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Cryogenic Trapped-Ion System for Multiqubit Quantum Memory

（申请清华大学工学硕士学位论文）

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研 究 生 ： 薛 瑞 尼

指 导 教 师 ： 郑 纬 民 教 授

副指导教师 ： 陈 文 光 教 授

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Cryogenic Trapped-Ion System for Multiqubit Quantum Memory

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Xue Ruini

Thesis Supervisor:	Professor Zheng Weimin
Associate Supervisor:	Professor Chen Wenguang

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学位论文指导小组、公开评阅人和答辩委员会名单

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李 1XX	教授	清华大学
王 XX	副教授	清华大学
张 XX	助理教授	清华大学

公开评阅人名单

刘 XX	教授	清华大学
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杨 XX	研究员	中国 XXXX 科学院 XXXXXXX 研究所

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摘　要

论文的摘要是对论文研究内容和成果的高度概括21。摘要应对论文所研究的问题及其研究目的进行描述，对研究方法和过程进行简单介绍，对研究成果和所得结论进行概括。摘要应具有独立性和自明性，其内容应包含与论文全文同等量的主要信息。使读者即使不阅读全文，通过摘要就能了解论文的总体内容和主要成果。

论文摘要的书写应力求精确、简明。切忌写成对论文书写内容进行提要的形式，尤其要避免“第 1 章……；第 2 章……；……”这种或类似的陈述方式。

关键词是为了文献标引工作、用以表示全文主要内容信息的单词或术语。关键词不超过 5 个，每个关键词中间用分号分隔。

关键词：关键词 1；关键词 2；关键词 3；关键词 4；关键词 5

ABSTRACT

An abstract of a dissertation is a summary and extraction of research work and contributions. Included in an abstract should be description of research topic and research objective, brief introduction to methodology and research process, and summary of conclusion and contributions of the research. An abstract should be characterized by independence and clarity and carry identical information with the dissertation. It should be such that the general idea and major contributions of the dissertation are conveyed without reading the dissertation.

An abstract should be concise and to the point. It is a misunderstanding to make an abstract an outline of the dissertation and words “the first chapter”, “the second chapter” and the like should be avoided in the abstract.

Keywords are terms used in a dissertation for indexing, reflecting core information of the dissertation. An abstract may contain a maximum of 5 keywords, with semi-colons used in between to separate one another.

Keywords: keyword 1; keyword 2; keyword 3; keyword 4; keyword 5

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LIST OF SYMBOLS AND ACRONYMS

PI	聚酰亚胺
MPI	聚酰亚胺模型化合物，N-苯基邻苯酰亚胺
PBI	聚苯并咪唑
MPBI	聚苯并咪唑模型化合物，N-苯基苯并咪唑
PY	聚吡咙
PMDA-BDA	均苯四酸二酐与联苯四胺合成的聚吡咙薄膜
MPY	聚吡咙模型化合物
As-PPT	聚苯基不对称三嗪
MAsPPT	聚苯基不对称三嗪单模型化合物，3,5,6-三苯基-1,2,4-三嗪
DMAsPPT	聚苯基不对称三嗪双模型化合物（水解实验模型化合物）
S-PPT	聚苯基对称三嗪
MSPPT	聚苯基对称三嗪模型化合物，2,4,6-三苯基-1,3,5-三嗪
PPQ	聚苯基喹噁啉
MPPQ	聚苯基喹噁啉模型化合物，3,4-二苯基苯并二嗪
HMPI	聚酰亚胺模型化合物的质子化产物
HMPY	聚吡咙模型化合物的质子化产物
HMPBI	聚苯并咪唑模型化合物的质子化产物
HMAsPPT	聚苯基不对称三嗪模型化合物的质子化产物
HMSPPT	聚苯基对称三嗪模型化合物的质子化产物
HMPPQ	聚苯基喹噁啉模型化合物的质子化产物
PDT	热分解温度
HPLC	高效液相色谱（High Performance Liquid Chromatography）
HPCE	高效毛细管电泳色谱（High Performance Capillary lectrophoresis）
LC-MS	液相色谱-质谱联用（Liquid chromatography-Mass Spectrum）
TIC	总离子浓度（Total Ion Content）
ab initio	基于第一原理的量子化学计算方法，常称从头算法
DFT	密度泛函理论（Density Functional Theory）
E_a	化学反应的活化能（Activation Energy）
ZPE	零点振动能（Zero Vibration Energy）
PES	势能面（Potential Energy Surface）
TS	过渡态（Transition State）
TST	过渡态理论（Transition State Theory）

$\Delta G^{\neq}$	活化自由能（Activation Free Energy）
κ	传输系数（Transmission Coefficient）
IRC	内禀反应坐标（Intrinsic Reaction Coordinates）
ν_i	虚频（Imaginary Frequency）
ONIOM	分层算法（Our own N-layered Integrated molecular Orbital and molecular Mechanics）
SCF	自洽场（Self-Consistent Field）
SCRF	自洽反应场（Self-Consistent Reaction Field）

CHAPTER 1 INTRODUCTION

研究生学位论文撰写，除表达形式上需要符合一定的格式要求外，内容方面上也要遵循一些共性原则。

通常研究生学位论文只能有一个主题（不能是几块工作拼凑在一起），该主题应针对某学科领域中的一个具体问题展开深入、系统的研究，并得出有价值的研究结论。学位论文的研究主题切忌过大，例如，“中国国有企业改制问题研究” 这样的研究主题过大，因为 “国企改制” 涉及的问题范围太广，很难在一本研究生学位论文中完全研究透彻。

1.1 论文的语言及表述

除国际研究生外，学位论文一律须用汉语书写。学位论文应当用规范汉字进行撰写，除古汉语研究中涉及的古文字和参考文献中引用的外文文献之外，均采用简体汉字撰写。

国际研究生一般应以中文或英文书写学位论文，格式要求同上。论文须用中文封面。

研究生学位论文是学术作品，因此其表述要严谨简明，重点突出，专业常识应简写或不写，做到立论正确、数据可靠、说明透彻、推理严谨、文字凝练、层次分明，避免使用文学性质的或带感情色彩的非学术性语言。

论文中如出现一个非通用性的新名词、新术语或新概念，需随即解释清楚。

1.2 论文题目的写法

论文题目应简明扼要地反映论文工作的主要内容，力求精炼、准确，切忌笼统。论文题目是对研究对象的准确、具体描述，一般要在一定程度上体现研究结论，因此，论文题目不仅应告诉读者这本论文研究了什么问题，更要告诉读者这个研究得出的结论。例如：“在事实与虚构之间：梅乐、卡彭特、沃尔夫的新闻观” 就比 “三个美国作家的新闻观研究” 更专业、更准确。

1.3 摘要的写法

论文摘要是对论文研究内容的高度概括，应具有独立性和自含性，即应是一篇简短但意义完整的文章。通过阅读论文摘要，读者应该能够对论文的研究方法及

结论有一个整体性的了解，因此摘要的写法应力求精确简明。论文摘要应包括对问题及研究目的的描述、对使用的方法和研究过程进行的简要介绍、对研究结论的高度凝练等，重点是结果和结论。

论文摘要切忌写成全文的提纲，尤其要避免“第 1 章……；第 2 章……；……”这样的陈述方式。

1.4 引言的写法

一篇学位论文的引言大致包含如下几个部分：1、问题的提出；2、选题背景及意义；3、文献综述；4、研究方法；5、论文结构安排。

- 问题的提出：要清晰地阐述所要研究的问题“是什么”。①
- 选题背景及意义：论述清楚为什么选择这个题目来研究，即阐述该研究对学科发展的贡献、对国计民生的理论与现实意义等。
- 文献综述：对本研究主题范围内的文献进行详尽的综合述评，“述”的同时一定要有“评”，指出现有研究状态，仍存在哪些尚待解决的问题，讲出自己的研究有哪些探索性内容。
- 研究方法：讲清论文所使用的学术研究方法。
- 论文结构安排：介绍本论文的写作结构安排。

1.5 正文的写法

本部分是论文作者的研究内容，不能将他人研究成果不加区分地掺和进来。已经在引言的文献综述部分讲过的内容，这里不需要再重复。各章之间要存在有机联系，符合逻辑顺序。

1.6 结论的写法

结论是对论文主要研究结果、论点的提炼与概括，应精炼、准确、完整，使读者看后能全面了解论文的意义、目的和工作内容。结论是最终的、总体的结论，不是正文各章小结的简单重复。结论应包括论文的核心观点，主要阐述作者的创造性工作及所取得的研究成果在本领域中的地位、作用和意义，交代研究工作的局限，提出未来工作的意见或建议。同时，要严格区分自己取得的成果与指导教师及他人的学术成果。

在评价自己的研究工作成果时，要实事求是，除非有足够的证据表明自己的研

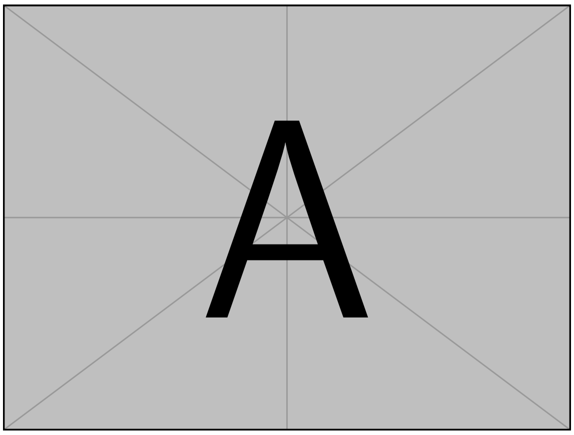
① 选题时切记要有“问题意识”，不要选不是问题的问题来研究。

究是 “首次”、“领先”、“填补空白” 的，否则应避免使用这些或类似词语。

CHAPTER 2 ION TRAPPING

2.1 插图

图片通常在 figure 环境中使用 `\includegraphics` 插入，如图 2.1 的源代码。建议矢量图片使用 PDF 格式，比如数据可视化的绘图；照片应使用 JPG 格式；其他的栅格图应使用无损的 PNG 格式。注意，LaTeX 不支持 TIFF 格式；EPS 格式已经过时。

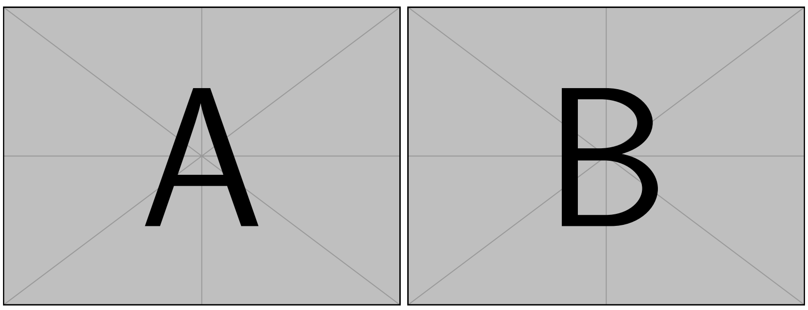


国外的期刊习惯将图表的标题和说明文字写成一段，需要改写为标题只含图表的名称，其他说明文字以注释方式写在图表下方，或者写在正文中。

Figure 2.1　示例图片标题

若图或表中有附注，采用英文小写字母顺序编号，附注写在图或表的下方。国外的期刊习惯将图表的标题和说明文字写成一段，需要改写为标题只含图表的名称，其他说明文字以注释方式写在图表下方，或者写在正文中。

如果一个图由两个或两个以上分图组成时，各分图分别以 (a)、(b)、(c)...... 作为图序，并须有分图题。推荐使用 subcaption 宏包来处理，比如图 2.2(a) 和图 2.2(b)。



(a) 分图 A　　(b) 分图 B

Figure 2.2　多个分图的示例

2.2 表格

表应具有自明性。为使表格简洁易读，尽可能采用三线表，如表 2.1。三条线可以使用 booktabs 宏包提供的命令生成。

Table 2.1 三线表示例

文件名	描述
thuthesis.dtx	模板的源文件，包括文档和注释
thuthesis.cls	模板文件
thuthesis-*.bst	BibTeX 参考文献表样式文件

表格如果有附注，尤其是需要在表格中进行标注时，可以使用 threeparttable 宏包。研究生要求使用英文小写字母 a、b、c…… 顺序编号，本科生使用圈码①、②、③…… 编号。

Table 2.2 带附注的表格示例

文件名	描述
thuthesis.dtx[a]	模板的源文件，包括文档和注释
thuthesis.cls[b]	模板文件
thuthesis-*.bst	BibTeX 参考文献表样式文件

[a] 可以通过 xelatex 编译生成模板的使用说明文档；使用 xetex 编译 thuthesis.ins 时则会从 .dtx 中去除掉文档和注释，得到精简的 .cls 文件。

[b] 更新模板时，一定要记得编译生成 .cls 文件，否则编译论文时载入的依然是旧版的模板。

如某个表需要转页接排，可以使用 longtable 宏包，需要在随后的各页上重复表的编号。编号后跟表题（可省略）和“（续）”，置于表上方。续表均应重复表头。

Table 2.3 跨页长表格的表题

表头 1	表头 2	表头 3	表头 4
Row 1			
Row 2			
Row 3			
Row 4			
Row 5			
Row 6			
Row 7			

续表 2.3　跨页长表格的表题

表头 1	表头 2	表头 3	表头 4
Row 8			
Row 9			
Row 10			

2.3 算法

算法环境可以使用 algorithms 或者 algorithm2e 宏包。

Algorithm 2.1 Calculate $y = x^n$

输入： $n \geq 0$
输出： $y = x^n$

$y \leftarrow 1$
$X \leftarrow x$
$N \leftarrow n$
while $N \neq 0$ **do**
  if N is even **then**
    $X \leftarrow X \times X$
    $N \leftarrow N/2$
  else $\{N$ is odd$\}$
    $y \leftarrow y \times X$
    $N \leftarrow N - 1$
  end if
end while

CHAPTER 3 EXPERIMENTAL SETUP

3.1 Introduction

中文论文的数学符号默认遵循 GB/T 3102.11—1993《物理科学和技术中使用的数学符号》①。该标准参照采纳 ISO 31-11:1992 ②，但是与 TEX 默认的美国数学学会（AMS）的符号习惯有所区别。具体地来说主要有以下差异：

1. 大写希腊字母默认为斜体，如

$$\mathit{\Gamma\Delta\Theta\Lambda\Xi\Pi\Sigma\Upsilon\Phi\Psi\Omega}.$$

注意有限增量符号 Δ 固定使用正体，模板提供了 `\increment` 命令。

2. 小于等于号和大于等于号使用倾斜的字形 $\leqslant$、$\geqslant$。
3. 积分号使用正体，比如 $\int$、$\oint$。
4. 偏微分符号 ∂ 使用正体。
5. 省略号 `\dots` 按照中文的习惯固定居中，比如

$$1, 2, \dots, n \quad 1 + 2 + \cdots + n.$$

6. 实部 $\Re$ 和虚部 $\Im$ 的字体使用罗马体。

以上数学符号样式的差异可以在模板中统一设置。另外国标还有一些与 AMS 不同的符号使用习惯，需要用户在写作时进行处理：

1. 数学常数和特殊函数名用正体，如

$$\mathrm{\pi} = 3.14\dots; \quad \mathrm{i}^2 = -1; \quad \mathrm{e} = \lim_{n \to \infty} \left(1 + \frac{1}{n}\right)^n.$$

2. 微分号使用正体，比如 dy/dx。
3. 向量、矩阵和张量用粗斜体（`\symbf`），如 $\mathbf{x}$、$\mathbf{\Sigma}$、T。
4. 自然对数用 $\ln x$ 不用 $\log x$。

英文论文的数学符号使用 TEX 默认的样式。如果有必要，也可以通过设置 `math-style` 选择数学符号样式。

关于量和单位推荐使用 siunitx 宏包，可以方便地处理希腊字母以及数字与单位之间的空白，比如：$6.4 \times 10^6\,\mathrm{m}$，$9\,\mathrm{\mu m}$，$\mathrm{kg\,m\,s^{-1}}$，$10\,^\circ\mathrm{C}$ to $20\,^\circ\mathrm{C}$。

① 原 GB 3102.11—1993，自 2017 年 3 月 23 日起，该标准转为推荐性标准。

② 目前已更新为 ISO 80000-2:2019。

3.2 The Cryostat

The cryostat is the key equipment of the cryogenic trapped ion system. We need to pay attention to some key technical indicators when choosing the model of the cryostat, designing the internal support structure and the assembly structure of the trap-related components. The most critical technical indicators are cooling capacity and vibration. Low temperature is the advantage of the cryogenic trap over the room-temperature trap. We can achieve low pressure by cryo-pumping to reduce the collision rate of trapped ions with residual background gas, thereby increasing the lifetime of trapped ions. The price of cryo-pumping is additional vibration, however, the vibration can be reduced to a degree that does not affect Quantum Gate Fidelity. In experiments, we often use these two parameters to characterize the cooling capacity. One is the lowest temperature that the system can reach when the cryogenic trap is not temperature stabilized, and the other is the heating power at the sample stage when the temperature of the cryogenic trap is stabilized above the liquid helium temperature zone and the vibration caused by liquid helium is reduced to a certain range. Another key technical indicator of the cryostat is the long-term stability at the sample, including changes in displacement and background electric field. This will affect the calibration period of the ion trap experiment. Calibration that is too frequent indicates a lack of robustness in the experiment system. There are several different types of cryostats on the market. One of these is the flow cryostat, which has lower cryocooler vibration noise but requires constant replenishment of cold liquid coolant, which is expensive and time-consuming. In contrast, the cryogenic trapped ion system in our lab uses a closed-loop Gifford-McMahon cryostat. This type of cryostat uses closed-cycle helium gas as operation material in cooling cycle and does not require constant refilling of the coolant. It is very convenient to use and cheap to maintain as it only needs external electric supply. One of the advantages of this closed-loop cryostat is that it has a Vibration Isolation System (VIS). The vibrating cold finger is mechanically separated from the main vacuum by a helium-filled exchange gas region at a pressure 0.03 bar above atmospheric. The VIS is the only mechanical coupling between the cold head and the main vacuum apparatus which is mounted on an optical breadboard. In the VIS region, it is sealed with a helium-confined rubber bellows. The helium gas serves as the thermal link between the cold finger and the sample stage where the ion trap is mounted. Another advantage of this closed-cycle cryostat is that its structure is relatively simple, and we can increase cooling capacity and reduce vibration through optimized design, because it is difficult to optimize each parameter independently in a complex system. The cryostat is model SHI-4XG-15-UHV, designed and manufactured by Janis Inc. In order to reduce vibration, we provide some design suggestions. The cryostat consists of a cold head, an exchange gas chamber and a vacuum chamber. The cold head is powered by a helium compressor. The models of cold head and helium compressor are RDK-415D2 and F70-H produced by Sumitomo Corporation of Japan. The cold head features two stages with different cooling powers: the 40 K stage has XX W, and the 4 K stage has XX W. The cold head must be fixed near the vacuum chamber, but there are only three interfaces of the cold head: the power supply, the supply high-pressure helium tube and the return high-pressure helium tube. Therefore, we placed the helium compressor and water cooler in the grey room of the laboratory to further isolate the source of vibration noise. The single continuous running time of the cold head can exceed 10,000 hours, which is enough for us to carry out long-term experiments. The exchange gas chamber is mainly composed of rubber bellow, helium pressure gauge and some helium valves, the top and bottom are respectively connected to the cold head and the vacuum chamber. The role of bellow is to reduce the vibration generated by the cold head and directly transmitted to the vacuum chamber, because rubber is more elastic than stainless steel. I think it is worth trying to replace the rubber bellow with a stainless-steel sheet that has been bent many times, because using a rubber bellow may cause leakage in the long-term operation of the system. Leakage of rubber bellow may come from three aspects. Firstly, the rubber material will deteriorate after a long-time use, our system has a leakage problem after about 2 years of operation, which is manifested as water inside the exchange gas chamber after the process of cooling down and warming up. Secondly, the rubber bellow is prone to defects during machining, we contacted our supplier to process a new rubber bellow after we found the leakage problem, and found that some of the rubber bellow had defects on the surface during many attempts. Finally, the sealing method of rubber bellow is worse than that of stainless steel, our cryostat uses o-ring to seal rubber bellow. We tried to have the supplier process different rubber bellow to test the leakage, such as testing different materials and thickness of rubber bellow, in some poor cases after a single cooling and reheating process will appear leakage, we finally used silicone rubber bellow and the thickness is twice the original and no leakage has been found so far.

3.3 Low Temperature and UHV System

The vacuum chamber resembles a cylinder with a diameter of about XX and a height of about XX. Externally, the upper part of the vacuum chamber has some feedthroughs connecting the electrical equipment to the vacuum equipment, and the lower part is a spherical octagon. The top of the vacuum chamber is in contact with the exchange gas chamber, and the bottom is the re-entrant window. In our experiments, we used a total of three electrical feedthroughs, one DC feedthrough to drive the voltage signal to the electrodes of the trap, another DC feedthrough to drive the thermometer and heater in the vacuum chamber, and an RF feedthrough to drive the RF signal to the resonator. Below them, there are a total of three Vacuum feedthroughs, one connected to an ion gauge (Agilent UHV-24P) to monitor the vacuum level in the vacuum chamber, one connected to a NEG-Ion pump (SAES NextTorr Z100) to pump out hydrogen, since hydrogen is the least efficiently cryo-pumped gas, and an angle valve to pump out vacuum during system maintenance. A spherical octagon holds eight XX diameter windows to provide optical access in the horizontal plane, the windows are made of UVFS and have different wavelength optical coatings according to the optical path design. We replaced one of the windows along the trap axis with an oven feedthrough, and installed both enriched 171Yb oven and enriched 174Yb oven on it, and finally tested them to work. However, assembly errors during installation may cause the Yb flux cannot enter the trap during ion loading, we can increase the translation degrees of freedom when designing the part to solve this problem. According to our experience, because of the large divergence angle of Yb flux, we just need to be able to see the trap and oven through the opposite window. The re-entrant window located at the bottom of the vacuum chamber has a diameter of XX, below which is the imaging system. The maximum numerical aperture allowed for imaging ions along the vertical direction is XX. The Re-entrant window is surrounded by a cake-shaped aluminum base placed on an optical breadboard, and the base carries the full weight of the vacuum chamber. We tried to fasten between the upper part of the vacuum chamber and the optical breadboard with an aluminum sloped beam, but it did not reduce the vibration of the trap, indicating that the current support structure is solid enough. The main components inside the vacuum chamber are the 40K shield, the 4K shield and the sample stage. These two shields are used to shield the ion trap from room temperature blackbody radiation, their material is aluminum, but copper may be a better choice because copper material has a higher thermal conductivity. The bottom of the two shields are eight 1” UVFS windows, which correspond to the spherical octagon and have the same optical coating. The glass is fixed in the groove by the Teflon holder in order to keep the windows from being crushed during the cooling procedure, however, because of the elasticity of Teflon, the positioning accuracy of the windows is poor, which may be the main source of optical aberration. The top of the 40K shield is in contact with the 40K stage of the cold head through the helium gas in the exchange gas chamber, which is usually higher than 40K, we named it that way just because it is intuitive. The top of the 4K shield is fixed to the sample stage, which is made of oxygen-free copper with a gold-plated surface to obtain a high thermal conductivity and to prevent oxidation during system maintenance. The sample stage and the 4K stage of the cold head are separated by a heat exchanger and cryogenic helium gas. The 4K stage can reach temperatures below 4K, and the heat exchanger is composed of a series of concentric circular oxygen-free copper sheets, which are designed to increase the cooling capacity at the sample stage. However, if the position between a pair of heat exchangers is shifted during operation and touches each other, it can introduce large vibrations to the sample stage, for example when floating the optical table. Although the cooling power of the 4K stage in the cold head reaches XX W, the cooling capacity of the sample stage in the vacuum chamber, which is directly available to the user, is much lower. The reduction of the cooling capacity comes from the heat conduction between the 4K stage and the sample stage and the heat leakage from the environment. In order to improve the heat transfer between the 4K stage and the sample stage, we can increase the surface area of the heat exchanger, we can also fill the exchange gas chamber with sufficient helium gas, and it is necessary to use oxygen-free copper to produce thermally conductive parts. In our experiments, we use auto gas charging system to stabilize the helium pressure in the exchange gas chamber at a fixed positive pressure. It is worth noting that the rubber bellow loses its vibration isolation function under negative pressure, and the life of the rubber bellow is reduced. The auto gas charging system was designed by PHYSIK and is based on the principle of using a PLC to read the helium pressure gauge and control the opening and closing moments of the helium valves, which will eventually stabilize the helium pressure gauge at 1.03 bar. There are two helium valves to control the helium inlet and outlet, and one safety value to allow excess helium to escape, preventing the bellow from bursting when the auto gas charging system is not working. The temperature stabilize system is a kit we purchased from Janis Inc. and consists of a thermometer, heater and temperature controller. The thermometer (DT-670-CU-HT-1.4H) is located inside the sample stage in the vacuum chamber and has a measurement range of 1.4K-500K, covering the cryostat operating range of approximately 4K-300K. The heater is a 25 Ohm resistor very close to the thermometer. The DC lines of the heater and the thermometer are connected to the temperature controller (Model 26 from CryoCon) on the instrument rack via a DC feedthrough on the vacuum chamber. In low temperature operation, the temperature of the Sample Stage can be stabilized at 6K±XXmK for a long time by setting the appropriate PID parameters. The output power of the heater is about 350mW, which means that the cooling power of the sample stage has a margin of 350mW. The auto gas charging system and The temperature stabilize system are the key systems for the long-term stability of the cryostat. Although the temperature of This cryostat has almost no drift, we can observe that the trap can shift ±1 μm during the experiment. The operation to avoid the effects of such position shifts by frequent calibration of the system parameters is very complicated, so this instability can be fatal for an experimental system. The long drift of the sample stage comes from the mechanical structure of the cryostat. The auto gas charging system can only stabilize the helium pressure near the rubber bellow, and the 40K stage and 4K stage of the cold head are not stabilized. Therefore, the pressure and temperature in the contact part of the vacuum chamber and the exchange gas chamber cannot be stabilized for a long time. However, this part is the support point of the sample stage, so the sample stage will be disturbed by these external environmental changes. We can consider fixing the sample stage to the room temperature area of the vacuum chamber, which will not move if the laboratory environment is stable, but this will inevitably increase the heat leakage from the room temperature area. In our experiments, we first pumped the vacuum chamber to 1E-6 mBar at room temperature using the Turbo Pump, then activated the NEG-Ion Pump for about 2 hours, and at the end of the operation the vacuum chamber vacuum level dropped to 1E-8 mBar. The vacuum chamber can reach a vacuum level of 3E-10 mBar with the effect of the cryo-pump.

3.4 Helical Resonator and Segmented Blade Trap

3.5 Mechanics Frame

3.6 Optics and Imaging System

3.7 Electronic Devices

CHAPTER 4 EXPERIMENTAL PROCEDURE

4.1 Start CryoServer

4.2 Cooling-down and warm-up

The cryogenic trapped-ion system is a relatively complex experimental system, and we need the system to be stable over a long period of time so that the reproducibility of the measurement results is high. Although the cryostat's core component, the cold head, can run continuously for more than XX hours, the maximum time this cryostat can run continuously is limited by the stability of the power supply, the stability of the laboratory temperature and humidity, and whether the exchange gas chamber is leaking. It took us about three years to get the system into a stable long-term state, after which we conducted a series of physical experiments on the experimental platform. However, during the three-year commissioning process, we inevitably need to conduct the cycle of cooling-down, malfunction, warm-up, and upgrade, during which the standardized operation helps to make the physical parameters of the system more repeatable, so we have developed a standardized operation procedure for this system.

4.2.1 Maintenance of the exchange gas chamber

If the cold head does not need to be removed for servicing, the exchange gas chamber does not require frequent maintenance and is always in an independent and stable state, whether it is being cooled down or warmed up.

The exchange gas chamber uses helium gas with a purity of XX. When we expose the exchange gas chamber to atmosphere or when it is first used, the internal gas needs to be purified. According to the cryostat manufacturer's recommendations, a purification is also required after several months of continuous running, but this is not normally done when the system is stable for a long period of time. How often the exchange gas chamber needs to be purified depends on the rate of impurity gases (nitrogen, oxygen, water vapour etc.) leaking in from the atmosphere.

When we need to purify the helium gas in the exchange gas chamber, the exchange gas chamber is first evacuated continuously for 0.5 hours with a dry scroll pump (Agilent IDP-7), then the valve connected to the dry scroll pump is closed and the valve connected to the helium gas is opened. The auto gas charging system will then raise the pressure to

1.03 bar and finally we close the valve to the helium gas. In general, the above operation is repeated three times to purify the helium gas in the exchange gas chamber.

When we need to cool down or warm up the system, and also when the system is running at low temperatures for a long time, we simply open the valve to the helium gas and keep the auto gas charging system running steadily.

4.2.2 Cooling-down

In the Cooling-down procedure, the physical parameters of the vacuum chamber are mainly adjusted and observed. The vacuum chamber is first connected to a turbo-molecular pump (TPS-compact Turbo Pumping System) via the angle valve and after approximately 48 hours of continuous operation the vacuum chamber reaches a vacuum level close to UHV. The ion gauge is switched on and reaches an indication of 5E-8 mBar, at which point we do not need to degas the ion gauge as the room temperature zone of the vacuum chamber does not eventually fall below 1E-10 mbar. Now we need to perform a time limited activation of the NEG Pump for 1 hour, then we perform several degas of the Ion Pump and keep the Ion Pump on. Now that the activation of the NEG-Ion Pump is complete, we close the angle valve and wait about 1 hour for the ion gauge to gradually decrease to 3E-9 mbar, when the vacuum chamber reaches the UHV vacuum level. We turn on the cold head and the temperature stabilize system, which will finish cooling down within 5 hours, but the system will not reach final stabilization for more than 24 hours. The temperature of the 4K stage is finally stabilised at 6K and the ion gauge is stabilised at 3E-10mbar.

4.2.3 Warm-up

The warm-up procedure is much easier than the cooling-down procedure because we do not need to obtain UHV during this process. we turn off the cryogenic and vacuum related instruments: the NEG-Ion pump, the ion gauge, the cold head. We can use the heater in the temperature stabilize system to heat the cryostat to speed up the warming process to room temperature, which takes about 24 hours or more. The system can also be allowed to warm up naturally to room temperature, which takes about 48 hours or more. Next, if necessary, we can move the cryostat into the service area for servicing. Before moving it out, we need to record the readings of all optical and electrical instruments. As the imaging system is embedded in the re-entrant window, we usually need to remove the objective lens.

REFERENCES

APPENDIX A 补充内容

附录是与论文内容密切相关、但编入正文又影响整篇论文编排的条理和逻辑性的资料，例如某些重要的数据表格、计算程序、统计表等，是论文主体的补充内容，可根据需要设置。

A.1 图表示例

A.1.1 图

附录中的图片示例（图 A.1）。

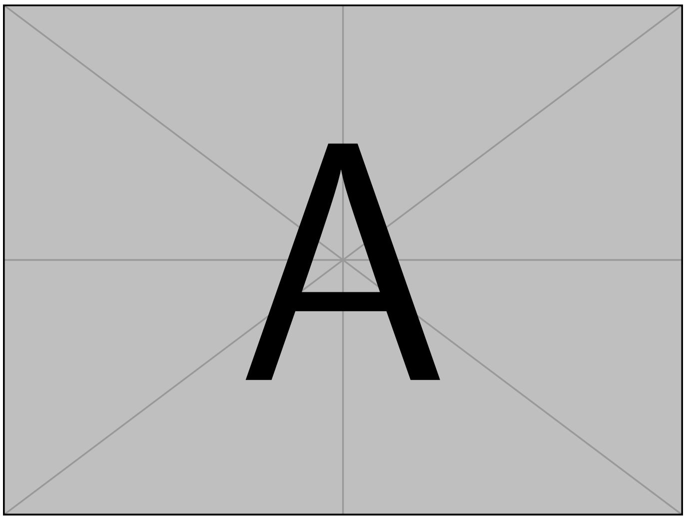


Figure A.1　附录中的图片示例

A.1.2 表格

附录中的表格示例（表 A.1）。

Table A.1　附录中的表格示例

文件名	描述
thuthesis.dtx	模板的源文件，包括文档和注释
thuthesis.cls	模板文件
thuthesis-*.bst	BibTeX 参考文献表样式文件
thuthesis-*.bbx	BibLaTeX 参考文献表样式文件
thuthesis-*.cbx	BibLaTeX 引用样式文件

A.2 数学公式

附录中的数学公式示例（公式 (A.1)）。

$$\frac{1}{2\pi \mathrm{i}} \int_\gamma f = \sum_{k=1}^{m} n(\gamma; a_k) \mathscr{R}(f; a_k) \tag{A.1}$$

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声　明

本人郑重声明：所呈交的学位论文，是本人在导师指导下，独立进行研究工作所取得的成果。尽我所知，除文中已经注明引用的内容外，本学位论文的研究成果不包含任何他人享有著作权的内容。对本论文所涉及的研究工作做出贡献的其他个人和集体，均已在文中以明确方式标明。

签　名：____________ 日　期：____________

RESUME

个人简历

197× 年 ×× 月 ×× 日出生于四川 ×× 县。

1992 年 9 月考入 ×× 大学化学系 ×× 化学专业，1996 年 7 月本科毕业并获得理学学士学位。

1996 年 9 月免试进入清华大学化学系攻读 ×× 化学博士至今。

在学期间完成的相关学术成果

学术论文

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专利

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COMMENTS FROM THESIS SUPERVISOR

论文提出了……

RESOLUTION OF THESIS DEFENSE COMMITTEE

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论文取得的主要创新性成果包括：

1. ……
2. ……
3. ……

论文工作表明作者在 ××××× 具有 ××××× 知识，具有 ×××× 能力，论文 ××××，答辩 ××××。

答辩委员会表决，（× 票/一致）同意通过论文答辩，并建议授予 ×××（姓名）×××（门类）学博士/硕士学位。