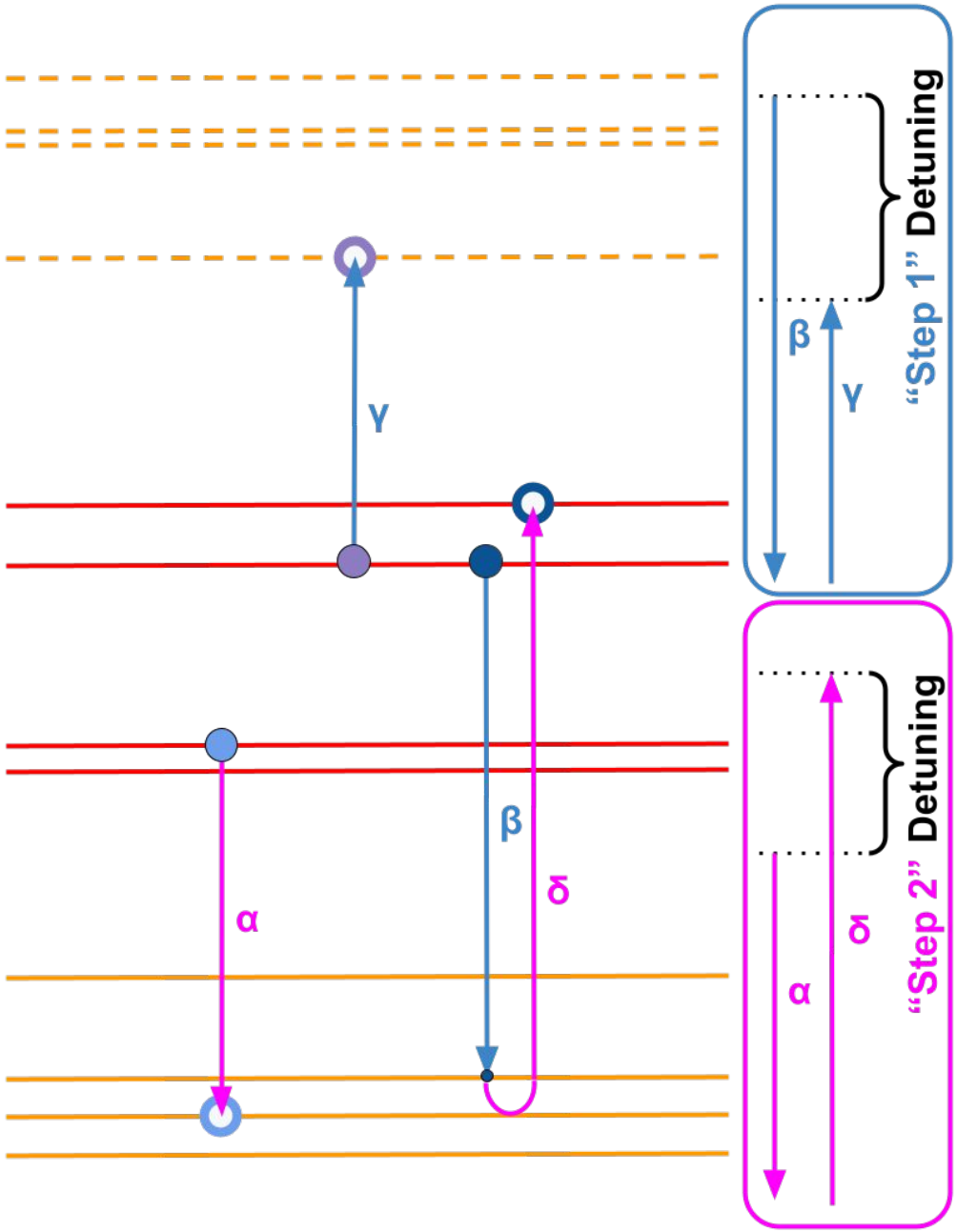
Three-body interactions, like this, occur instead of two-body interactions if they decrease the overall detuning of the interaction.

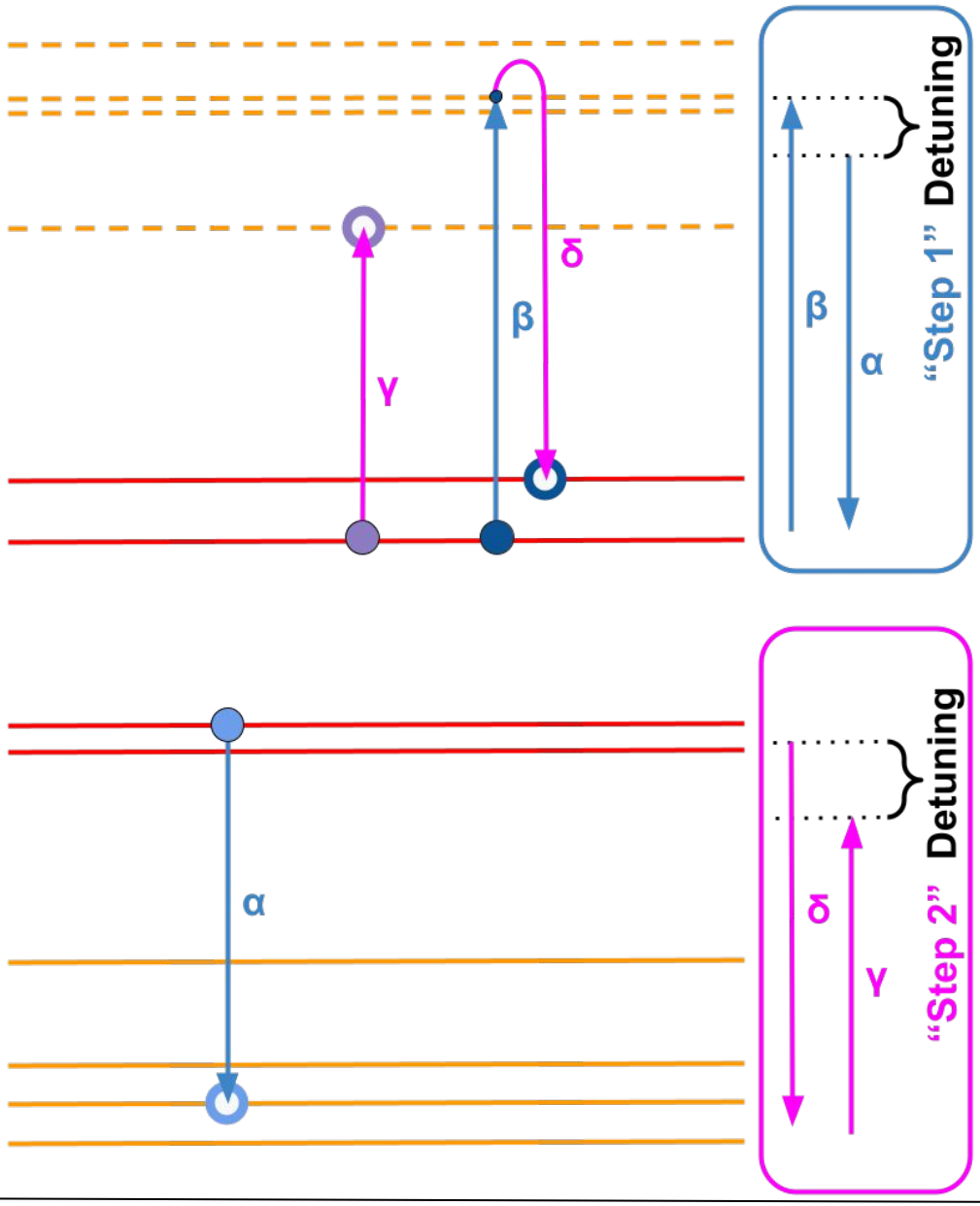


One Possible Path to Final State

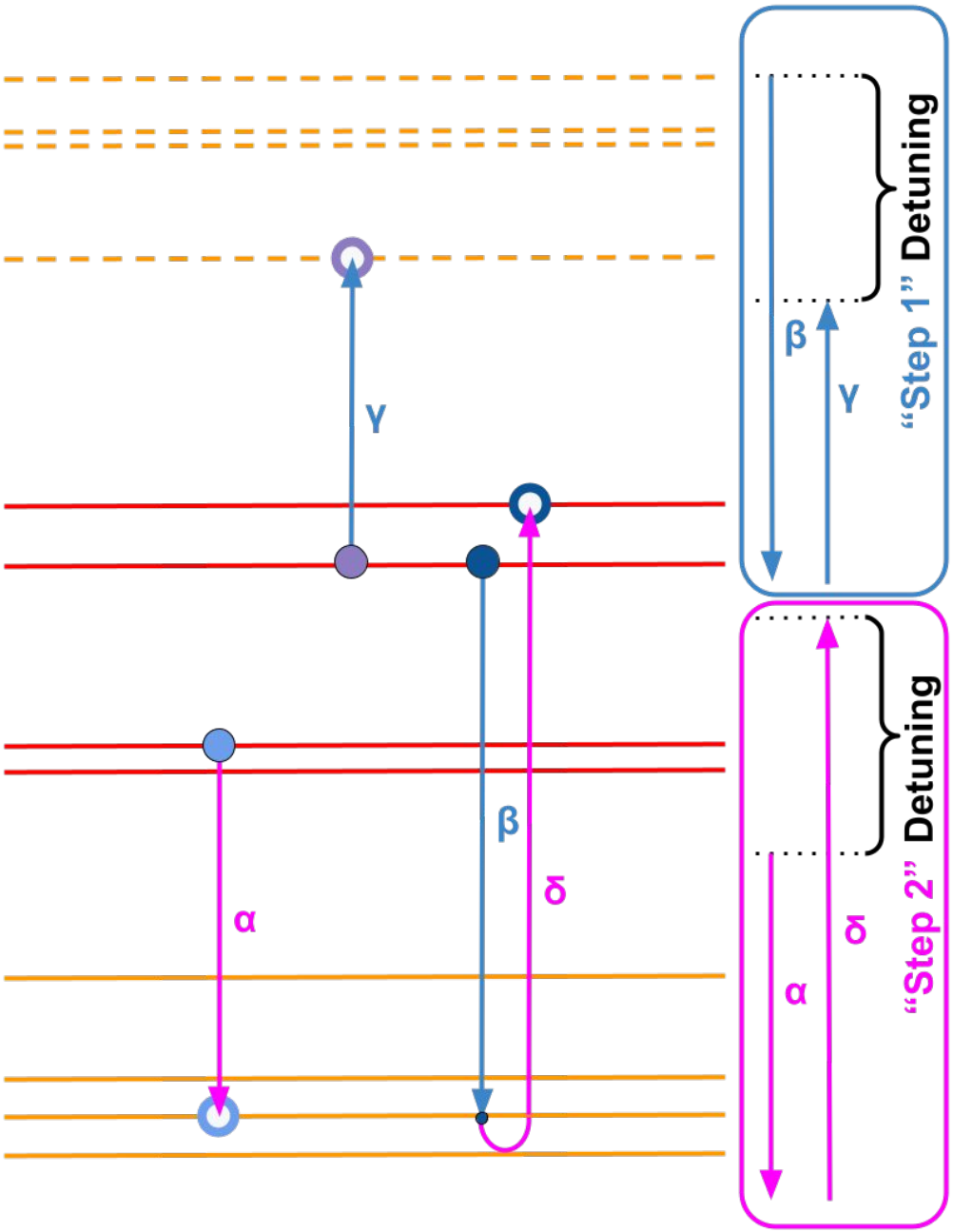


There are many possible "paths" for the atoms to take to their final energy levels. It is convenient to think of the interaction as occurring in two "steps" or two sets of two-body interactions, for which energy is conserved at the cluster level (if one atom goes down a cluster, another goes up a cluster).

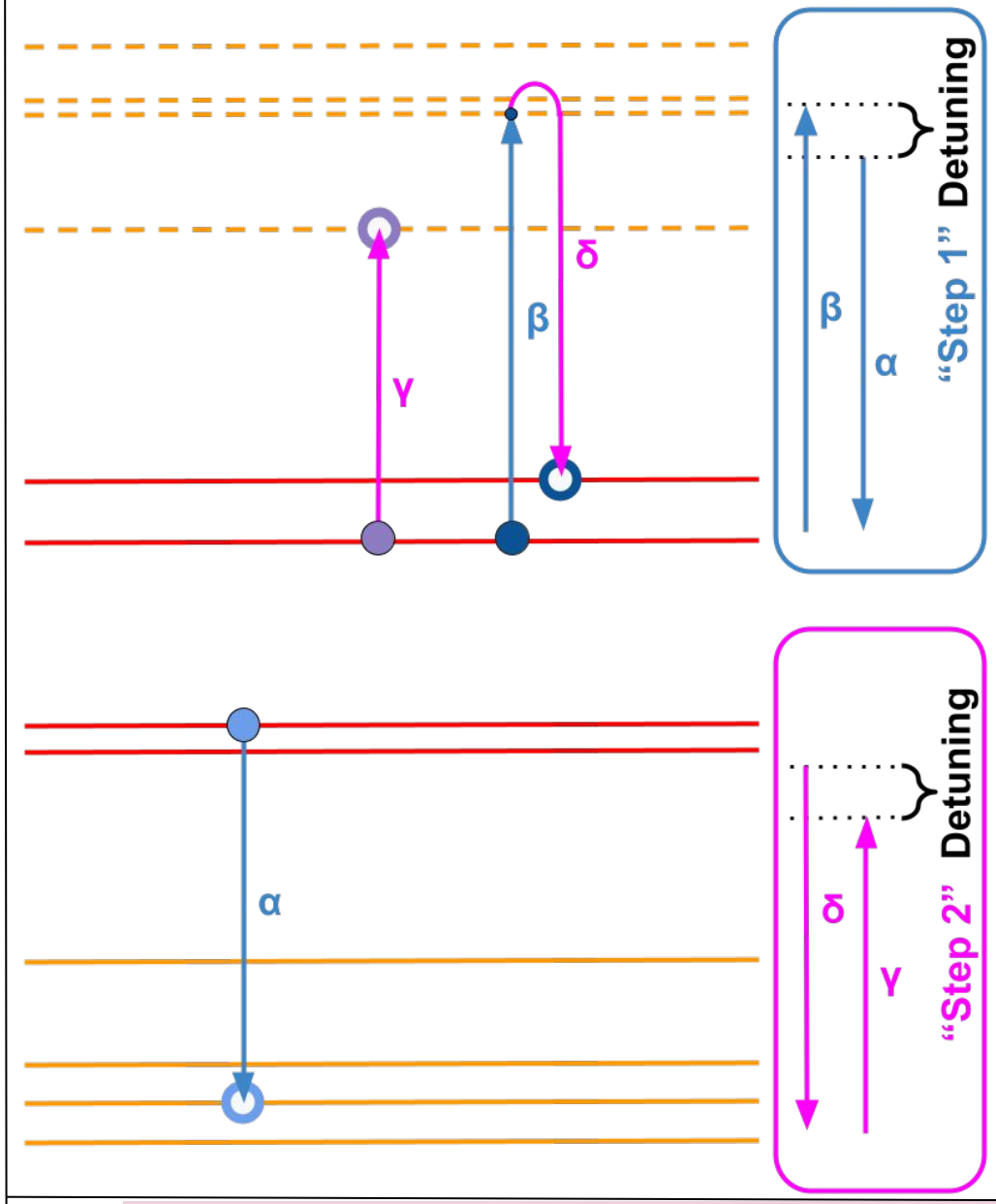




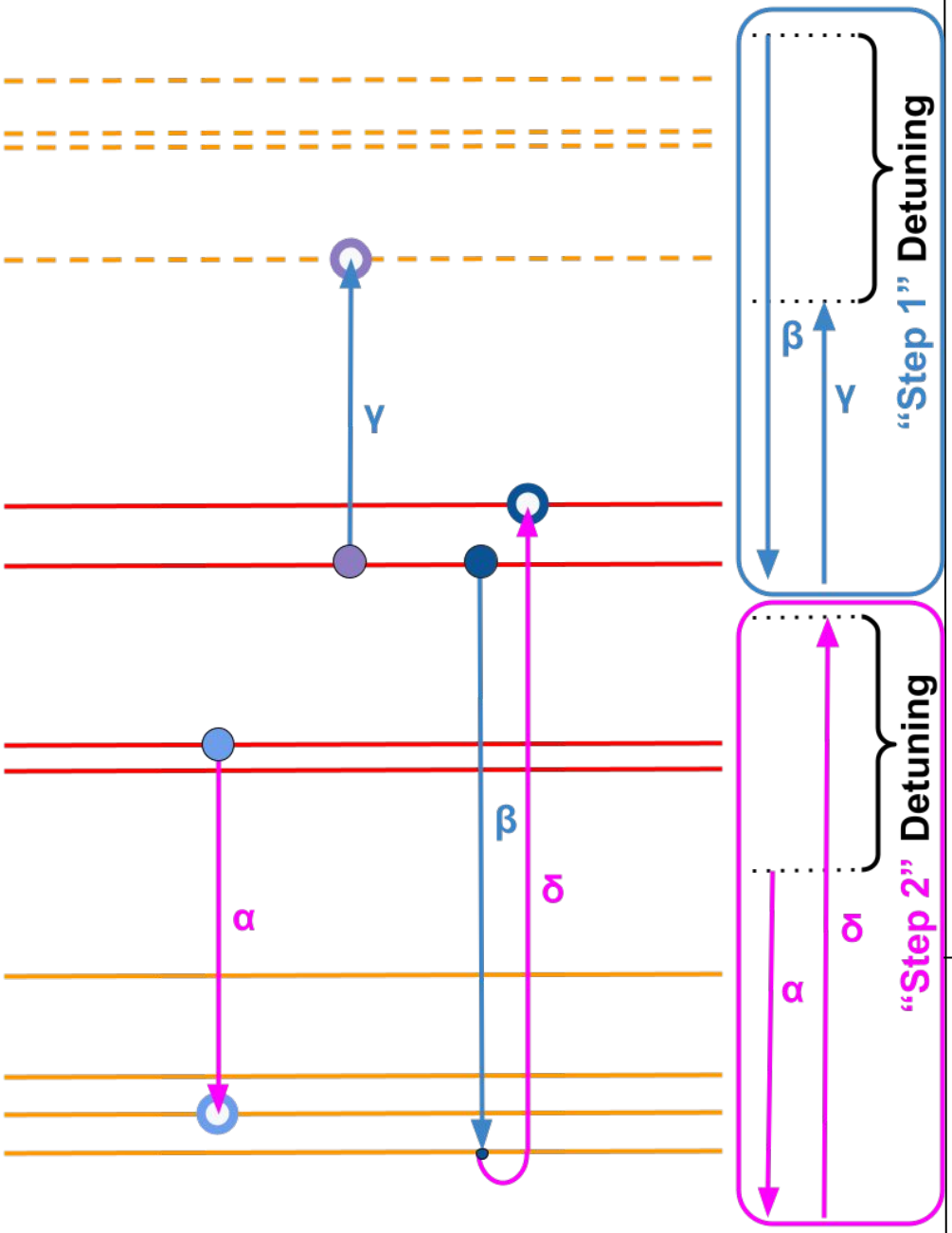
Although it is convenient to think of a path as having two steps, the third "helper" atom never actually populates the energy level that it "goes to" at the end of the first step.

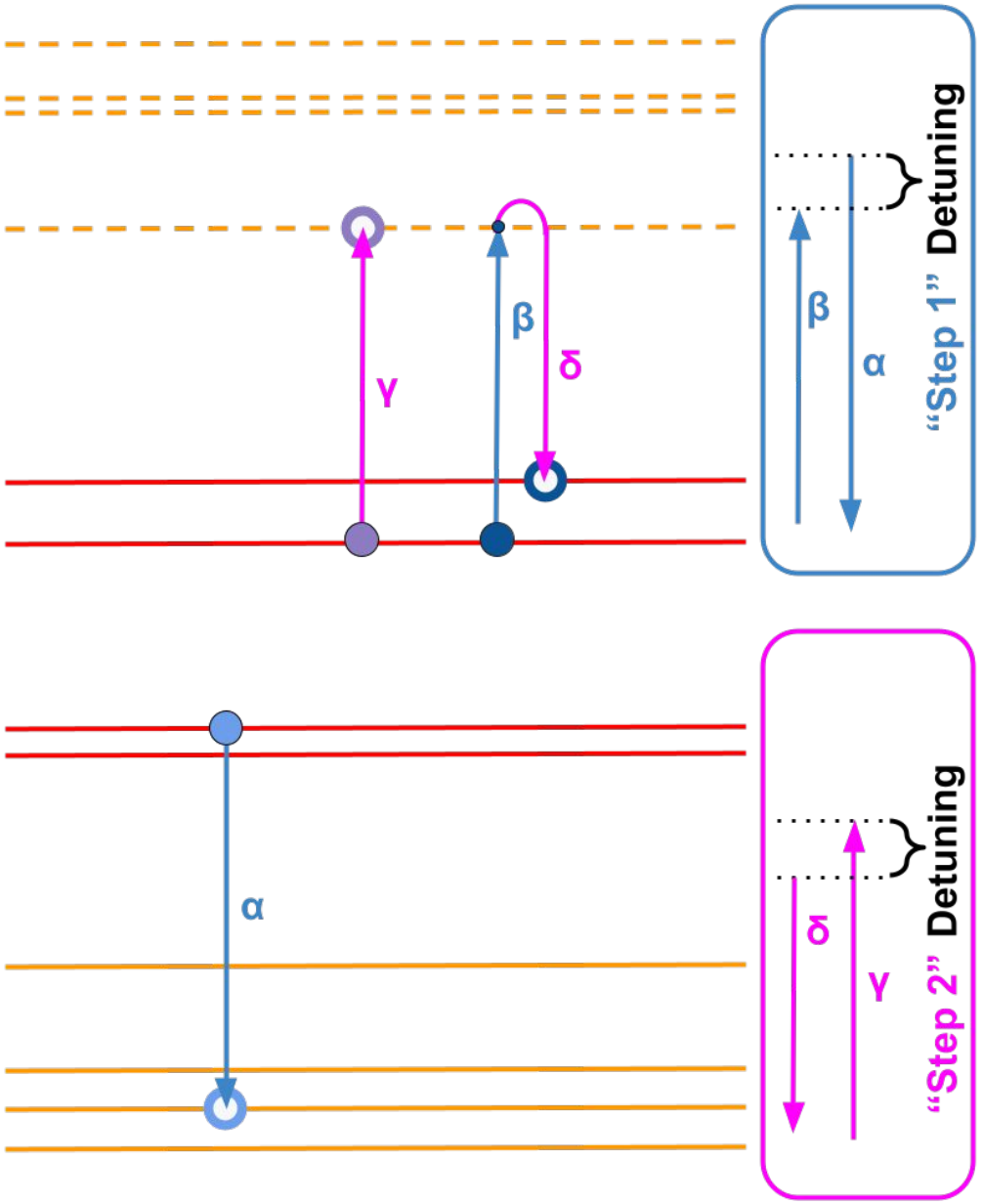


An Unlikely Path



The detuning in the intermediate steps should be large. Otherwise, it may be more likely for two two-body interactions to occur, during the first of which the third atom actually populates the energy level at the end of the "first step" in the three-body path.





If the detuning of the steps is smaller than the dipole moment of the two-body interaction between the two non-helper atoms, the path will not be taken, and the path will not be considered in our calculation of the matrix element.