

# Engineering momentum profiles of cold-atom beams

D Hudson Smith

*Clemson University, Clemson, South Carolina 29634, USA*

Artem G Volosniev

*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*

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## INTRODUCTION

Scattering is one of the most important observational tools in science. In physics, it is used in almost all subfields to understand internal structure of particles, materials, structures (cite).

In systems of cold atoms scattering might seem obsolete because the energies are so low that usually only a few parameters determine physics, i.e., the system is in a universal regime. However, even at these low temperatures observables can strongly depend on the incoming momentum (see Figure 1a). For example, ...

*Figure 1a: examples where observables depend strongly on the incoming momentum: time-dependent one- and two-body scattering, three-body recombination, polaron. Figure 1b: a sketch of the set-up for engineering beams with desirable momentum profiles: two reservoirs and a link between them.*

Here we study how to create fluxes with cold atoms, which can be used to study systems of cold atoms in scattering experiments. We illustrate using the one-dimensional Bose polaron problem.

## DESIGN

### Physical System

Describe the system. The system has three parts: Two reservoirs and a link between them; see Figure 1a. One reservoir is made of a non-interacting (for simplicity) gas of particles at temperature  $T$ . We call these particles probes or  $A$ . The reservoir is connected to the link. The link is a potential that acts only on particles  $A$  (for simplicity). The second reservoir is made of interacting particles  $B$ . These particles make a system of interest, which we would like to analyze.

### Finding a Link Potential

We now present our procedure for finding a link potential that produces the desired flux properties. This simple process involves a global search over a family of possible link potentials in order to minimize the difference between the desired and the actual flux properties. We perform this search using the well-known global optimization routine called Differential Evolution (DE) [? ]. This evolutionary-based search is suitable given the non-convex nature of the optimization problem. Despite its simplicity, DE does a good job of balancing the need to search the entire space against the need to learn from subsequent trials in the optimization process in order to speed up convergence with minimal complication in terms of choosing the right model settings. Before detailing our procedure, we emphasize that our goal is not to find the “best” link potential in terms of a theoretical cost function; one that is “good enough” in terms of experimental requirements will do. This relaxed goal removes many complications. For instance, as long as a discovered potential is *good enough* we do not even need to worry about whether or not the DE routine has converged. Similarly, if we run the routine twice and arrive at two very different but similarly *good enough* solutions, we do not have to worry about which solution is “right”. We can just pick our favorite and proceed.

To start, we must specify the ideal desired flux profile  $T(k)$  where  $k$  is the incident momentum. This could be, for instance, a “comb” profile that only allows particle flux near a specified momentum, but our prescription applies to a broad class of flux profiles.

We also must specify the form of the link potential,  $V(x, \boldsymbol{\theta})$ , with unknown parameters  $\boldsymbol{\theta}$ . The functional form of the link potential should be chosen to represent the class of physically realizable potentials within the experimental context. In our case, we assume a sum of Gaussian potentials:

$$V(x, \{\mathbf{A}, \boldsymbol{\mu}, \boldsymbol{\sigma}\}) = \sum_{i=1}^N \frac{A_i}{\sqrt{2\pi\sigma_i^2}} \exp \left[ -\frac{(x - \mu_i)^2}{2\sigma_i^2} \right], \quad (1)$$

where  $N$  is the number of Gaussian potentials (and the length of the parameter vectors  $\mathbf{A}$ ,  $\boldsymbol{\mu}$ , and  $\boldsymbol{\sigma}$ ).

In addition to specifying the form of the link potential, we may also need to specify a set of constraints on the parameters themselves in order to reflect the limitations in creating the physical potentials. In our case, we will

enforce the following constraints

$$\sum_{i=1}^N \mu_i = 0 \tag{2}$$

$$\sigma_i > 0 \quad \forall i \in \{1, 2, \dots, N\} \tag{3}$$

$$0 \leq A_i < A^{\max} \quad \forall i \in \{1, 2, \dots, N\} \tag{4}$$

In addition there may be generic constraints on the potential itself

It is clear that by changing the potential in the link we can change the flux. Let us describe how we compute potentials to create desirable fluxes. In this section we discuss this. Describe the procedure here: We set the desirable momentum profile, guess a potential, calculate the corresponding transmission coefficient, minimize the parameters.

*Figure 2: Examples of a few profiles that can be created: comb, evaporative, anti-evaporative etc. In the insets are the corresponding potentials.*

## ILLUSTRATION

The Bose polaron problem is very interesting, and many groups are studying it now. It is an open question how to measure the effective mass of the impurity in one-dimensional set-ups. There was one experiment, however the results are unclear. Also it is interesting to understand when the model breaks, i.e., at which momenta. We propose the following experiment: One reservoir – probes, the link is from Fig. 2 (comb), the second reservoir is an interacting homogeneous Bose gas (for simplicity). Provide some realistic numbers. Probably some simple calculations (in the suppl. material).

*Figure 3: Bose polaron set-up. Measurement of the effective mass – the change of the energy upon interaction change.*

## SUMMARY

We have shown how to create beams of particles to probe systems of cold atoms. We have illustrated the idea using the Bose polaron problem. Other interesting examples include ...