Modulational instability in spin-orbit coupled Bose- Einstein condensates

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Since the successful experimental realization of Bose-Einstein condensates (BECs) in the mid-90's tremendous developments have been made in understanding the physics of ultra-cold matter. In this connection, the recent break-through in achieving spin-orbit (SO) coupled BECs paved the way for many practical applications including spin Hall effect, topological insulators, etc. In this work, we study the modulational instability (MI) in a quasi-two-dimensional SO coupled BEC with Rabi coupling. The degree of instability in a BEC can be characterized by the modulational instability, and identified as a requisite mechanism to understand various physical effects due to nonlinearity. By considering the mean field model for the SO coupled BEC, we systematically analyze the effect of SO and Rabi coupling on MI under different configurations of intra- (g) and inter- (g_{12}) component interactions. Our analysis reveals that the SO coupling inevitably destabilizes the initial steady state for equal densities of the spin components, and thereby making the system become unstable for all combinations of interaction strengths. We also show that the conventional MI immiscibility condition, $g_{12} > g$ for repulsive two component BEC system is no longer significant when SO coupling is present. First, we demonstrate MI in the presence of SO coupling for the case of repulsive intra and inter-component interactions. Particularly, we obtain the expressions for MI gain in the momentum space, i.e., as a function of k_x and k_y and analyze the variation of gain over the wavenumbers, which shows the direction dependent behaviour of MI.

Further, we discuss the condition for MI with attractive intra- and repulsive inter-component interactions. We identify the emergence of new instability bands in the MI gain plot, which arise as a consequence of SO coupling. Next, we discuss the nature of MI with repulsive intra-component and attractive inter-component interactions and portray the variation of MI gain for g and g_{12}. Along the similar lines with the earlier cases, the SO coupling results in new instability bands and enhances the MI. In addition, we also study MI in the case of attractive intra- and inter-component interactions. It is also known, from the theory of MI in BEC, that attractive interactions naturally support for MI. Although, SO coupling is not fundamental for the origin of MI, however, SO coupling significantly influences the instability region in terms of peak gain and width as evident from the present study. Overall, the effect of SO coupling can be understood as a means to achieve MI in repulsive interactions, and also enhance instability in the system.

It is also important to see the effect of SO coupling, while in the presence of Rabi coupling on the MI gain for fixed wavenumbers k_x and k_y. Figure 1 depicts the MI gain, as a function of SO (k_L) and Rabi (Γ) coupling strengths, in a SO coupled BEC of uniform density (n). It is evident from

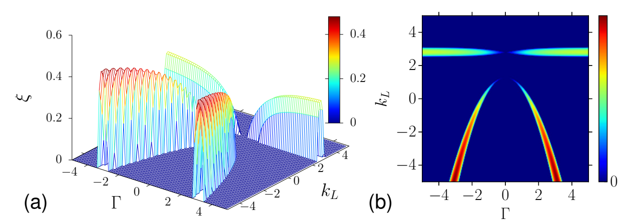

Figure 1: (a) 3D surface plot showing the MI gain, $\xi = |\Im(\Omega_-)|$, and (b) the corresponding 2D contour plot for the parameters $k_L = 1$, $\Gamma = 1$, $g = 1$, $g_{12} = 1$, $n = 0.3$, $k_x = 2$ and $k_y = 1$.

our choice of parametric space; the instability bands are symmetric for both positive and negative values of the Rabi and SO coupling. One can also infer that the MI is possible even for zero SO coupling, provided the Rabi coupling is $\Gamma > 0$. In the case of attractive interaction, SO coupling manifest in enhancing the MI. Thus, a comprehensive study of MI in two-dimensional spin-orbit coupled BECs of pseudo-spin components is presented.

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