Solving tricky quantum optics problems with help from (artificial) intelligence

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1 Introduction

The rapid advent of artificial intelligence (AI) is changing the way science is done. As with many new tools (calculators, e-mail, internet, etc.), we usually begin by applying these tools to solve common tasks better than it is possible with existing tools (e.g., performing arithmetical operations with a calculator rather than a slide rule). However, the real power of new tools lies in enabling completely new uses (e.g. collaborative paper writing with colleagues anywhere in the world, enabled by the Internet). We are convinced that the use of AI in science will bring a plethora of new uses and capabilities, some of which are already apparent today. An example is that AI is "democratizing" science by enabling any reasonably qualified scientist to perform sophisticated modeling using highly specialized algorithms, without the need to master software packages. AI takes the role of an expert colleague who can understand the "professor" formulating the question and is also able to run the dedicated software, thus eliminating the "middleman".

Here, we describe how we test AI abilities and new ways of "interacting with the tool" with three problems in quantum optics:

i. A straightforward question; however, known to trick even mature physicists in the field.

ii. A subtle problem with important applications that, while known for some years, is still a subject of current research.

iii. A problem of current research with somewhat unsettled solution.

Based on experience with these problems, we make observations regarding the possible utility of modern AI in the scientific process. In essence, every scientist now has access to sophisticated tools previously accessible only to specialists. This brings forward the importance of ideas rather than techniques. Of course, the speed with which ideas can be elaborated, tested in detail, and perhaps executed is reduced from months and years to the scale of minutes.

We also remark on the striking similarity of the AI behavior to that of students.

2 Problem One: State Populations upon Optical Pumping

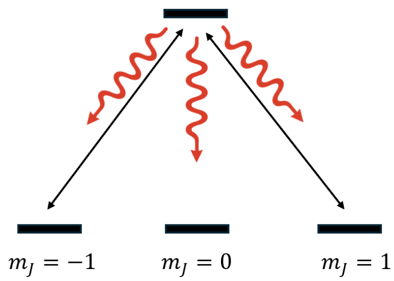
The first problem we discuss is a rather straightforward quantum optics question. However, in our experience, most physicists, including experts in the specific subfield, tend to give an incorrect answer, at least initially.

2.1 Formulation of the problem

Consider an ensemble of stationary atoms in the ground $J = 1$ state (see Fig. ??), in the absence of external fields. The atoms are optically pumped with monochromatic light propagating along z, which is linearly polarized along x. The excited state has angular momentum $J = 0$ and it decays spontaneously back to the ground state. There is no other relaxation in the system other than this spontaneous decay. Initially, the ground state is unpolarized, so that the population is equally distributed among the ground-state sublevels.

Assuming that the initial population of each of the ground-state Zeeman sublevels is $1/3$, what are the populations after optical pumping is complete?

a



b

State	$m_J = -1$	$m_J = 0$	$m_J = 1$
Initial population	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Final population	0	1	0
	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$
	$\frac{1}{6}$	$\frac{2}{3}$	$\frac{1}{6}$

Figure 1: Problem One. a). A $J = 1 \to J' = 0$ transition optically pumped with x-linearly polarized light. Spontaneous decay from the excited state is the only relaxation process considered in the problem. b). The initial populations of three lower-state Zeeman sublevels are all equal, $1/3$ of the total population resides in each of them. The lower section of the table shows plausible population distribution after optical pumping is complete. Which row represents the correct answer?

2.2 "Human" solution

Most physicists presented with this problem initially think that the populations of the $m_j = -1$, 0, and 1 sublevels are 0, 1, and 0, respectively (see Table **??**, the first line in "Final population"). In fact, atoms in the $m_j = 0$ cannot be excited by light, in contrast to the atoms in the other two sublevels. If an atom exited from a $|m_j| = 1$ sublevel spontaneously decays back into one of these sublevels, it has a chance to get reexcited, until it lands in the "dark" $m_j = 0$ state.

What is wrong with this solution is that it ignores the fact that there is not one but two dark states in the problem. The second dark state is an equal-weight superposition of $m_j = -1$ and $m_j = 1$, which is

$$\frac{1}{\sqrt{2}}\left(|m_j = -1\rangle + |m_j = 1\rangle\right) \tag{1}$$

for x-polarized light.

One way to see that there are indeed two dark states is to look at the same problem with the quantization axis chosen along the light polarization. In this case, light only drives the $\Delta m_j = 0$ transition, and the $|m_j| = 1$ sublevels are "dark".

Upon realization that only atoms in the "bright" superposition of the $|m_j| = 1$ sublevels orthogonal to the superposition (1), some physicists conclude that the final populations are $1/6$, $2/3$ and $1/6$. However, this is wrong again as this ignores the spontaneous decay of the excited state back to the dark superposition.

Finally, the correct solution for the populations is $1/4$, $1/2$, and $1/4$, which can be verified, once again, turning to the picture with the quantization axis chosen along the light polarization: the final population of each of the dark states is equal to $1/2$ of the total initial population and the sole dark state is empty.

State	$m_J = -1$	$m_J = 0$	$m_J = 1$
Initial population	1/3	1/3	1/3
Final population	0	1	0
	1/6	2/3	1/6
	1/4	1/2	1/4

2.3 Interaction with AI

maybe this is a way to format the interaction with the AI

– Describe the prompt and summarize the AI's approach, quoting key parts of its reasoning or specific steps, especially if highlighting a particular strength or weakness. "The AI was prompted to solve [...]. It correctly identified the relevant principle (e.g., conservation of energy) but made a calculation error in step 4, stating [quote the erroneous calculation or statement]. While the initial setup was correct, this error led to an incorrect final answer. See Appendix A for the full transcript."

2.4 Results

3 Problem Two: Resonant Transitions Between Decaying States (The Burshtein Effect)

3.1 Formulation of the problem

Consider two states, A and B, with energy gap δ between them. At time $t = 0$, state A is populated and state B is empty. A resonant excitation field drives the transitions between the two states. The strength of the driving field is characterized by the Rabi frequency Ω. We are interested in the population of state B as a function of time for several different cases for the relaxation rates of the two states Γ_A and Γ_B; it is assumed that the states decay into unobserved states:

Case 1: $\Gamma_A = \Gamma_B = 0\,;$

Case 2: $\Gamma_A = 0;\ \Gamma_B \ll \Omega\,;$

Case 3: $\Gamma_A = 0;\ \Gamma_B \gg \Omega\,;$

Case 4: $\Gamma_A = \Gamma_B = \Gamma \gg \Omega\,.$

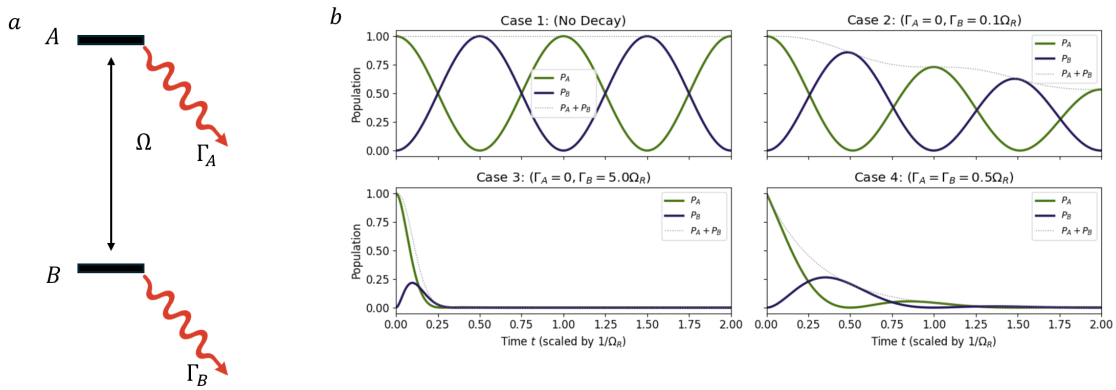


Figure 2: Caption

3.2 Interaction with AI

3.3 Results

4 Problem Three: Degenerate Mirrorless Lasing

4.1 Formulation

Mirrorless lasing (MR) is a process of generation of a directed nearly monochromatic radiation, without any mirrors, by a medium (in our case, an ensemble of atoms) exposed to a pump laser beam. ML is usually associated with "pencil-like" pumping; it often occurs in both forward and backward direction with respect to the pump beam. Degenerate mirrorless lasing (DML) refers to a situation where the emitted radiation is at a frequency that is the same (or close to) the frequency of the pump light.

Consider a $J = 1 \rightarrow J' = 2$ transition. There is no relaxation in the system except for the spontaneous decay from the upper state to the lower state. The atoms are stationary. The pumped volume is a cylindrical of length LL and radius RR; the atomic number density is n. The atoms are illuminated with resonant cw light with linear z polarization.

What are the conditions for mirrorless lasing in the forward and backward directions for light with x polarization? The axis of the cylinder is the y axis.

4.2 Interaction with AI

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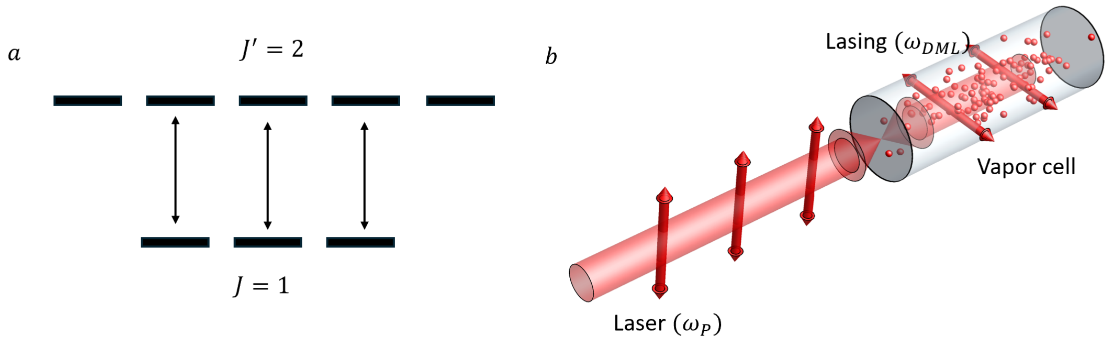

Figure 3: Caption

4.3 Results

5 Discussion

5.1 General Observations

5.2 When the Solution is Incorrect

5.3 Teaching AI to be Self-Critical

We can improve the AI a lot by using more tools:

1. like having it a knowledge base so that it doesn't make the same mistakes, this allows it to be self aware of the past and previous conversations we have had with it.

2. we can also use other tools like giving the AI the power of sequential thinking, with which it can correct and recheck what it says and it can improve the solution it gives and learn from its short-comings. this can either turn into the AI thinking more and going in a rabbit hole where we can trace it's thoughts or give it a saturation of where to stop. This is different than training the model as we are using a pretrained model and giving it access to more context.

3. presently, the SOTA models have decent context window but as the technology involves, the context windows will become more and the models more capable, which will lead to better answers

4.

5.4 Pros and Cons of AI Training Data

6 Conclusions

I have a feeling that we will find AI to be an extremely helpful, efficient "colleague", not immune to errors and misconceptions but ready to efficiently deal with them in cooperation with the "user".

We can maybe give an outlook of some related and future work, for example, mention the use of AI for the design of experimental setups.

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References

References

A Supplementary Material