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Connection between superelastic and inelastic electron-atom collisions involving polarized collision partners

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It is shown how the results of a recent experiment by Jiang, Zuo, Vušković, and Bederson [Phys. Rev. Lett. **68**, 915 (1992)], who investigated low-energy electron scattering from laser-excited *polarized* sodium atoms in the initial $(3p)\ ^2P^{\circ}_{3/2}$ $(F=3, M_F=3)$ state, can be related to the inelastic $3S \rightarrow 3P$ transition involving initially *unpolarized* electron and atom beams. Hence, this method can provide an independent check of the traditional electron-scattering experiment with unpolarized beams.

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In a recent publication, Jiang *et al.* [1] investigated low-energy electron scattering from laser-excited sodium atoms in the initial $(3p)\ ^2P^{\circ}_{3/2}(F=3, M_F=3)$ state. The purpose of this report is to outline how their particular experiment with *polarized* atoms can be related to the inelastic $3S \rightarrow 3P$ transition involving initially *unpolarized* electron and atom beams. Hence, this method can provide an independent check of the traditional electron-scattering experiment with unpolarized beams.

To illustrate our point, we begin with the density matrix $\rho_{\rm out}$ of the final state. Its matrix elements for scattering through an angle θ are given by [2]

$$(\rho_{\rm out})^{\theta, M_1' M_1}_{m_1' m_1} = \sum_{m_0', m_0, M_0', M_0} f(M_1' m_1', M_0' m_0'; \theta) \times f^*(M_1 m_1, M_0 m_0; \theta) \times \rho_{m_0' m_0} \rho_{M_0' M_0} . \qquad (1)$$

In Eq. (1), the f's are the scattering amplitudes, the matrix elements $\rho_{m_0' m_0}$ and $\rho_{M_0' M_0}$ describe the preparation of the initial projectile and target beams, and the M's and m's ("0" for initial, "1" for final state) are the magnetic quantum numbers of the target atoms and the electron spins, respectively. The cross section for any given experimental arrangement can be obtained in a straightforward way from Eq. (1). In our special case of interest where the magnetic quantum numbers are not observed after the collision, this cross section is given by

$$\frac{d\sigma}{d\Omega} \equiv \sigma(\theta) = \frac{k_1}{k_0} \sum_{\substack{m_1, m_1', M_1, M_1' \\ (m_1' = m_1, M_1' = M_1)}} (\rho_{\rm out})^{\theta, M_1' M_1}_{m_1' m_1} , \qquad (2)$$

where k_0 (k_1) is the initial (final) linear momentum of the projectile .

Jiang *et al.* [1] actually observe the recoil atoms, but they relate their signal to that obtained with electrons if both electrons scattered to the left as well as those scattered to the right through an angle θ are counted. Hence, they divided their result by 2 to find an average cross section.

If one assumes parity conservation in the collision process, however, their published result is the same as that which one would obtain with 50% of the target atoms in the state with $M_F = +3$ and the other 50% in $M_F = -3$ for scattering only to the left [1]. Consequently, the initial density matrix can be written as

$$\rho_{m_0' m_0} \rho_{M_0' M_0} = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \times \begin{pmatrix} \frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{2} \end{pmatrix} , \qquad (3)$$

where the 2×2 matrix stands for the projectile spin while the 7×7 matrix describes the $|F, M_F\rangle$ preparation of the atoms.

The next step in the analysis assumes that explicitly spin-dependent forces, such as the spin-orbit interaction, as well as any effect of the nuclear spin can be neglected in the collision process. Using standard formulas (see, for example, Ref. [3]), the amplitudes can then be recoupled with the final result

$$\sigma_{\rm Jiang} = \tfrac{1}{2} \sum_{M_{L_1}} \left(\sigma_{M_{L_1}, +1} + \sigma_{M_{L_1}, -1} \right) , \qquad (4)$$

where

$$\sigma_{M_{L_1}, M_{L_0}} \equiv \frac{k_1}{k_0} \sum_{S} \frac{2S_t + 1}{4} |f^{S_t}_{M_{L_1}, M_{L_0}}|^2 . \qquad (5)$$

In (5), the M_L's are the orbital angular momentum components and S_t is the total spin (singlet and triplet in this case). Our result is similar to that given by Jiang *et al.* [1], except that we have applied the usual flux and spin normalization in the scattering amplitudes that was also applied by Zhou, Norcross, and Whitten [5] when they provided the numerical data for comparison.

The next step in the analysis is to look at the cross section for completely unpolarized initial beams. For the $3P \to 3S$ transition, this is given by

$$\sigma_{\rm un} = \tfrac{1}{3}\left(\sigma_{+1} + \sigma_0 + \sigma_{-1}\right) , \tag{6}$$

where we have omitted the final state $M_{L_1} \equiv 0$ and introduced the factor $1/3$ to account for the average over the initial orbital angular-momentum components.

While Eq. (6) is independent of any particular coordinate system, the "natural frame," where the quantization axis is perpendicular to the scattering plane, is very suitable to analyze the experiment of the Jiang *et al.* [1]; in fact, this has been used in setting up the initial density matrix (3) above. For any transition between P states and S states of different parity, parity conservation of the interaction implies that the scattering amplitudes and, consequently, the cross sections for transitions between the sublevels with magnetic quantum number $M_L = 0$ must vanish in this frame (see, for example, Ref. [4]). Hence, we find for the above $3P \to 3S$ transition that

$$\sigma_{\rm un} = \tfrac{1}{3}\left(\sigma_{+1} + \sigma_{-1}\right) = \tfrac{2}{3}\,\sigma_{\rm Jiang} \, . \tag{7}$$

For the cross section $\sigma_{\rm un}$, however, time-reversal invariance of the transition operator (or "detailed balance") may be used. This gives

$$\sigma_{\rm Jiang} \equiv \frac{3}{2}\,\sigma_{\rm un}(3P \to 3S) = \frac{1}{2}\,\frac{E_{3S}}{E_{3P}}\,\sigma_{\rm un}(3S \to 3P) \, , \tag{8}$$

where E_{3P} and E_{3S} are the projectile energies when the atomic electron is in the $3P$ or the $3S$ state, respectively. Equation (8) has indeed been verified by using the close-coupling results of Zhou, Norcross, and Whitten [5] who transformed their superelastic scattering amplitudes into the "natural frame."

In conclusion, due to the special way the experiment of Jiang *et al.* [1] was performed, it is possible to relate the outcome to the corresponding time-reversed experiment with unpolarized particles, as long as the final state is any S state of even parity for their initial P state of odd parity. Hence, the data can be used as an independent check of $3S \to 3P$ atomic recoil as well as electron-scattering experiments – provided the assumptions about spin-dependent forces and the effect of the nuclear spin are fulfilled. While this is generally accepted for the sodium target, it may not be true for heavier systems such as cesium. Hence, this experiment (and its counterparts) might allow for a very interesting test of the assumptions about the collision dynamics, since the hyperfine structure can realistically only be resolved in the laser-excited superelastic case.

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