

Bragg Scattering with ultracold Erbium atoms

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1. Gutachter: Prof. Dr. Martin Weitz
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CHAPTER 1

Introduction

Erbium Bose-Einstein Condensate

This chapter has the objective of briefly review some relevant properties of Erbium, which will clarify what makes it relevant in the study of ultra cold atoms. After this, the basic theory of Bose-Einstein condensation will be discussed, along with a brief description of the experimental phases and tools required to create and observe an Erbium Bose-Einstein Condensate (BEC). This experimental realization will be the foundation on which the following chapters will be grounded when discussing further experimental achievements.

2.1 Properties of atomic erbium

Erbium is a chemical element with an atomic number of 68, which belongs to the series of the Lanthanides. It is also part of the group called Rare-earth elements and it was first discovered by G. Monsander in 1843 [1]. The name of “Erbium” comes from the name of the Swedish village of Ytterby, the place where it was extracted. At that time, the similarity of rare-earth metals’ chemical properties made their distinction extremely difficult. For this reason, what G. Monsander thought to be pure Erbium oxide was in fact a mixture of different rare-earth metal oxides. The element is not obtained in a reasonably pure form until 1937 by W. Klemm and H. Bommer [2].

Considering some basic properties of this element, under standard conditions erbium is in a solid state. It has a silver shining surface, which oxidizes with air contact. This rare-earth metal has a melting point of 1802 K and boiling point of 3136 K. As a result, to be able to work with a free atomic gas of erbium requires to heat up the solid erbium metal to high temperatures [3].

The number of stable isotopes of Erbium is 6 and they can be seen in Table 2.1. All of them are bosons with nuclear spin of zero, in exception of ^{167}Er , which is a fermion with spin of $7/2$. The chosen isotope for this experiment is ^{168}Er because of its bosonic nature, high abundance and favorable scattering properties.

In addition to these properties, erbium atoms have a rather complex energetic level scheme due to its open 4f shell. This one lacks 2 electrons to be completely filled, which makes erbium to have an electronic ground state with an orbital angular momentum value of $L = 5$ and a high magnetic moment of seven Bohr magneton $7\mu_B$ [5]. This high value for the orbital angular momentum in the ground state of erbium provides several advantages for Raman-coupling processes. Leading to longer coherence times and stronger synthetic magnetic fields when comparing with other alkali metals like rubidium or cesium, commonly used in ultracold atoms experiments [6].

Isotope	Abundance [%]	Atomic Mass [u]	Nuclear Spin [\hbar]
Er ¹⁶²	0.14	161.928775	0
Er ¹⁶⁴	1.61	163.929198	0
Er ¹⁶⁶	33.60	165.930290	0
Er ¹⁶⁷	22.95	166.932046	7/2
Er ¹⁶⁸	26.80	167.932368	0
Er ¹⁷⁰	14.90	169.935461	0

Table 2.1: Table with the stable isotopes of Erbium that can be found on Nature with their respective Abundance ratio, Atomic mass and Nuclear Spin. Spectroscopy data taken from [4].

A scheme of erbium energy levels together with the atomic transitions used in this experiment can be seen in figure 2.1. The scheme shows that the electronic ground state of erbium is $[\text{Xe}] 4f^{12}6s^2$, where $[\text{Xe}]$ represents the complete electronic configuration of Xenon¹. Moreover, the used optical transitions are represented by colored arrows in the figure and its spectroscopic data is shown in table 2.2. From now on, these three transitions will respectively be referred to as the 401nm, 583nm, and 841nm transitions.

Finally, it must be noted that aside from the discussed application in ultracold atoms, erbium is used in multiple commercial applications. One prominent example is the use of erbium as a fiber amplifier in doped silicon fibers [7]. Furthermore, in nuclear physics it is used as neutron absorbing control rods [8].

Parameters			Transitions		
Name	Symbol	Unit	401nm	583nm	841nm
Wavelength in vacuum	λ	nm	400.91	582.84	841.22
Lifetime	τ	μs	0.045	0.857	20
Natural linewidth	$\Delta\nu_0$	kHz	33 370	185.71	7.96
Decay rate	γ	s^{-1}	2.22×10^8	1.17×10^6	5.00×10^4
Saturation intensity	I_S	mW cm^{-1}	71.80	0.12	1.74
Doppler temperature	T_D	μK	848.69	4.46	0.19
Doppler velocity	v_D	cm s^{-1}	21.5	1.49	0.31

Table 2.2: Spectroscopic data for the optical transitions of Erbium used in this experiment. These transitions are called the 401nm, 583nm, and 841nm transitions and can be seen in figure 2.1. Data taken from [5, 9–12]

2.2 Bose-Einstein Condensation

A BEC is generally defined as a state of matter formed when a gas of bosons with a low density is cooled to near-zero temperatures (typically a few hundreds nanokelvins). To understand this definition and the next theoretical principles is necessary to define what is a boson.

In quantum mechanics, bosons are particles with an integer value in their spin. Because of this,

¹ $[\text{Xe}] = 1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$



Figure 2.1: Energy level scheme of Erbium represented as a function of the total angular momentum J. This scheme shows only a range of energies relevant for the experiment of up to 25000 cm⁻¹. The different arrows show us the used transitions and for which phase of the experiment they are used for. The red lines represent energy states with even parity and the black lines those with odd parity. Data taken from [13].

also have a symmetric wave function under the interchange of two particles, which allows bosons to have the same quantum state. Unlike its counterpart fermions, which have a half odd integer spin and an anti-symmetric wave function. Leading to Pauli's exclusion principle that avoids more than one fermion to occupy the same quantum state [14].

It was the Indian physicist S. N. Bose in 1924, the first one who described in a successful way an ideal gas of non interacting free photons, behaving like mass-less bosons. His idea was initially rejected for publication in scientific journals. However, Bose sent the manuscript to A. Einstein, who recognized its importance, translated the paper to german and saw to it that was published [15]. After this, Einstein extended Bose's treatment to massive particles and predicted the occurrence of a phase transition in a gas of non-interacting atoms, what is today known as a BEC [16, 17].

These publications led to Bose-Einstein statistics, a model that explains the energetic behavior of a non-interacting gas of indistinguishable bosons. The average occupation number of a given non-degenerate state i with energy E_i is:

$$f(E_i) = \frac{1}{e^{(E_i - \mu)/k_B T} - 1} \quad (2.1)$$

2.3 Experimental preparation

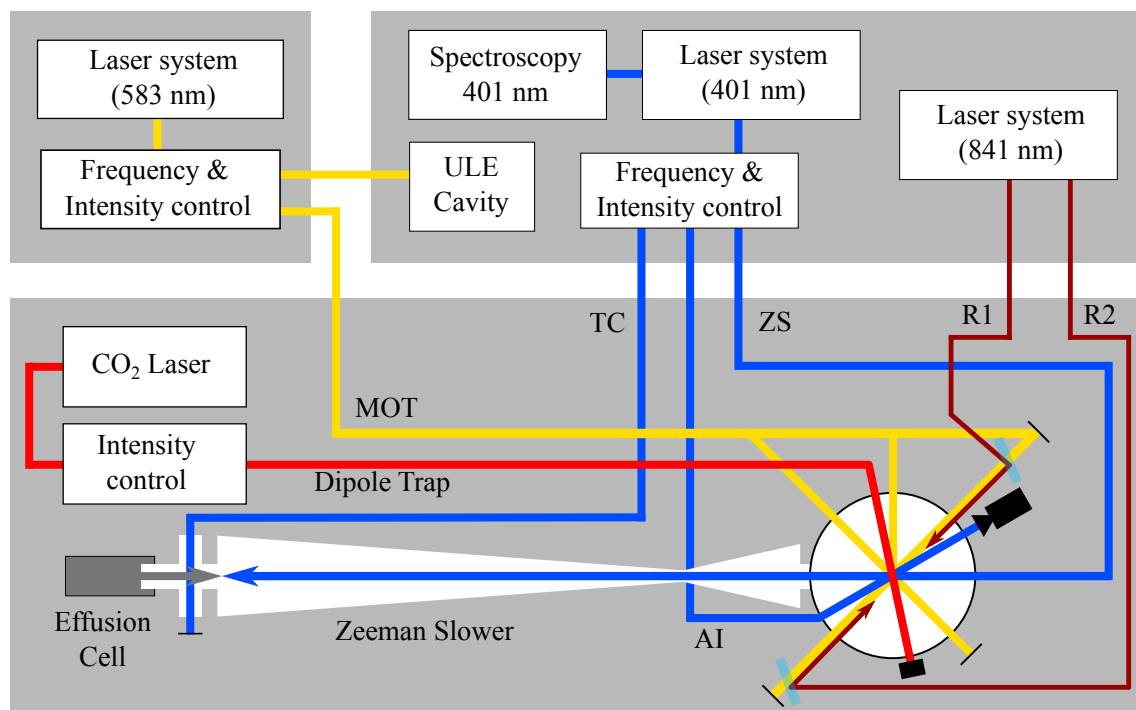


Figure 2.2: Scheme of the experimental set up

Bibliography

- [1] C. Mosander, XXX. *On the new metals, lanthanum and didymium, which are associated with cerium; and on erbium and terbium, new metals associated with yttria*, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **23** (1843) 241 (cit. on p. 3).
- [2] W. Klemm and H. Bommer, *Zur Kenntnis der Metalle der seltenen Erden*, *Zeitschrift für anorganische und allgemeine Chemie* **231** (1937) 138 (cit. on p. 3).
- [3] J. Emsley, *The Elements (Oxford Chemistry Guides)*, 3rd ed., Clarendon Press; Oxford University Press, 1998, ISBN: 978-0198558194 (cit. on p. 3).
- [4] J. E. Sansonetti and W. C. Martin, *Handbook of Basic Atomic Spectroscopic Data*, *Journal of Physical and Chemical Reference Data* **34** (2005) 1559 (cit. on p. 4).
- [5] H. Y. Ban et al., *Laser cooling transitions in atomic erbium*, *Opt. Express* **13** (2005) 3185 (cit. on pp. 3, 4).
- [6] X. Cui et al., *Synthetic gauge field with highly magnetic lanthanide atoms*, *Phys. Rev. A* **88** (1 2013) 011601 (cit. on p. 3).
- [7] R. Mears et al., *Low-noise erbium-doped fibre amplifier operating at 1.54 μ m*, English, *Electronics Letters* **23** (19 1987) 1026, ISSN: 0013-5194 (cit. on p. 4).
- [8] J. Emsley, *Nature's building blocks: an AZ guide to the elements*, Oxford University Press, 2011 (cit. on p. 4).
- [9] J. J. McClelland, *Natural linewidth of the 401-nm laser-cooling transition in Er I*, *Phys. Rev. A* **73** (6 2006) 064502 (cit. on p. 4).
- [10] J. E. Lawler, J.-F. Wyart and E. A. D. Hartog, *Atomic transition probabilities of Er I*, *Journal of Physics B: Atomic, Molecular and Optical Physics* **43** (2010) 235001 (cit. on p. 4).
- [11] E. A. D. Hartog, J. P. Chisholm and J. E. Lawler, *Radiative lifetimes of neutral erbium*, *Journal of Physics B: Atomic, Molecular and Optical Physics* **43** (2010) 155004 (cit. on p. 4).
- [12] R. J. Lipert and S. C. Lee, *Isotope shifts and hyperfine structure of erbium, dysprosium, and gadolinium by atomic-beam diode-laser spectroscopy*, *Applied Physics B* **57** (1993) 373, ISSN: 1432-0649 (cit. on p. 4).
- [13] A. Kramida, Y. Ralchenko and J. Reader, *NIST Atomic Spectra Database (version 5.8)*, 2020, URL: <https://physics.nist.gov/asd> (cit. on p. 5).
- [14] W. Pauli, *Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren*, *Zeitschrift für Physik* **31** (1925) 765, ISSN: 0044-3328 (cit. on p. 5).

Bibliography

- [15] Bose, *Plancks Gesetz und Lichtquantenhypothese*, *Zeitschrift für Physik* **26** (1924) 178, ISSN: 0044-3328 (cit. on p. [5](#)).
- [16] A. Einstein, *Quantentheorie des einatomigen idealen Gases*, *Sitzungsberichte der Preussischen Akademie der Wissenschaften* **22** (1924) 261 (cit. on p. [5](#)).
- [17] A. Einstein, *Quantentheorie des einatomigen idealen Gases. Zweite Abhandlung*, *Sitzungsberichte der Preussischen Akademie der Wissenschaften* **50** (1925) 3 (cit. on p. [5](#)).

APPENDIX **A**

Useful information

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Acronyms

BEC Bose-Einstein Condensate