

# Festkörperphysik

**Prof. Andreas Schilling**

Vorlesung: Di 13:00 - 14:45 Hörsaal Y16G05

Vorlesung/Übungen: Fr 8:15 -10:00 Hörsaal Y15G20

Vorlesungsbeginn: Di 19. September 2023

## **Inhalt der Vorlesung:**

### **I. Anordnung von Atomen und Molekülen**

Periodizität und Symmetrie, Bravais-Gitter, Symmetrieeigenschaften der Kristalle, Millersche Indizes, einfache Kristallstrukturen

### **II. Beugung am Kristallgitter**

Reziprokes Gitter, Brillouin-Zonen, Laue-Gleichungen, Braggsche Reflexionsbedingung, Strukturamplitude, atomarer Streufaktor, Debye-Waller-Faktor, Röntgen- und Neutronenstreuung

### **III. Bindungen im Kristall**

Ionenbindung, kovalente Bindung, metallische Bindung, Van-der-Waals-Bindung, Wasserstoff-Brücken-Bindung

### **IV. Phononen**

Eigenschwingungen von Kristallgittern, Quantisierung von Gitterschwingungen (Phononen) Impuls der Phononen,

### **V. Thermische Eigenschaften von Isolatoren**

Spezifische Wärme des Gitters, anharmonische Effekte (thermische Ausdehnung von Festkörpern, Wärmeleitung in Isolatoren)

### **VI. Elektronenzustände im Kristall**

Fermi-Dirac-Verteilung, freies Elektronengas, spezifische Wärme und magnetische Suszeptibilität des Elektronengases, elektrische und thermische Leitfähigkeit von Metallen, Hall-Effekt, Zyklotronfrequenz, Landau-Zylinder, Bloch-Funktionen, Fermi-Körper, Bahnen im Magnetfeld

### **VII. Metalle, Halbleiter und Isolatoren**

Metalle, Halbleiter, Isolatoren, Halbmetalle, Bandlücke, effektive Masse und Löcher, Eigenleitung und Störstellenleitung in Halbleitern

### **VIII. Magnetismus**

Para- und Diamagnetismus, Curie Gesetz, Ferromagnetismus, Antiferromagnetismus, Bandmagnetismus

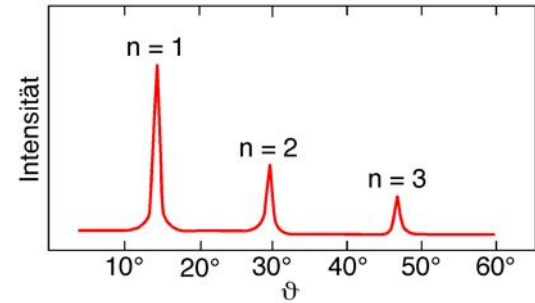
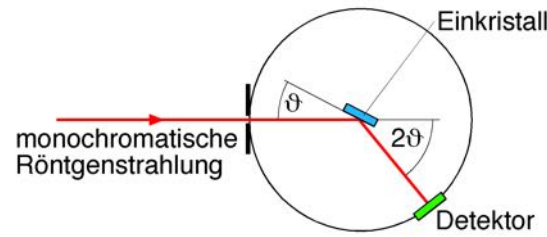
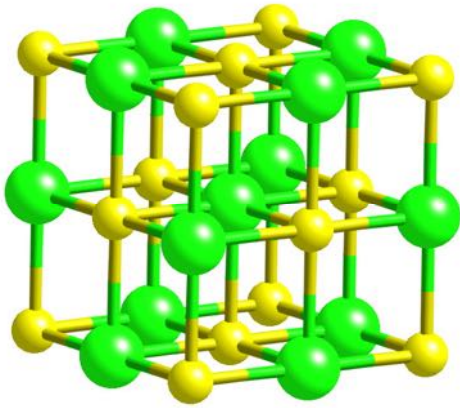
## Literatur (kleine Auswahl)

- **Rudolf Gross, Achim Marx, *Festkörperphysik*, (Oldenbourg Verlag)**  
<https://ezproxy.uzh.ch/login?url=https://www.degruyter.com/document/doi/10.1515/9783110782394/html>
- K. Kopitzki und P. Herzog, *Einführung in die Festkörperphysik*, (Teubner Studienbücher Physik)  
<https://ezproxy.uzh.ch/login?url=https://link.springer.com/book/10.1007/978-3-662-53578-3>
- C. Kittel, *Einführung in die Festkörperphysik*, (Oldenbourg Verlag)  
Nur als Hardcopy in der Bibliothek, dafür in Deutsch oder Englisch  
[https://uzb.swisscovery.slsp.ch/permalink/41SLSP\\_UZB/1d8t6qj/alma990113957980205508](https://uzb.swisscovery.slsp.ch/permalink/41SLSP_UZB/1d8t6qj/alma990113957980205508)
- H. Ibach und H. Lüth, *Festkörperphysik*, (Springer-Verlag)  
<https://ezproxy.uzh.ch/login?url=https://link.springer.com/book/10.1007/978-3-540-85795-2>



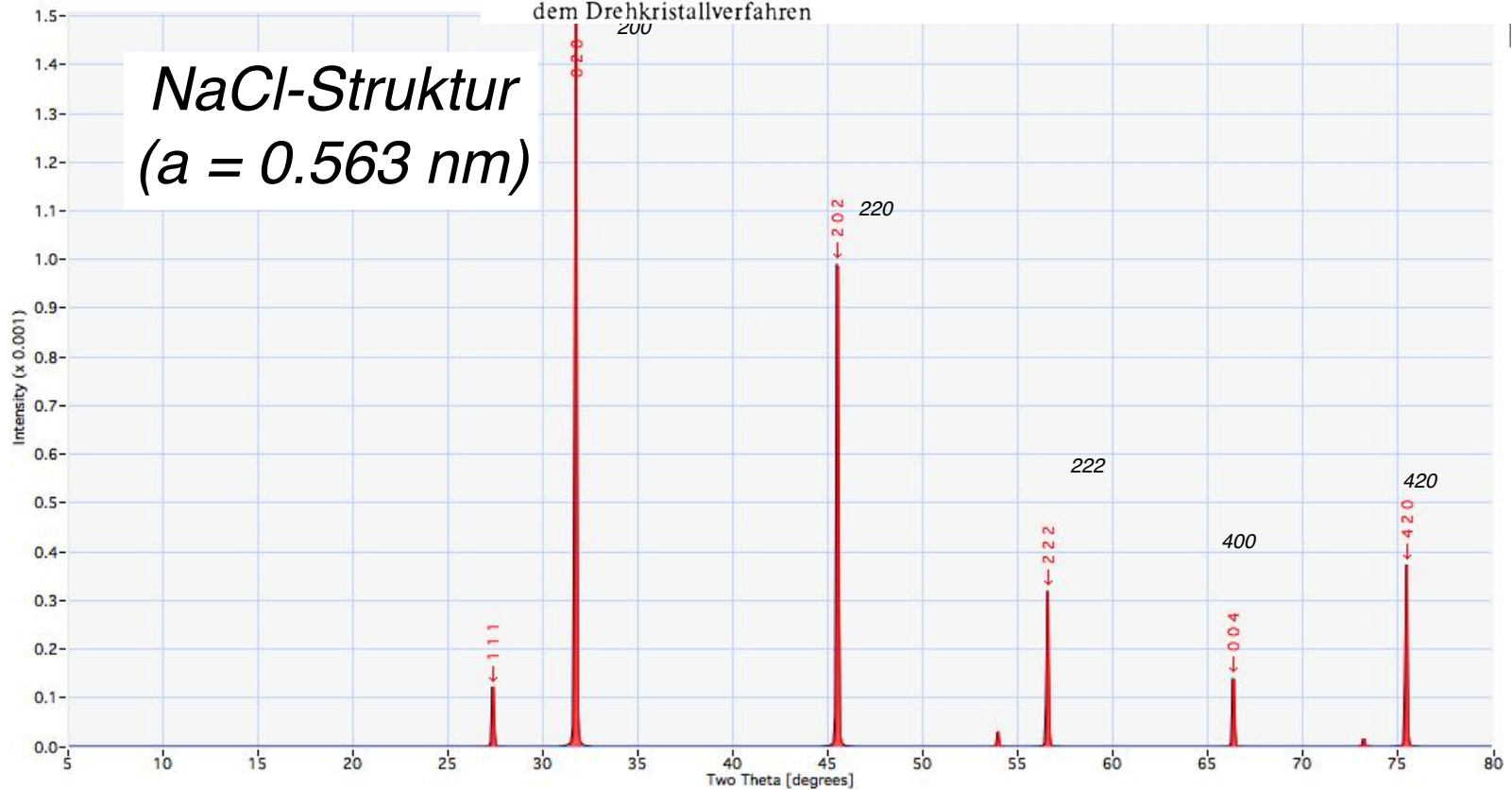
**I. Anordnung von Atomen und Molekülen**

# Bragg'sches Drehkristall-Verfahren



Schema einer Vorrichtung zur Aufnahme eines Röntgenspektrums nach dem Drehkristallverfahren

Röntgenspektrum nach dem Drehkristallverfahren





# Transmissions- Elektronenmikroskopische Aufnahme

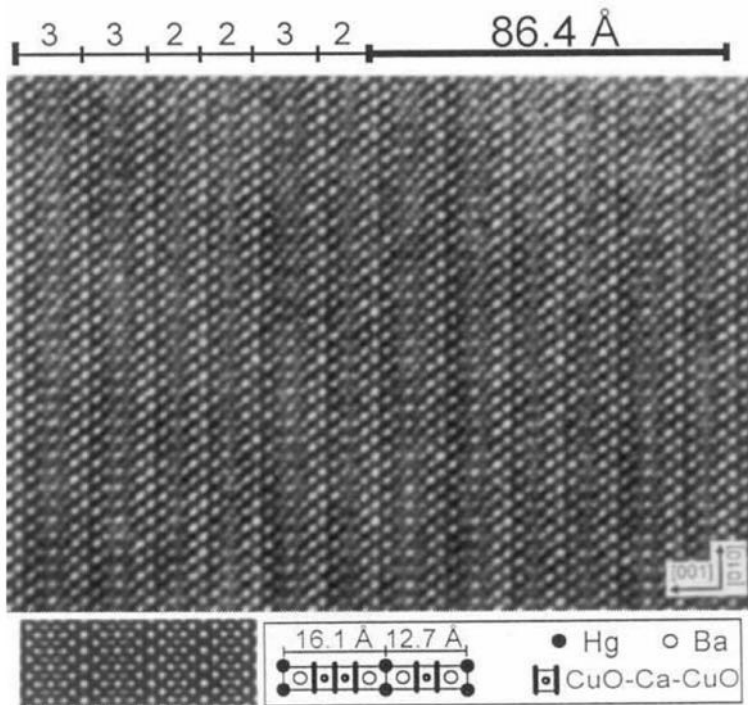


FIG. 1 HRTEM image of a grain in [100] orientation, containing layers of Hg-1212 and Hg-1223. Here, they are stacked in a periodic sequence forming a supercell with  $c \approx 86.4 \text{ \AA}$  (see text). A contrast simulation ( $c_s = 1.1 \text{ nm}$ ,  $E = 300 \text{ keV}$ , defocus  $-870 \text{ \AA}$ , specimen thickness  $23 \text{ \AA}$ ) is inserted. The stacking sequence in terms of the number of Cu-O planes and an enlarged schematic drawing of the involved unit cells are included.

## Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O system

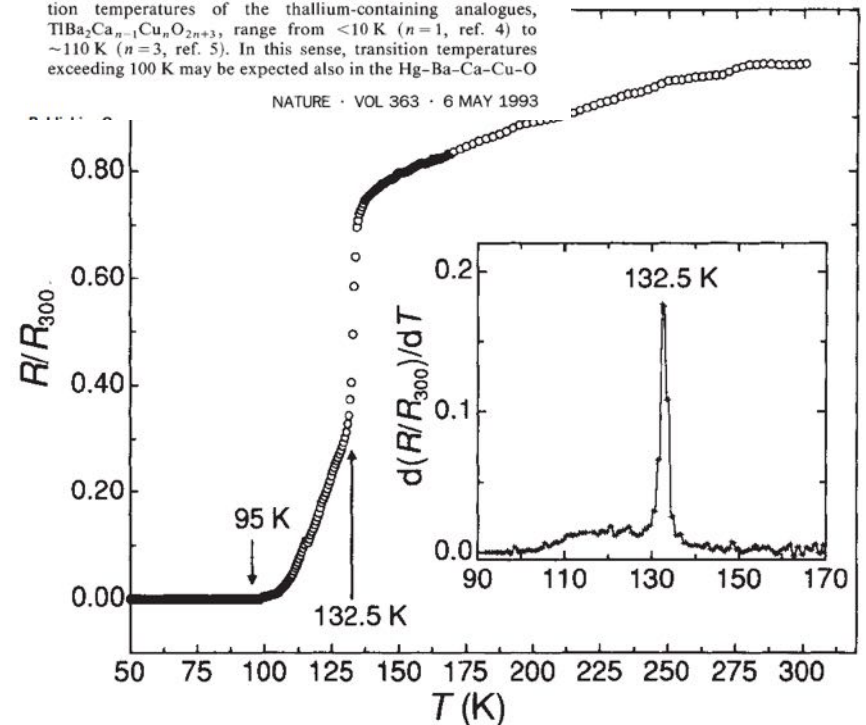
A. Schilling, M. Cantoni, J. D. Guo & H. R. Ott

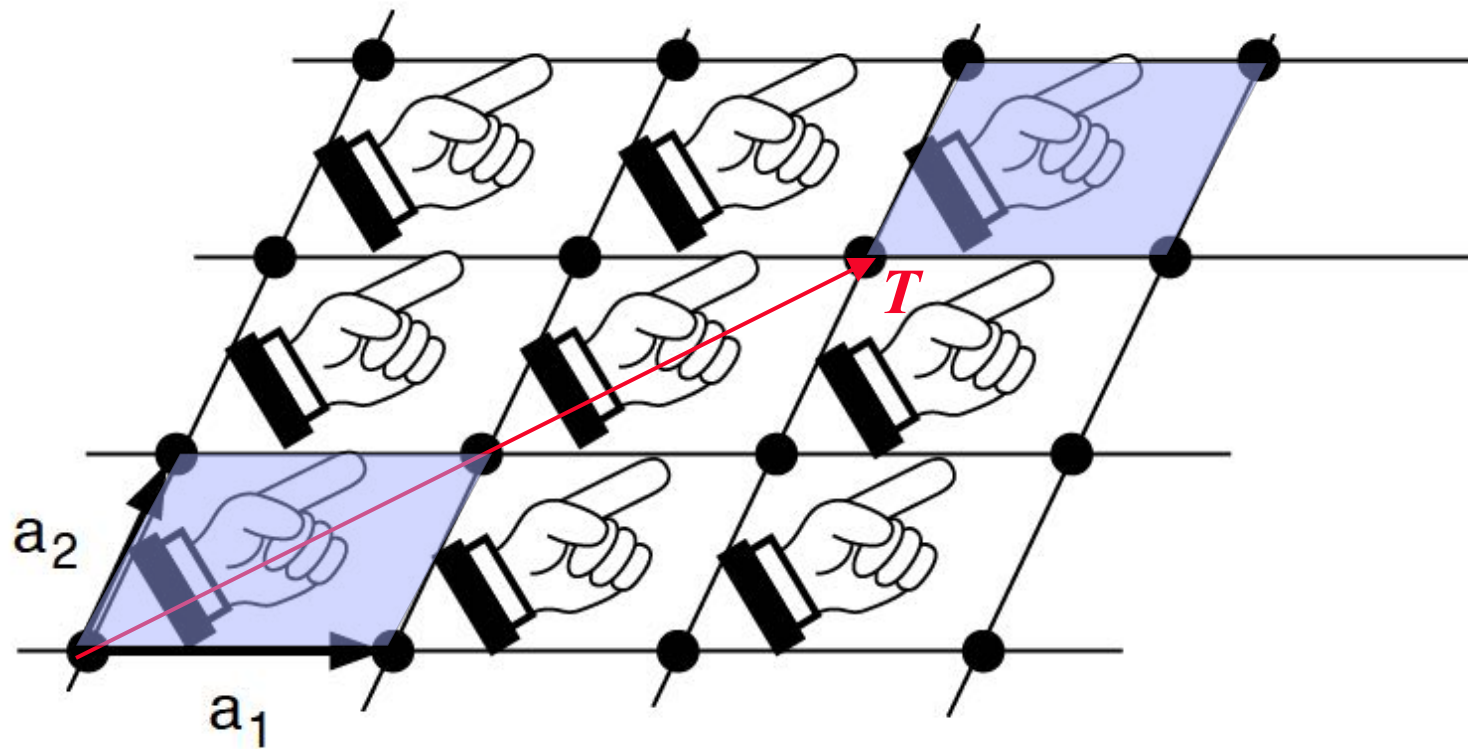
Laboratorium für Festkörperphysik, ETH Höggerberg, 8093 Zürich, Switzerland

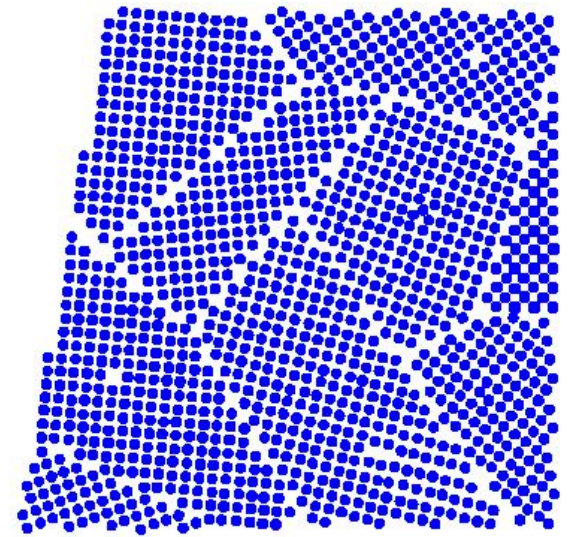
THE recent discovery<sup>1</sup> of superconductivity below a transition temperature ( $T_c$ ) of 94 K in  $\text{HgBa}_2\text{CuO}_{4+\delta}$  has extended the repertoire of high- $T_c$  superconductors containing copper oxide planes embedded in suitably structured (layered) materials. Previous experience with similar compounds containing bismuth and thallium instead of mercury suggested that even higher transition temperatures might be achieved in mercury-based compounds with more than one  $\text{CuO}_2$  layer per unit cell. Here we provide support for this conjecture, with the discovery of superconductivity above 130 K in a material containing  $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{1+x}$  (with three  $\text{CuO}_2$  layers per unit cell),  $\text{HgBa}_2\text{CaCu}_2\text{O}_{6+x}$  (with two  $\text{CuO}_2$  layers) and an ordered superstructure comprising a defined sequence of the unit cells of these phases. Both magnetic and resistivity measurements confirm a maximum transition temperature of  $\sim 133 \text{ K}$ , distinctly higher than the previous established record value of 125–127 K observed in  $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$  (refs 2, 3).

The structural similarity of  $\text{HgBa}_2\text{CuO}_{4+\delta}$  (Hg-120; ref. 1) to a member of the thallium-containing family of copper oxides,  $\text{TlBa}_2\text{CuO}_5$  (Tl-1201), suggests the existence of compounds with the general composition  $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$ . The transition temperatures of the thallium-containing analogues,  $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+3}$ , range from  $<10 \text{ K}$  ( $n=1$ , ref. 4) to  $\sim 110 \text{ K}$  ( $n=3$ , ref. 5). In this sense, transition temperatures exceeding 100 K may be expected also in the Hg-Ba-Ca-Cu-O

NATURE · VOL 363 · 6 MAY 1993

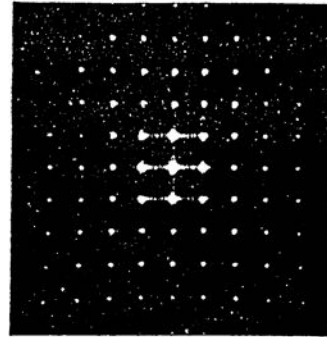
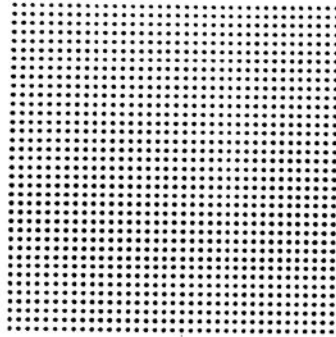




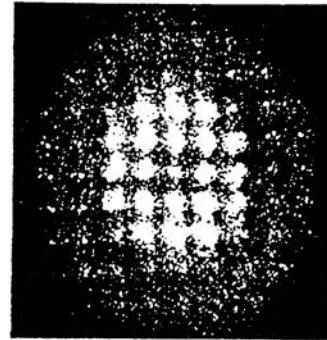
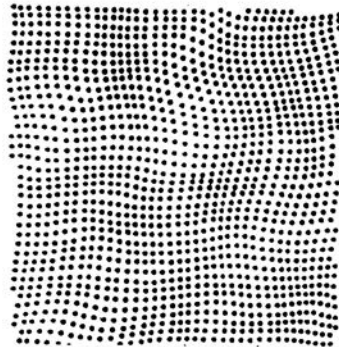


*Stahl*: polykristallin



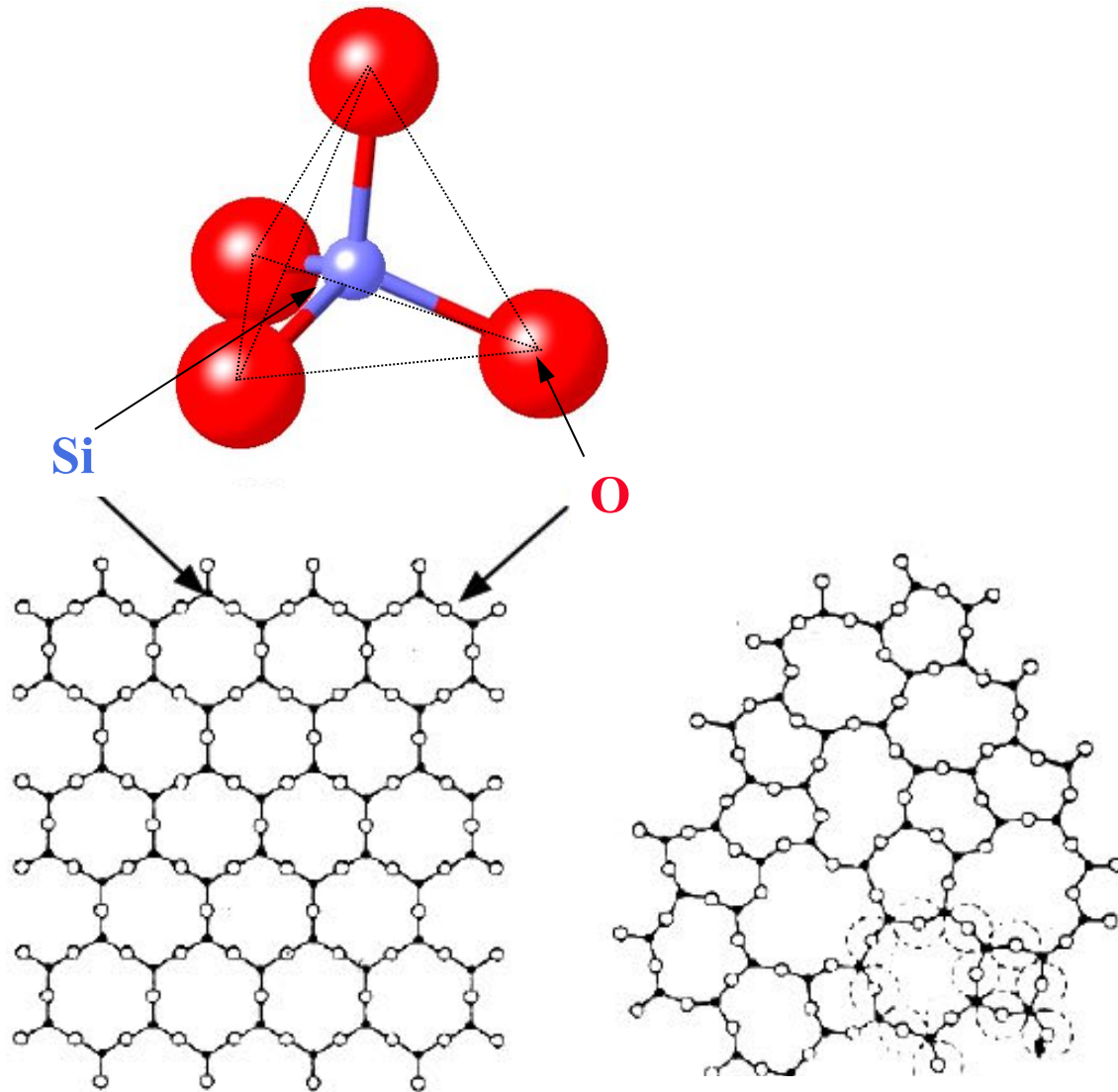


. Modell und Beugungsbild einer kristallinen Struktur

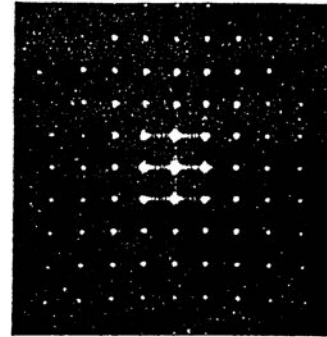
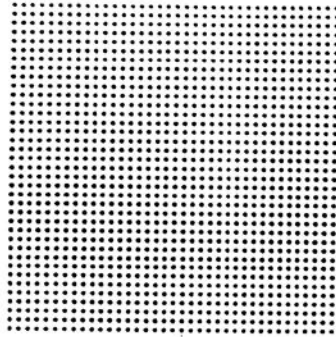


. Modell und Beugungsbild einer parakristallinen Struktur

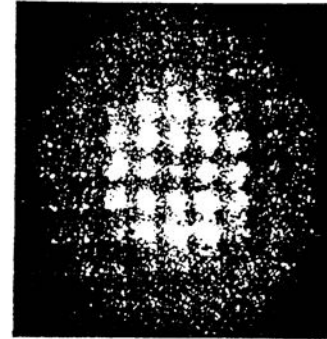
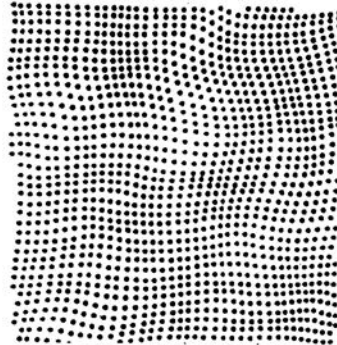
# Struktur von kristallinem und amorphem Quarz



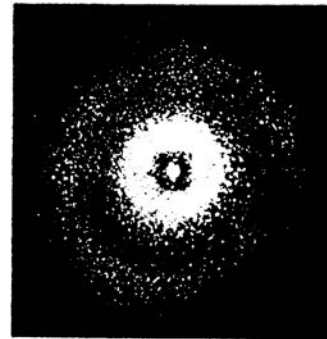
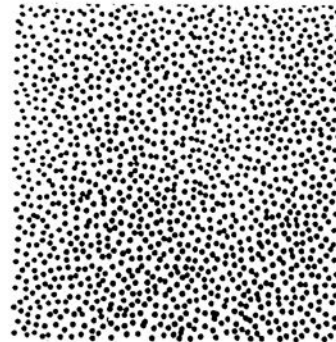
Amorphes GeSbTe als Farbdisplay



Modell und Beugungsbild einer kristallinen Struktur

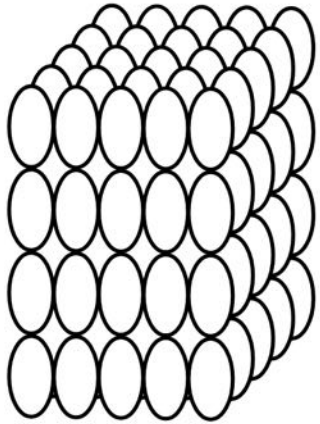


Modell und Beugungsbild einer parakristallinen Struktur

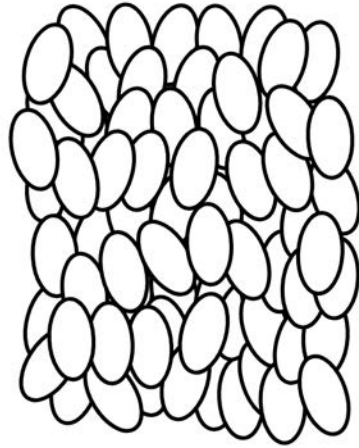
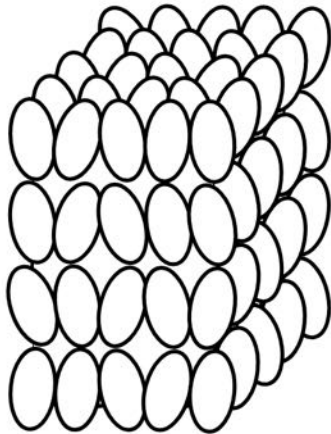


Modell und Beugungsbild einer amorphen Struktur

Solid



Mesophases

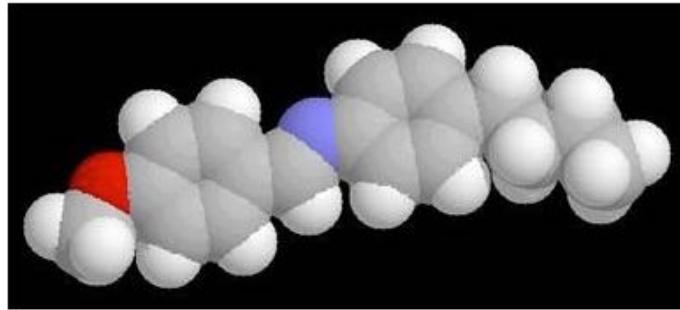


Liquid

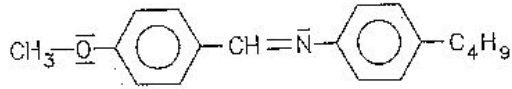




# Flüssigkristalle



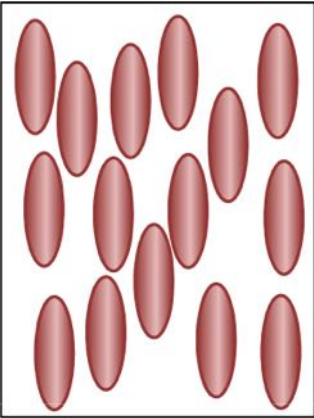
Schmelzpunkt: 22 °C  
 Klärpunkt: 47 °C



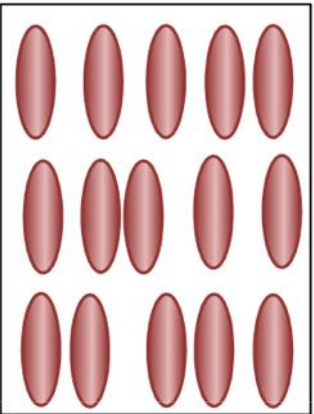
Methoxybenzylidenbutylanilin (MBBA)



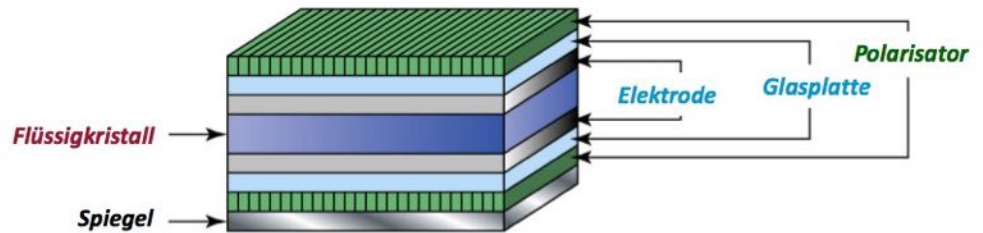
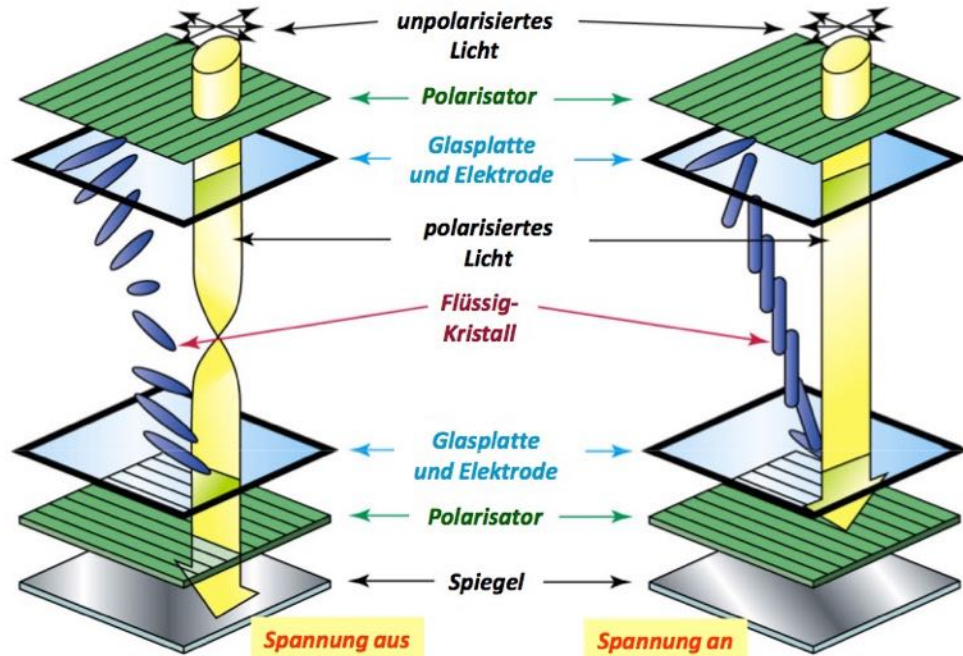
**flüssig**



**nematisch**

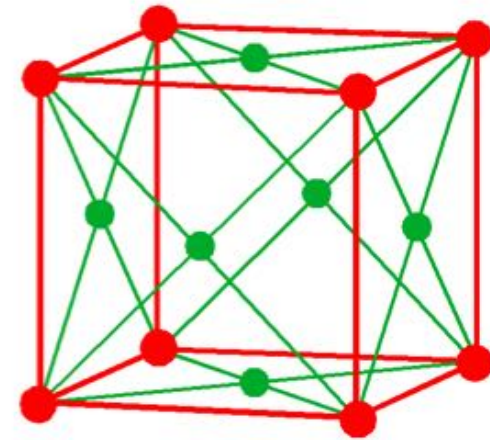


**smektisch**



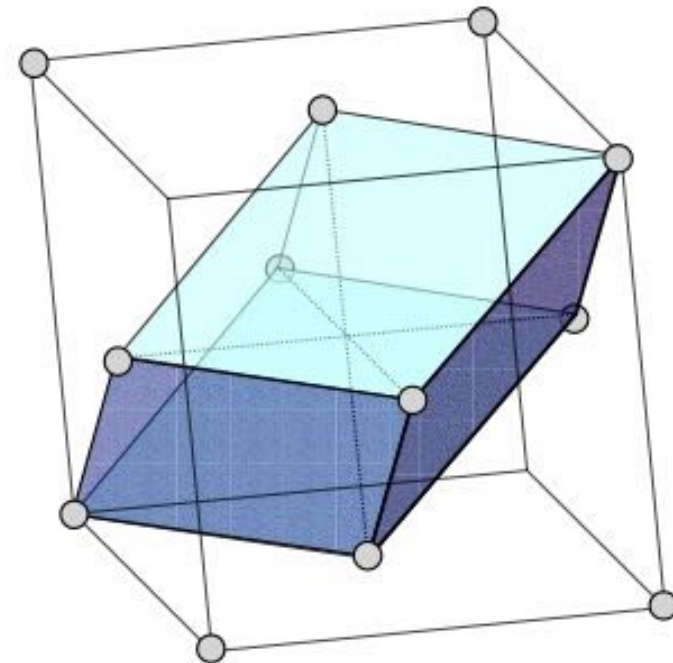
Zur prinzipiellen Funktionsweise von LCD-Anzeigen.

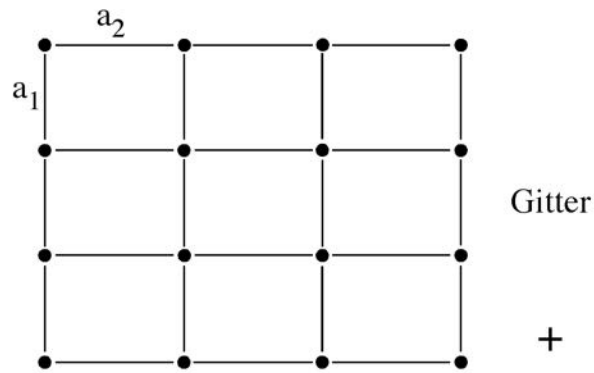
*Diese mehrfach primitive  
Einheitszelle enthält vier (!)  
Gitterpunkte*



Kubisch  $F$

*Die einfach primitive  
Einheitszelle ist kein Würfel!*



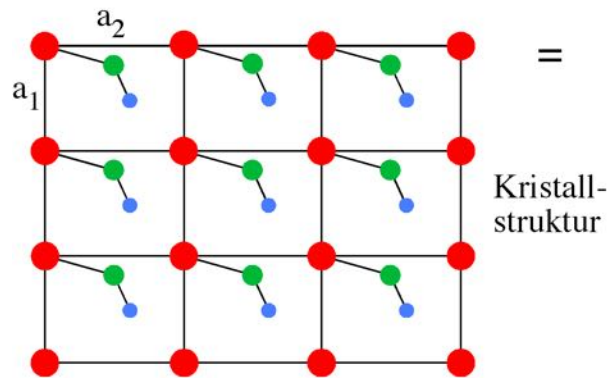


Gitter

+



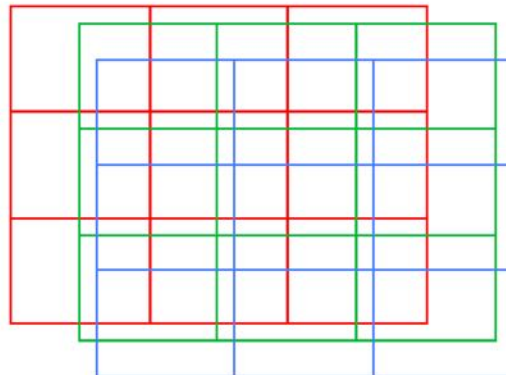
Basis



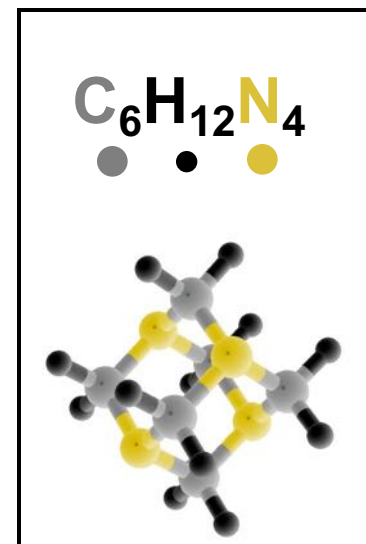
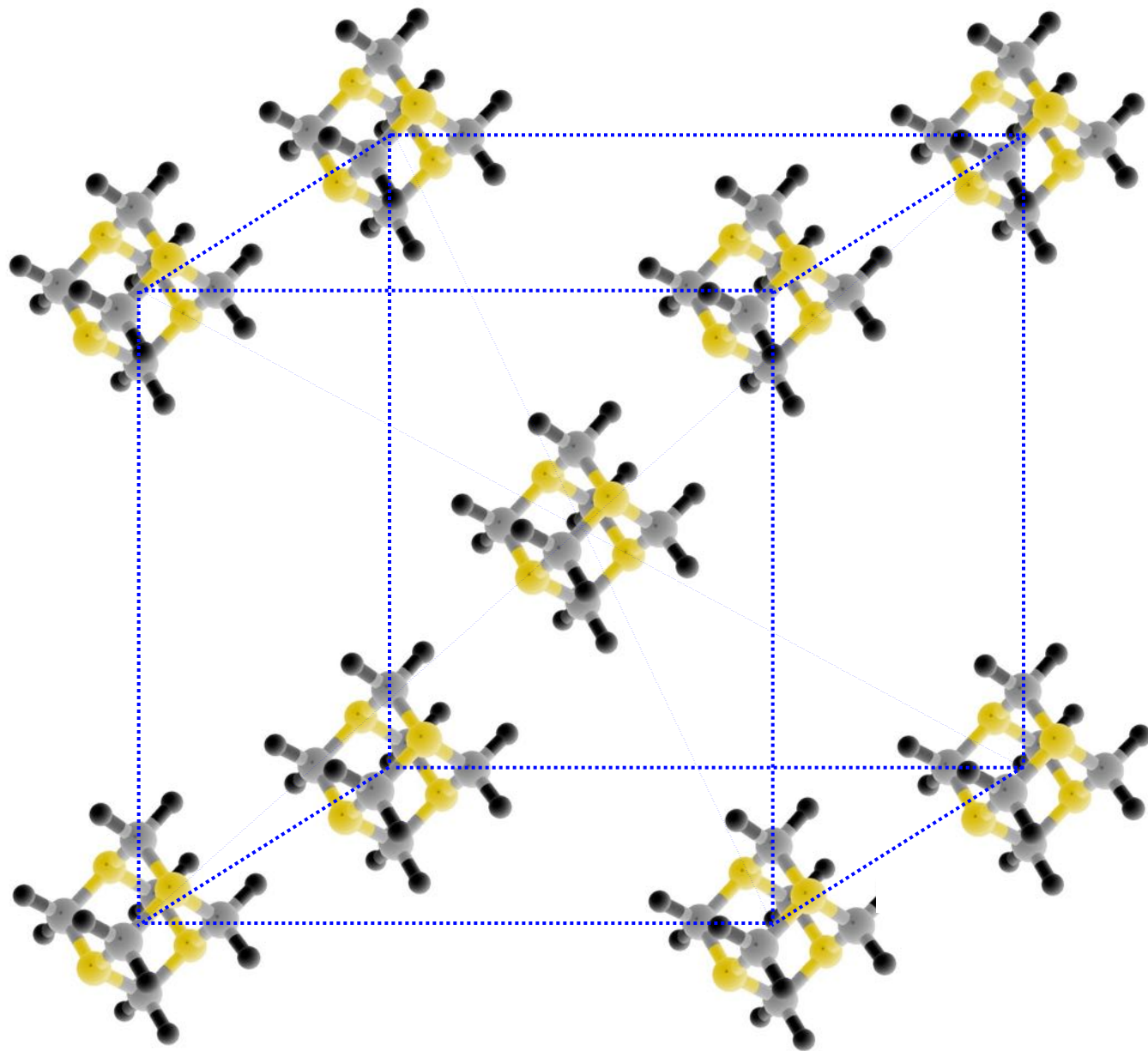
=

Kristallstruktur

Beziehung von Gitter, Basis und Kristallstruktur zueinander; Gitter und Kristallstruktur sind Projektionen auf (001)

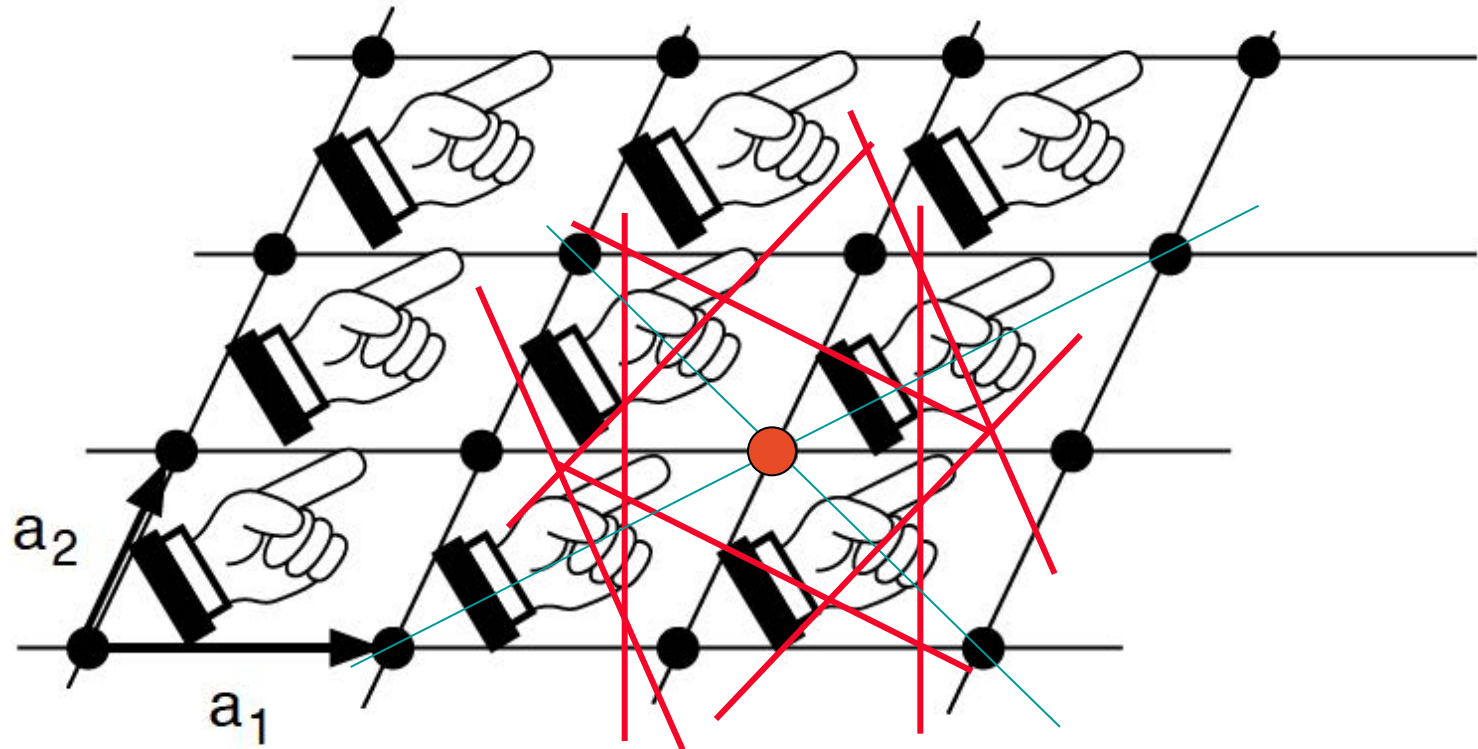


Alle Bausteine der in oben gezeigten Kristallstruktur liegen auf den Eckpunkten von kongruenten Gittern



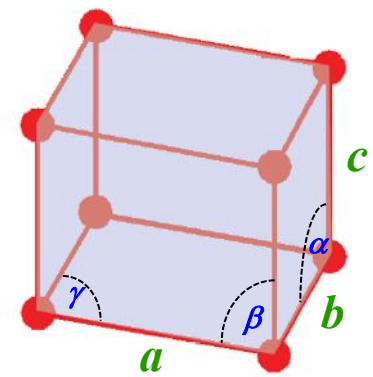


# Wigner-Seitz-Zelle

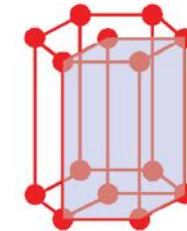
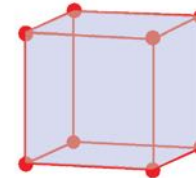
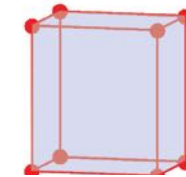
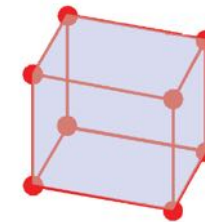
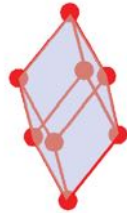
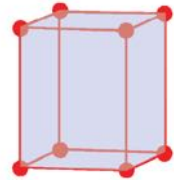
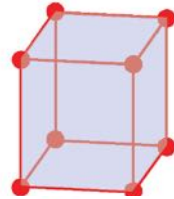




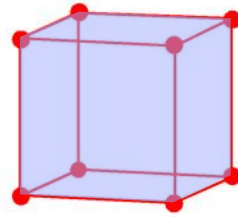
# Die 7 einfachsten Kristallsysteme



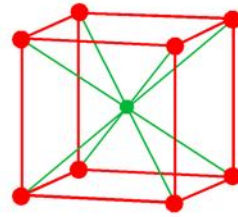
System	Einschränkungen bezüglich der Achsen und Winkel der gebräuchlichen Einheitszelle
Triklin	$a \neq b \neq c$ $\alpha \neq \beta \neq \gamma$
Monoklin	$a \neq b \neq c$ $\alpha = \gamma = 90^\circ \neq \beta$
Orthorhombisch	$a \neq b \neq c$ $\alpha = \beta = \gamma = 90^\circ$
Tetragonal	$a = b \neq c$ $\alpha = \beta = \gamma = 90^\circ$
Kubisch	$a = b = c$ $\alpha = \beta = \gamma = 90^\circ$
Rhomboedrisch (oder trigonal)	$a = b = c$ $\alpha = \beta = \gamma < 120^\circ, \neq 90^\circ$
Hexagonal	$a = b \neq c$ $\alpha = \beta = 90^\circ$ $\gamma = 120^\circ$



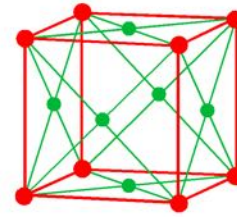
# Die 14 Bravais-Gitter



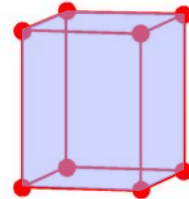
Kubisch *P*



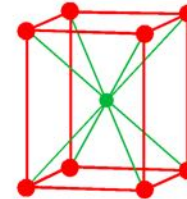
Kubisch *I*



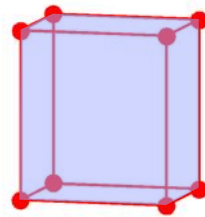
Kubisch *F*



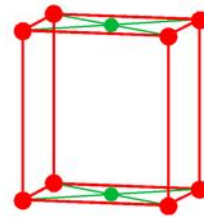
Tetragonal *P*



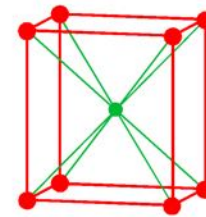
Tetragonal *I*



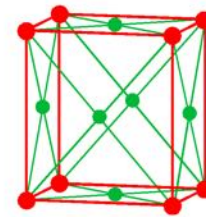
Orthorhombisch *P*



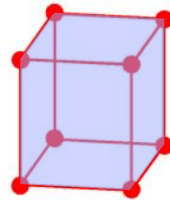
Orthorhombisch *C*



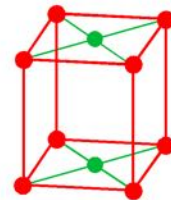
Orthorhombisch *I*



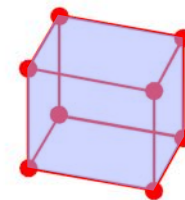
Orthorhombisch *F*



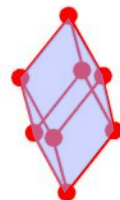
Monoklin *P*



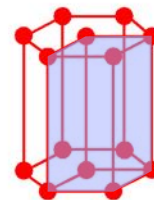
Monoklin *C*



Triklin



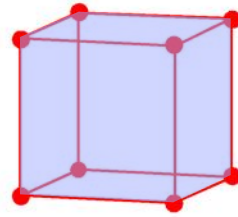
Rhomboedrisch *R*



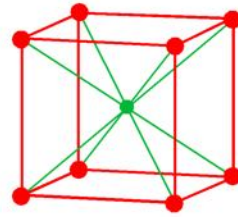
Hexagonal *P*



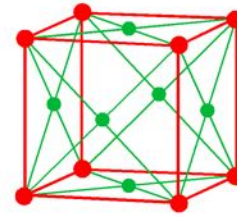
# Die 14 Bravais-Gitter



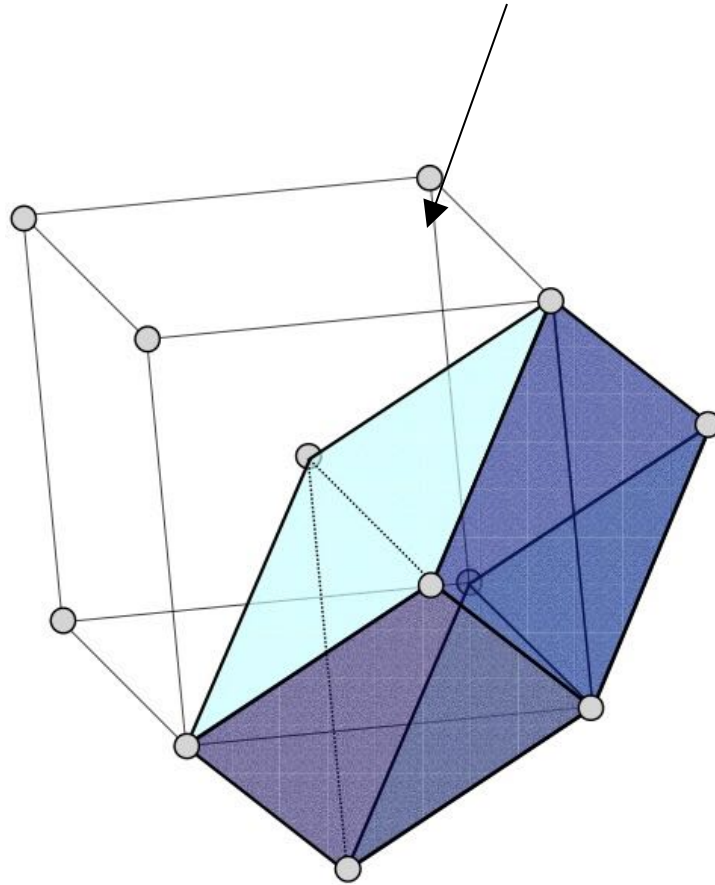
Kubisch *P*



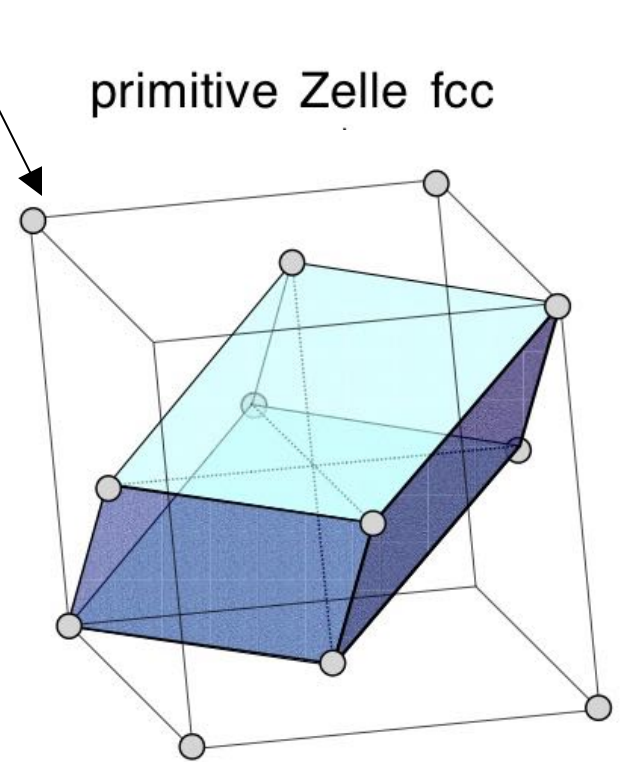
Kubisch *I*



Kubisch *F*

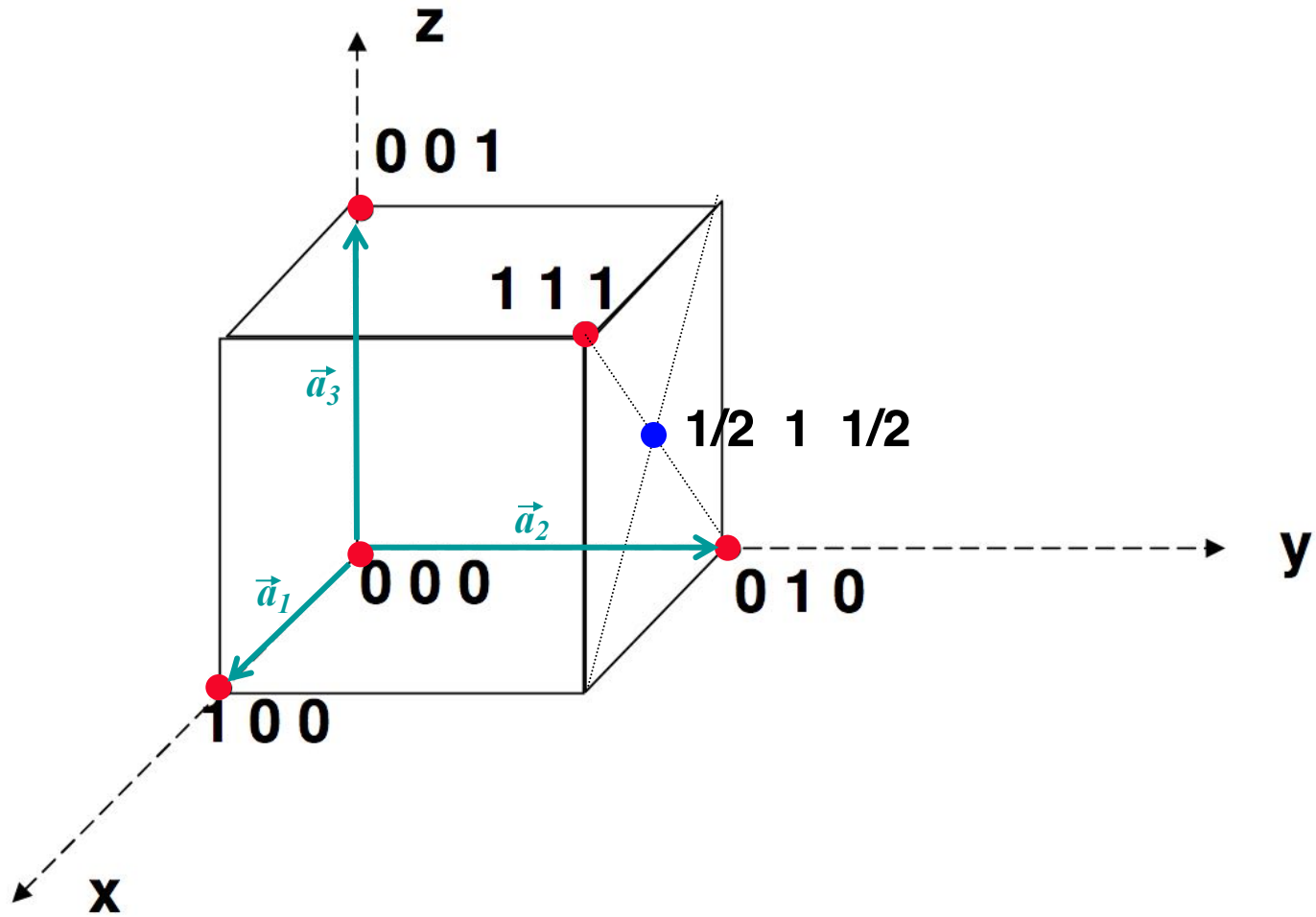


primitive Zelle bcc

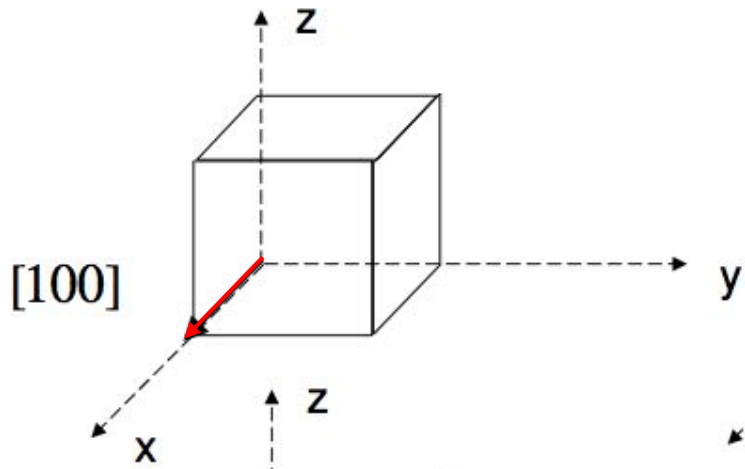


primitive Zelle fcc

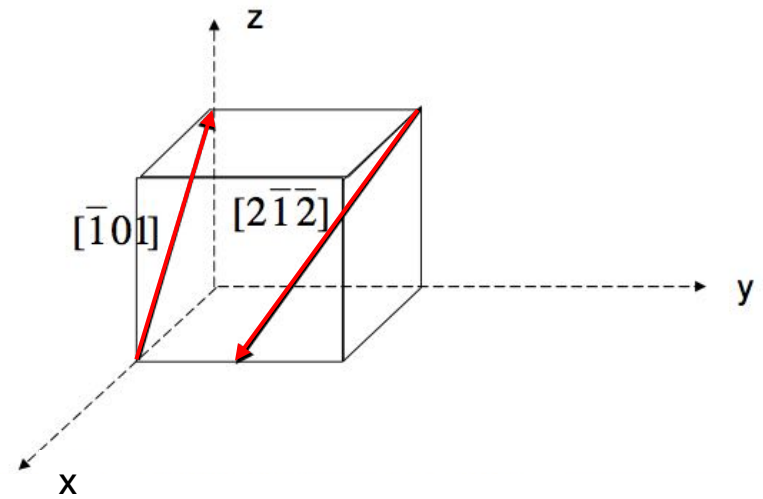
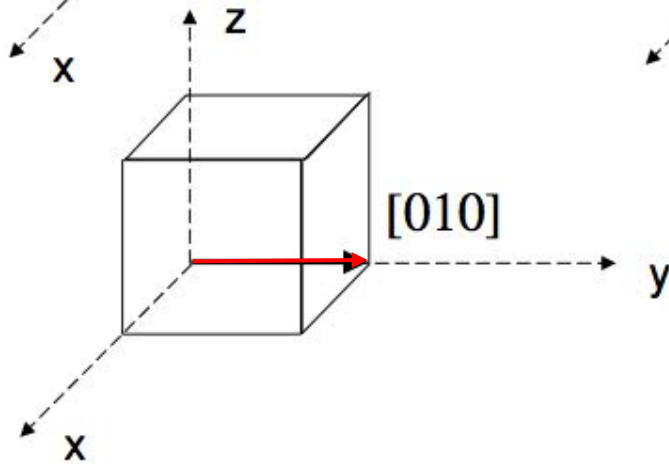
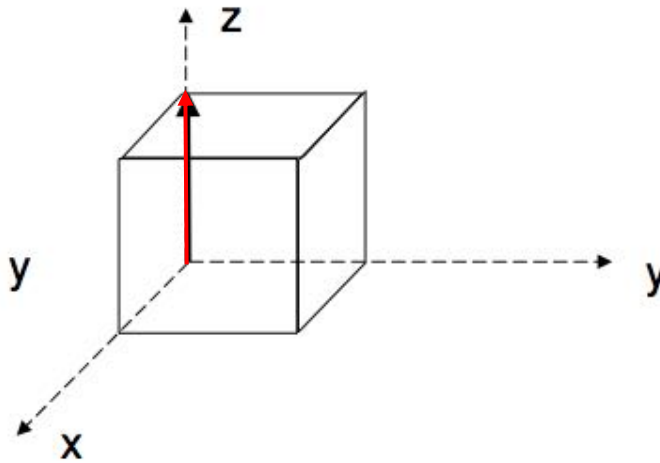
# *Atomkoordinaten*



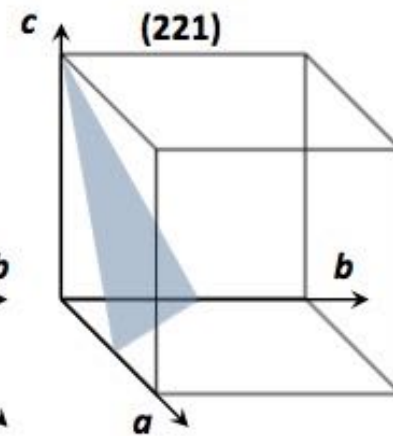
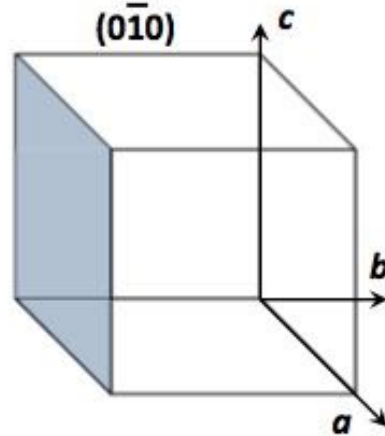
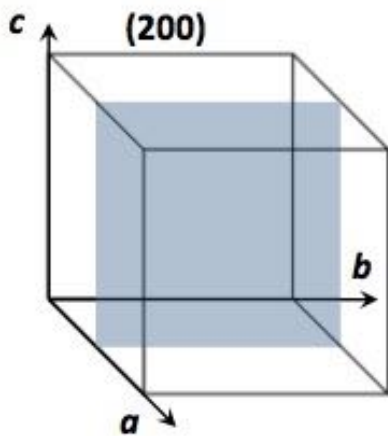
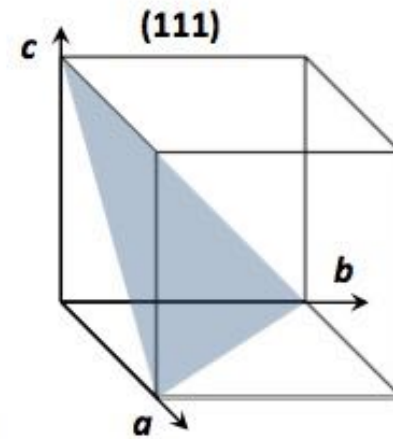
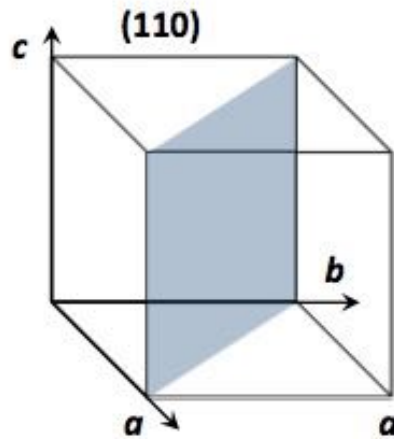
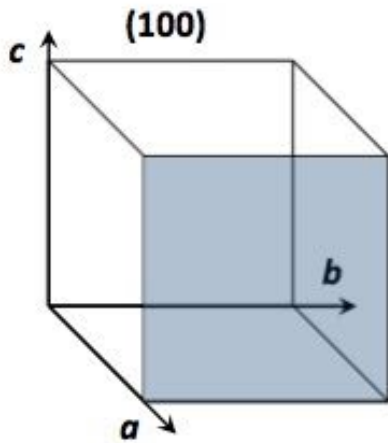
# *Richtungen im Kristall*

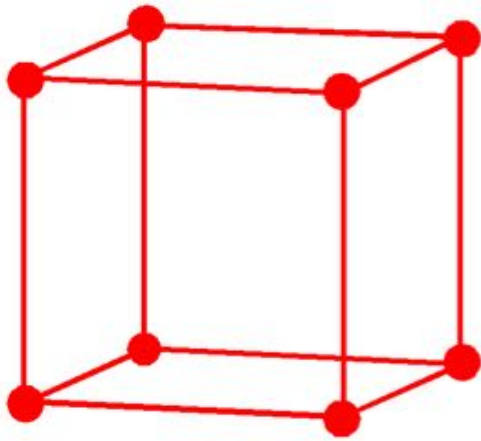


$[001]$

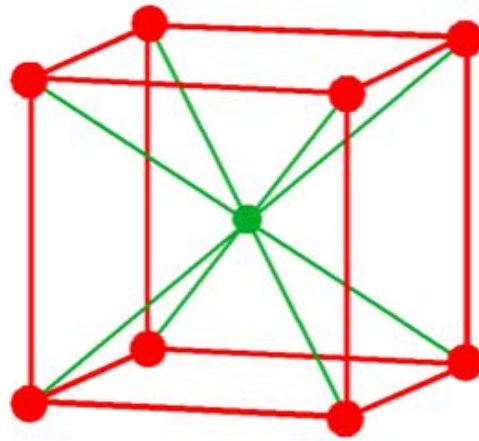


# Netzebenen



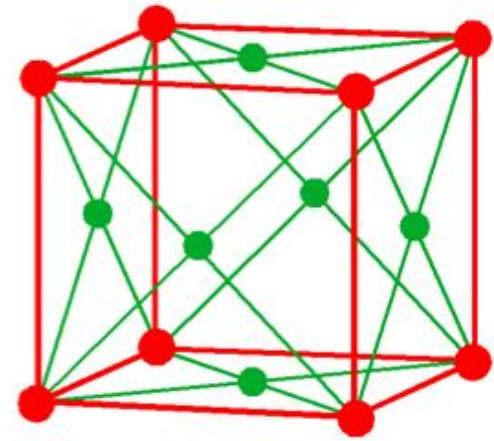


Kubisch *P*



Kubisch *I*

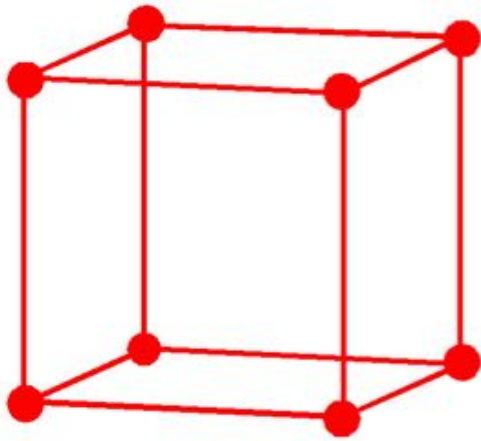
*bcc*



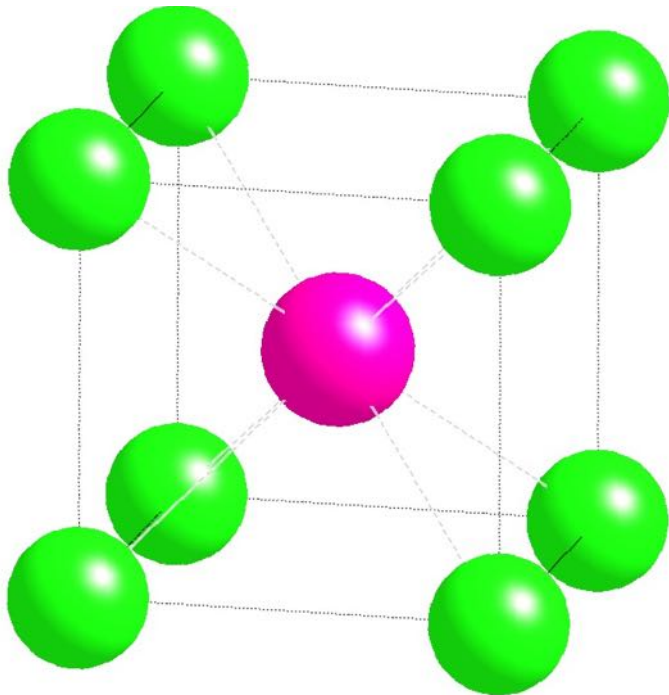
Kubisch *F*

*fcc*



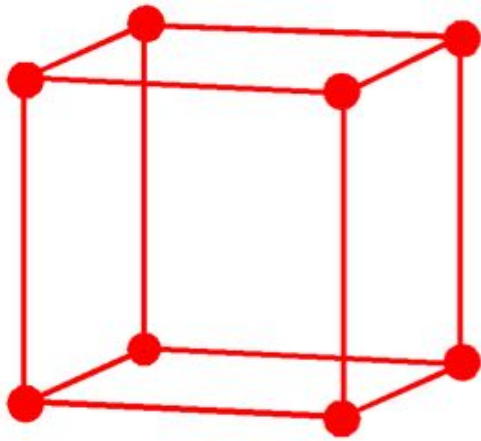


Kubisch *P*

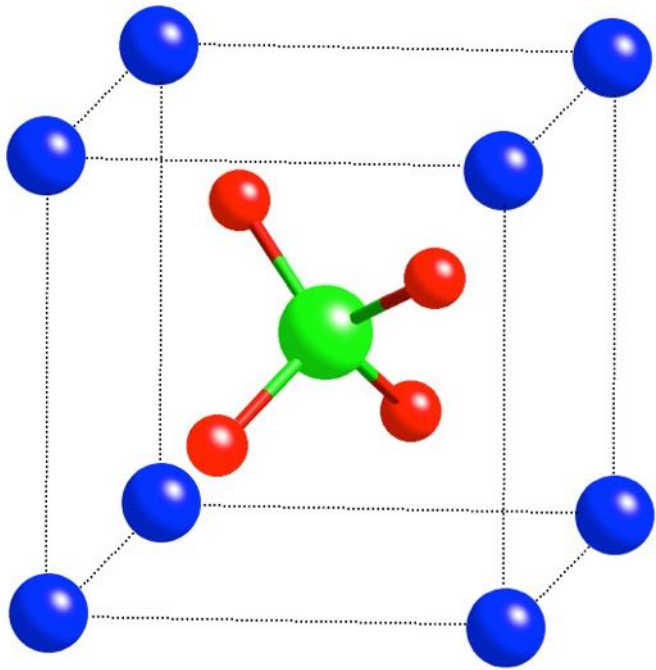


CsCl-Struktur

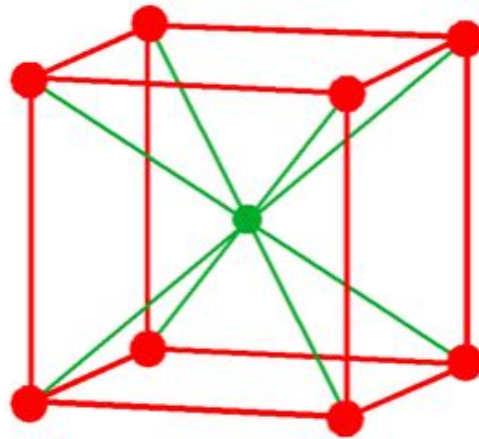




Kubisch *P*



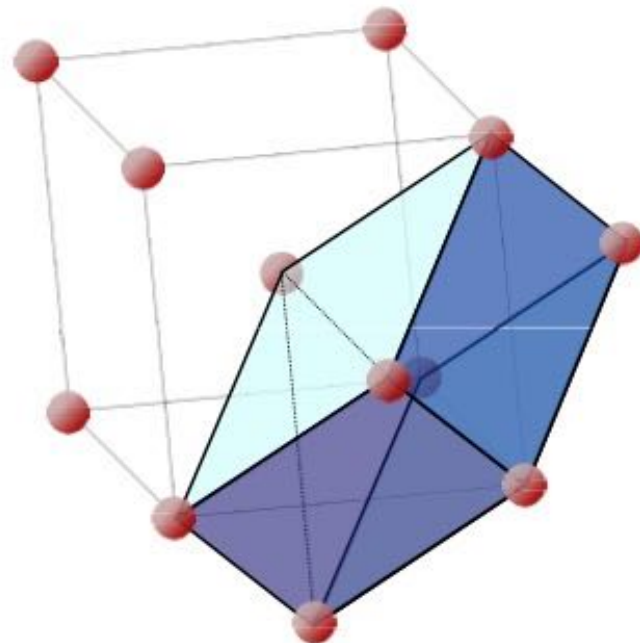
$\text{NH}_4\text{Cl}$



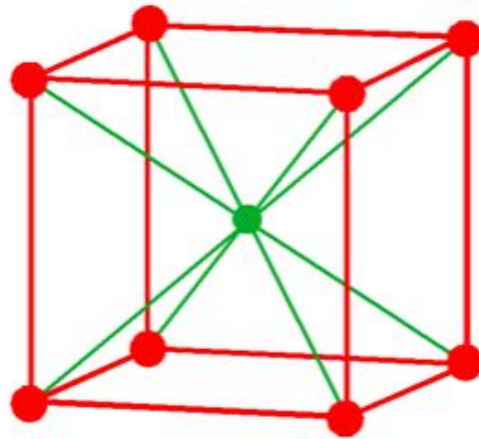
Kubisch I  
*bcc*

*Elemente Na, K, Rb, W, .....*

*Achtung: primitive  
Einheitszelle ist kein Würfel!*



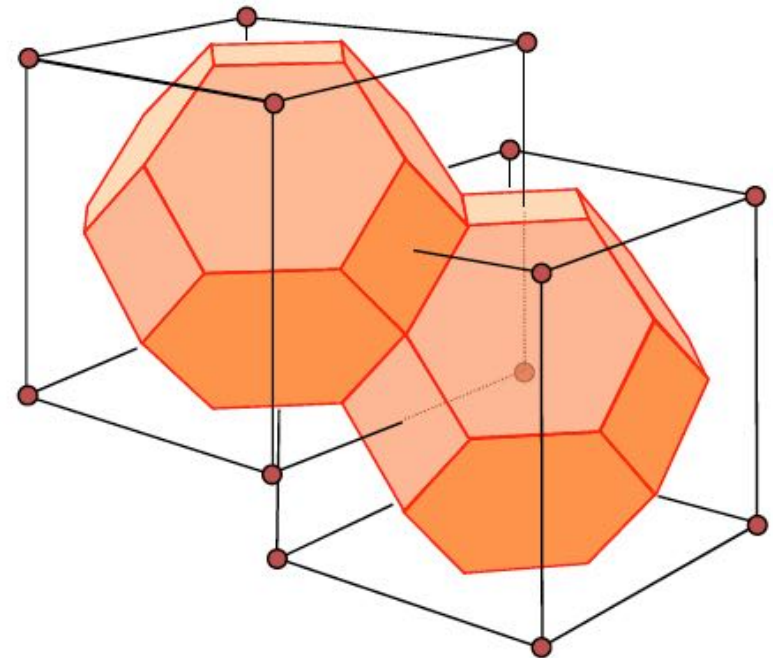
primitive Zelle bcc



Kubisch I

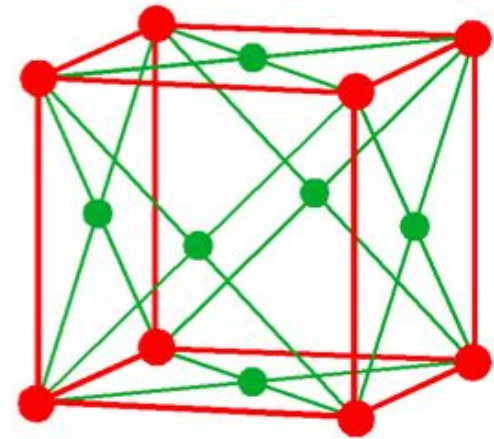
*bcc*

Wigner-Seitz Zelle für bcc



*Elemente Na, K, Rb, W, .....*

*Achtung: primitive  
Einheitszelle ist kein Würfel!*



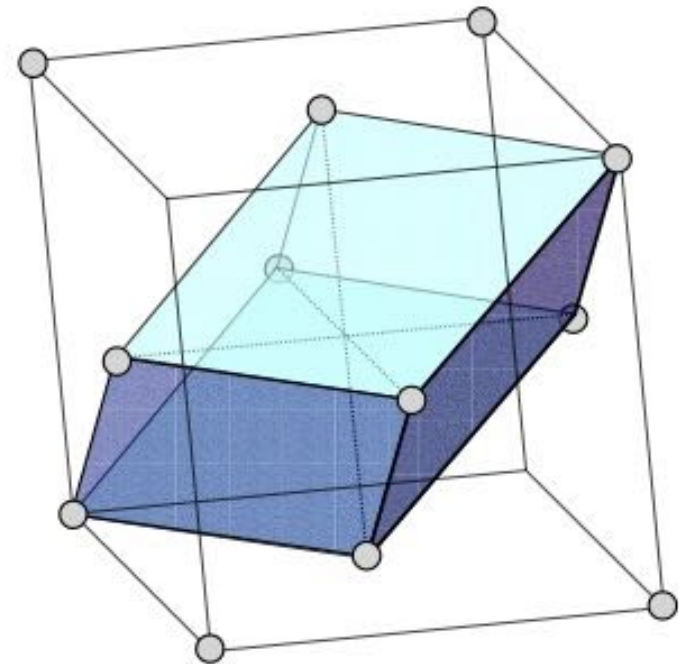
Kubisch  $F$

primitive Zelle fcc

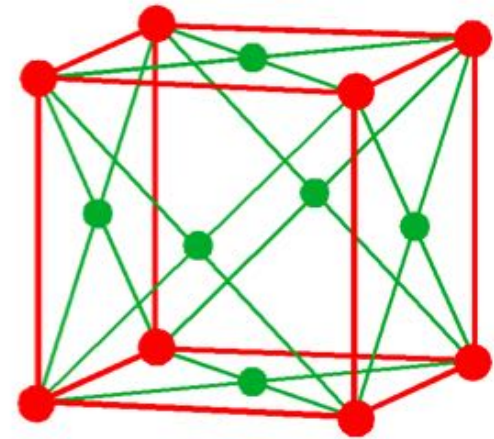
*Mit einer Atomsorte:*

*Elemente Al, Cu, Ag, Au, .....*

*Achtung: primitive  
Einheitszelle ist kein Würfel!*







Kubisch *F*

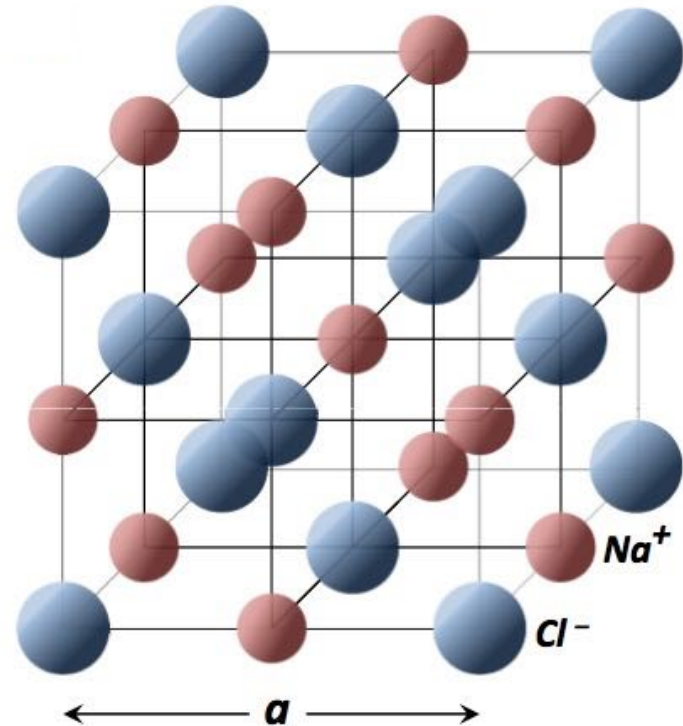
*fcc*

*NaCl Struktur*

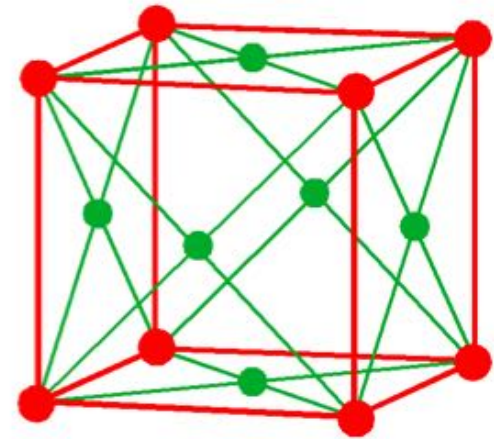
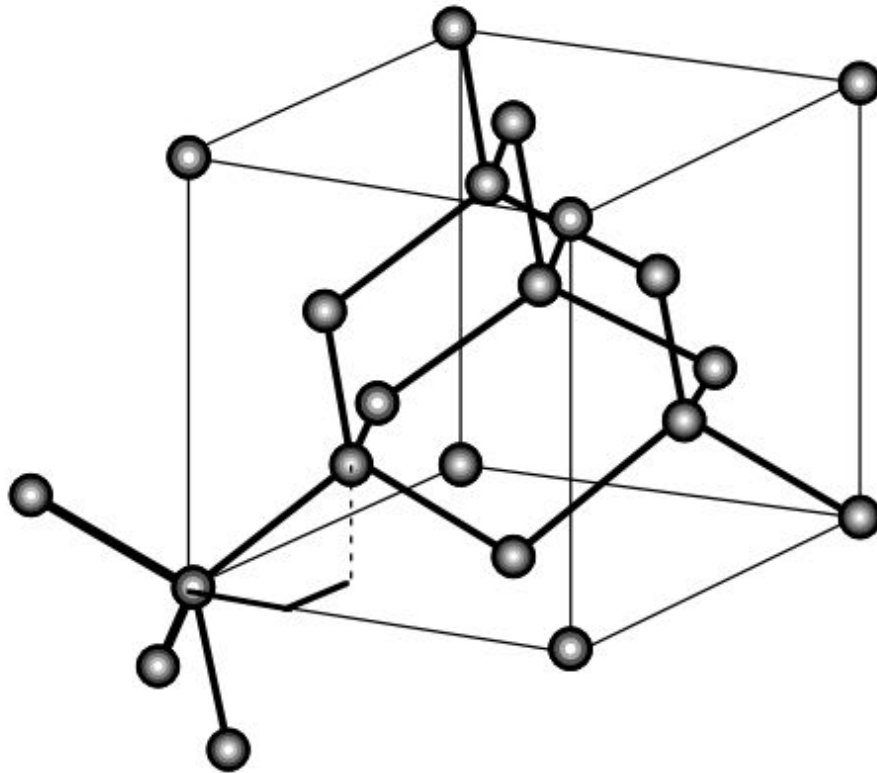
*(KCl, LiF, ....)*

**Cl**    **0 0 0**  
**0 1/2 1/2 & zyklisch**

**Na**    **1/2 1/2 1/2**  
**0 1/2 0 & zyklisch**



*Diamantstruktur (C, Si, Ge, ...)*



Kubisch *F*  
*fcc*

**C**

**0 0 0**

**0 1/2 1/2 & zyklisch**

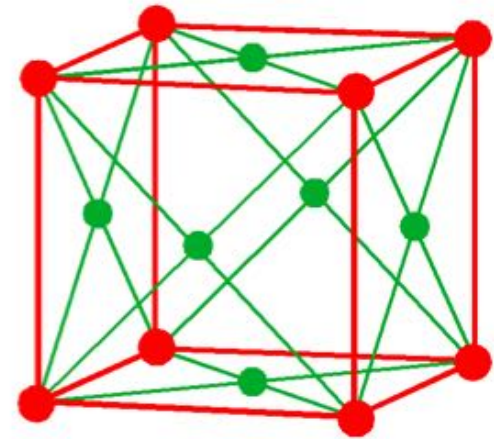
**1/4 1/4 1/4**

**1/4 3/4 1/4**

**& zyklisch**

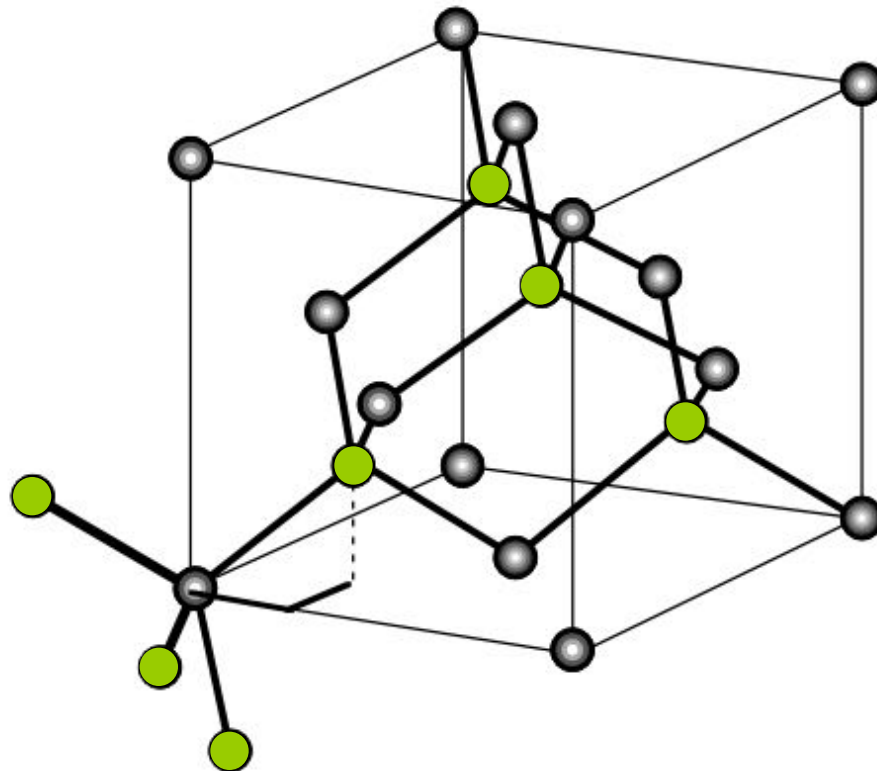
***Kubische ZnS-Struktur („Zinkblende“)***

***(CuF, AgJ, CdS, ZnS, ZnSb, SiC)***



Kubisch *F*

*fcc*



**Zn**

**0 0 0**

**0 1/2 1/2 & zyklisch**

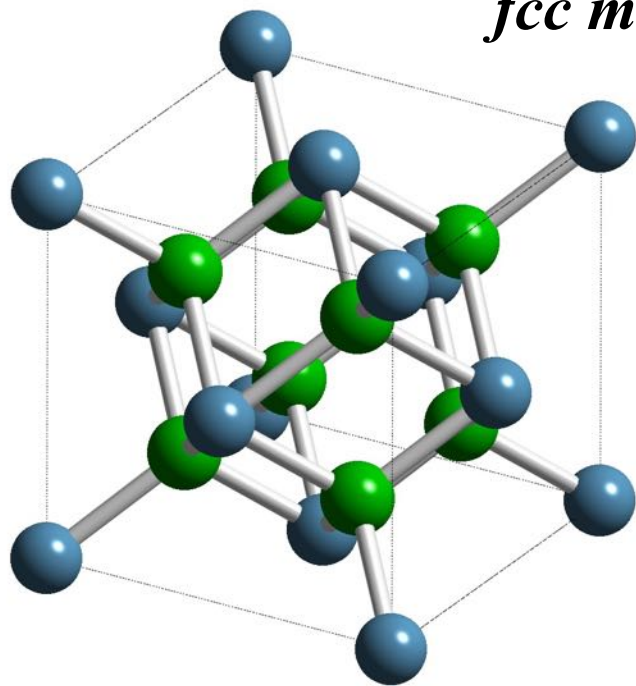
**S**

**1/4 1/4 1/4**

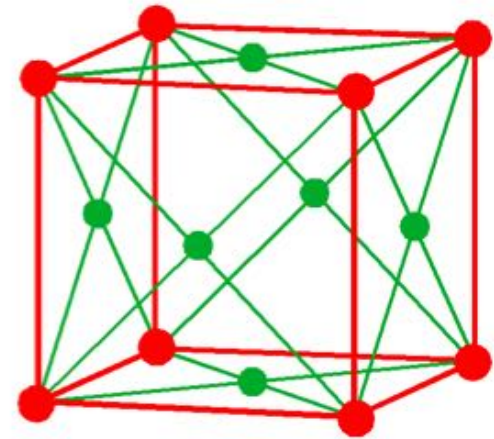
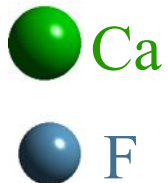
**1/4 3/4 1/4**

**& zyklisch**

*Fluorit  $\text{CaF}_2$*

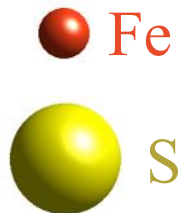
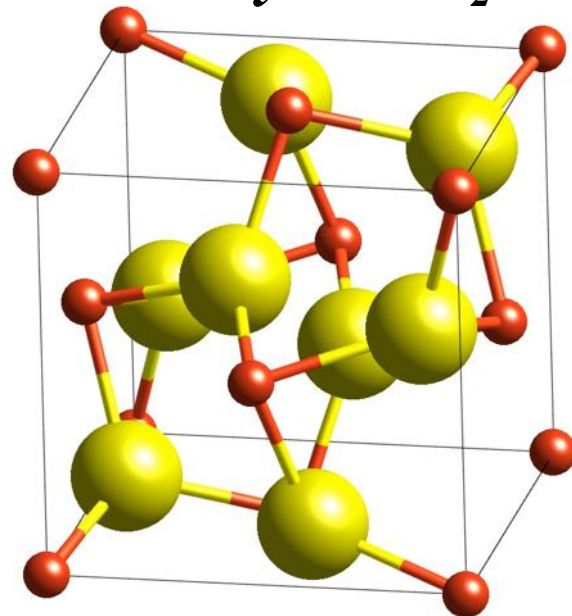


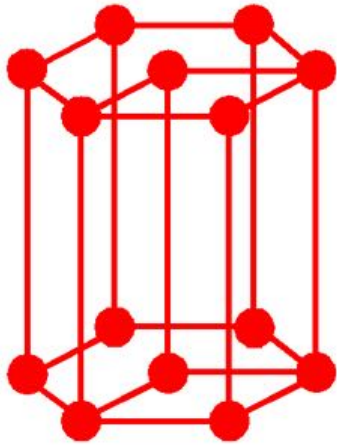
*fcc mit 3-atomiger Basis*



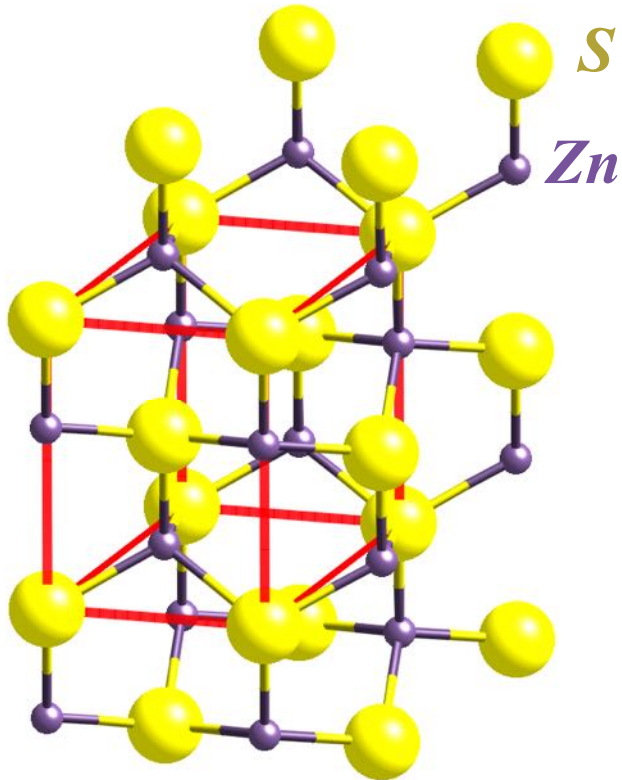
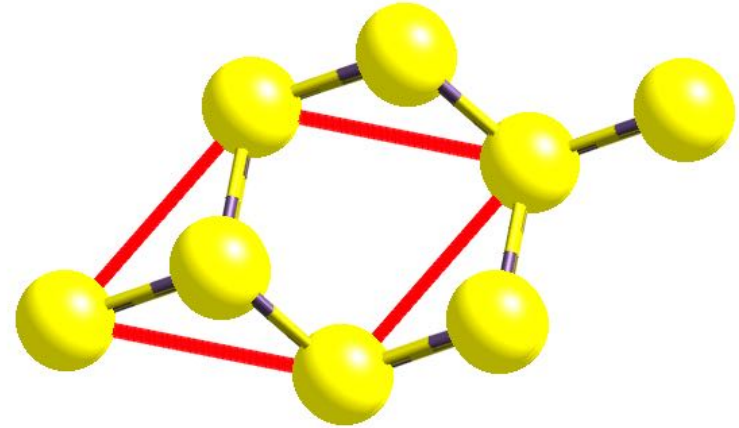
Kubisch *F*  
*fcc*

*Pyrit  $\text{FeS}_2$*



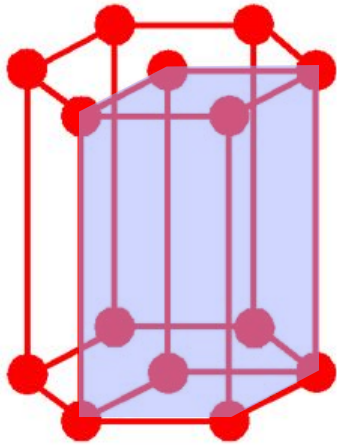


Hexagonal *P*

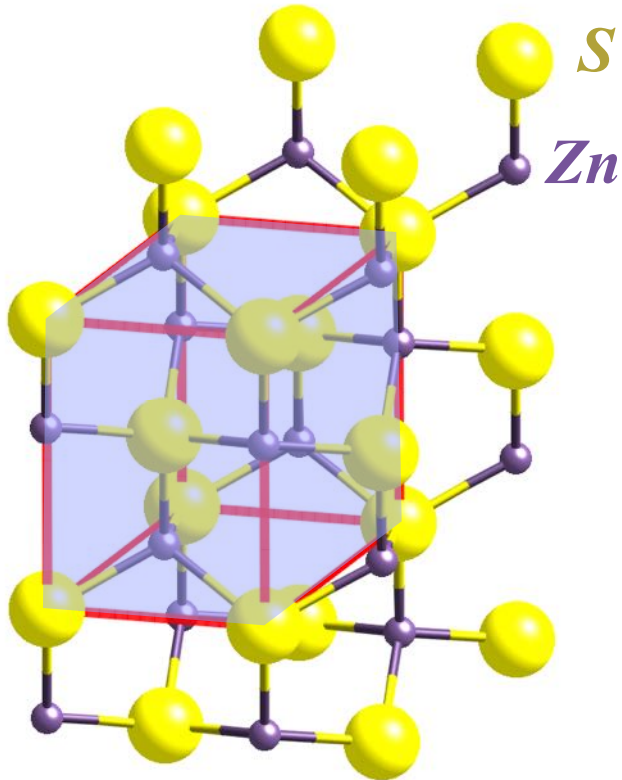
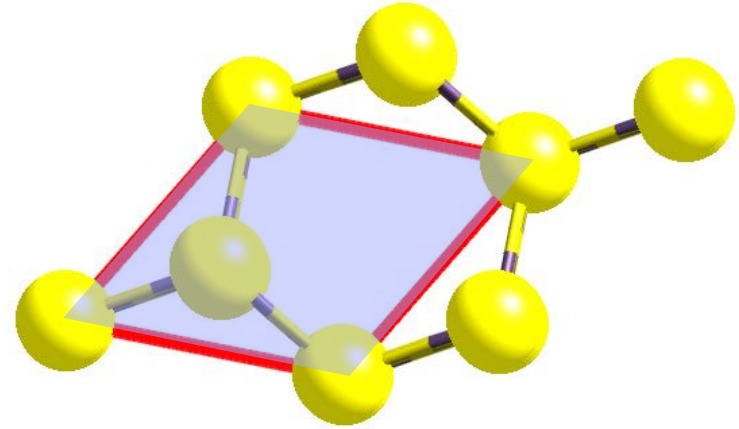


*Wurtzit - hexagonales ZnS*

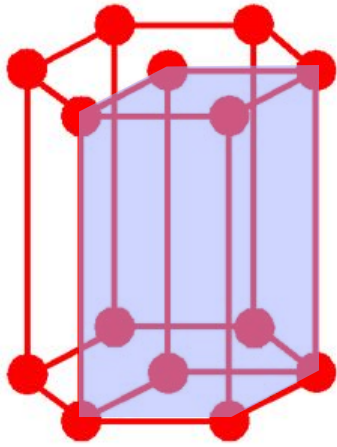




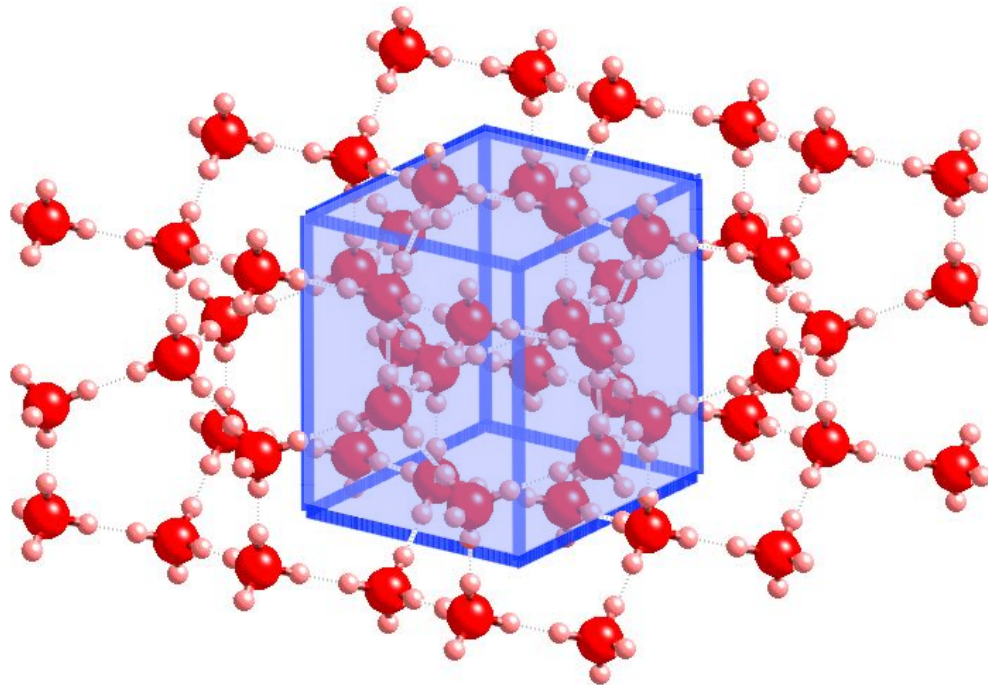
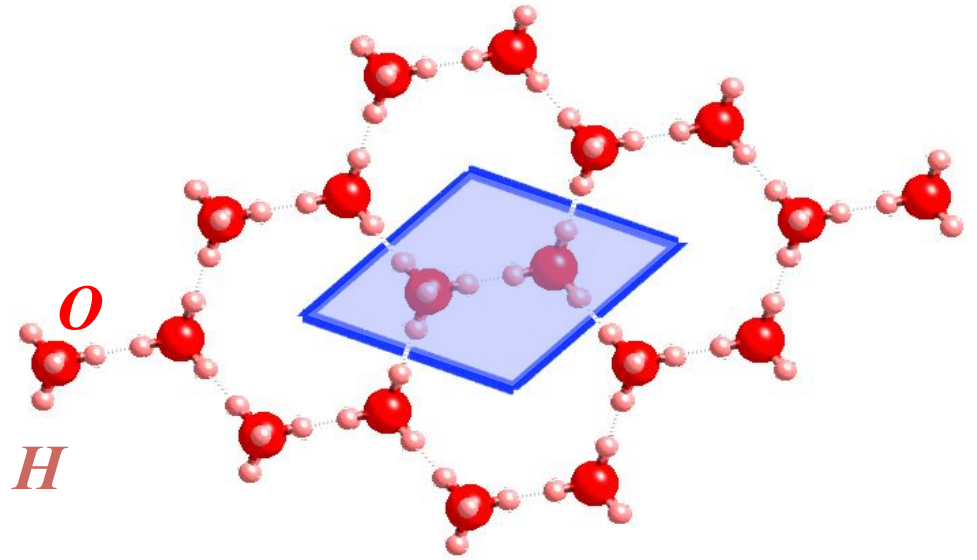
Hexagonal  $P$



*Wurtzit - hexagonales ZnS*

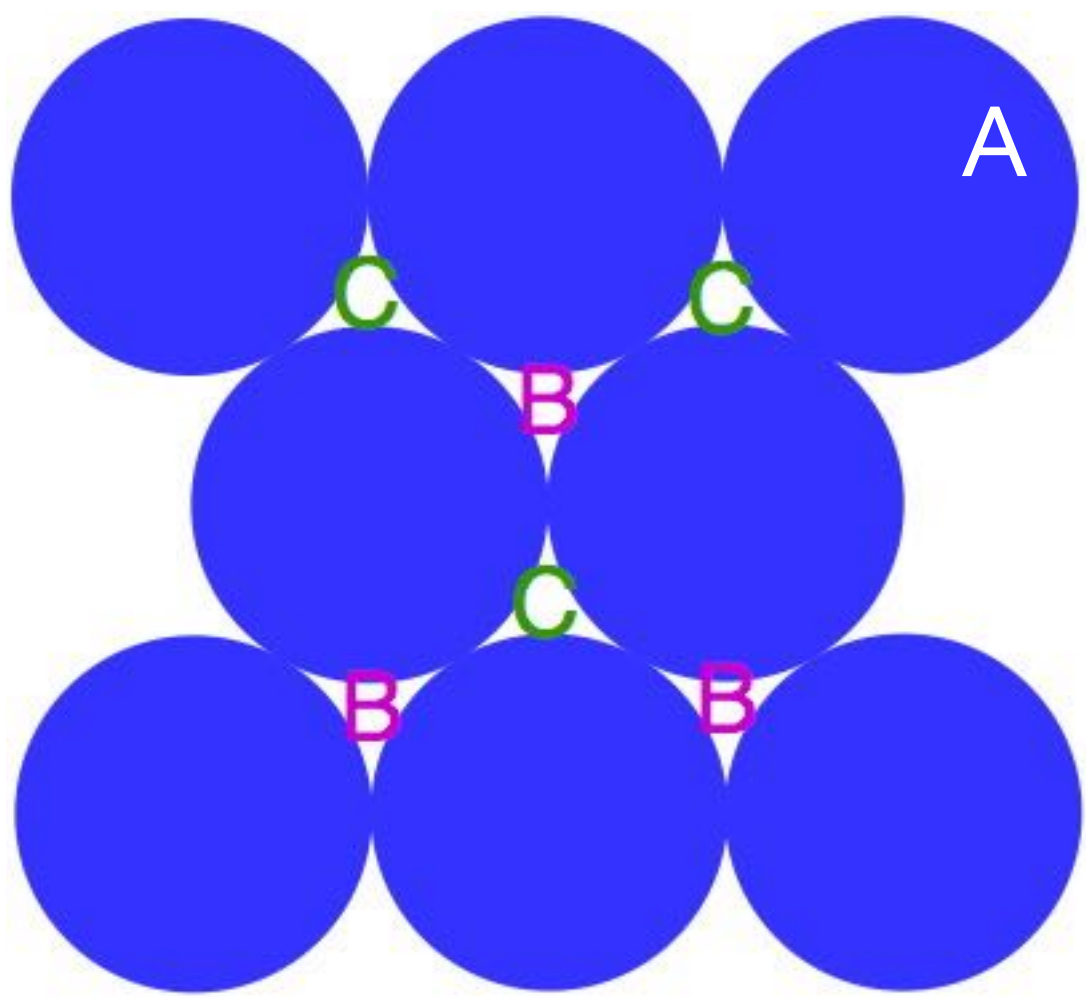


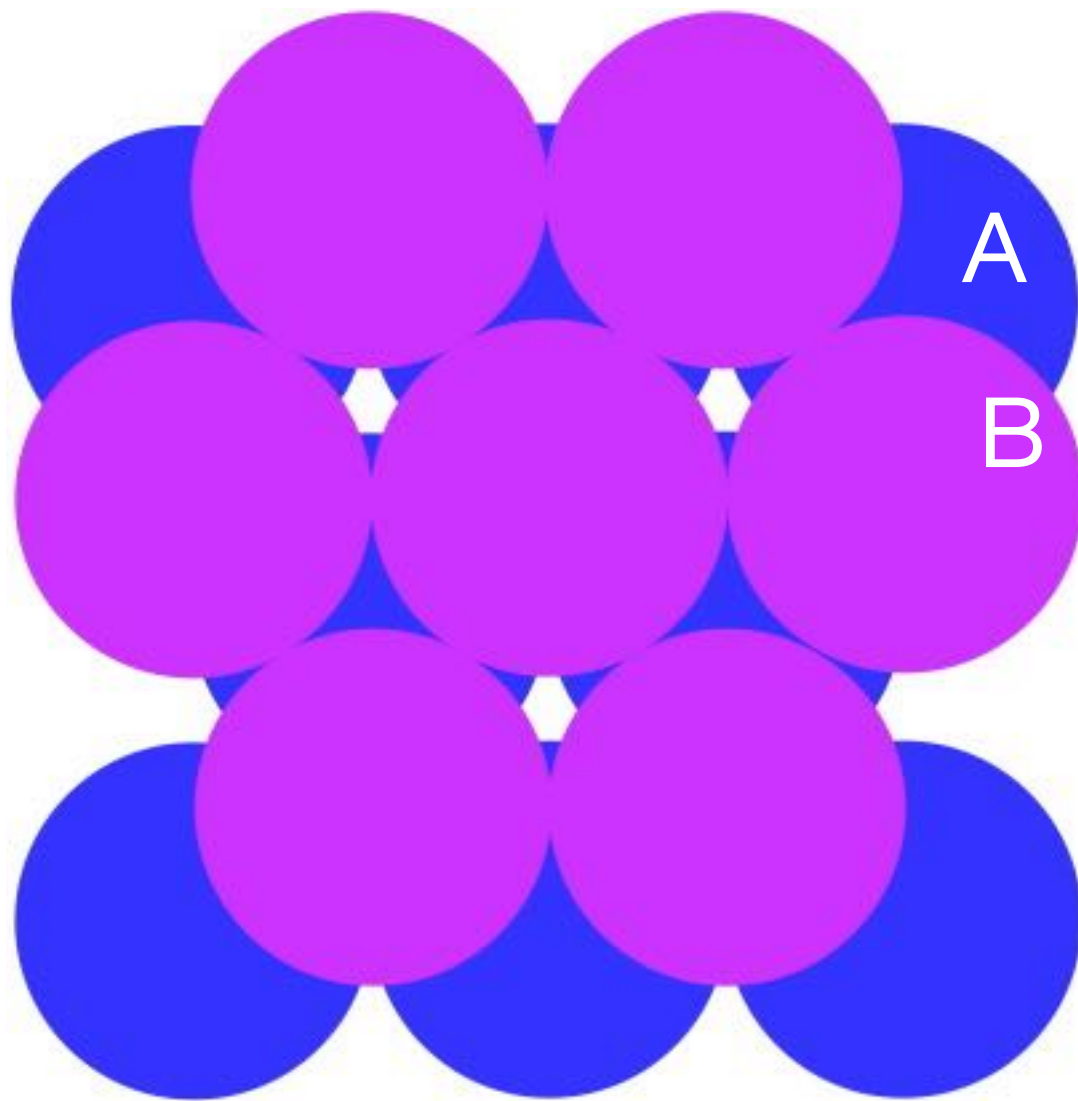
Hexagonal *P*

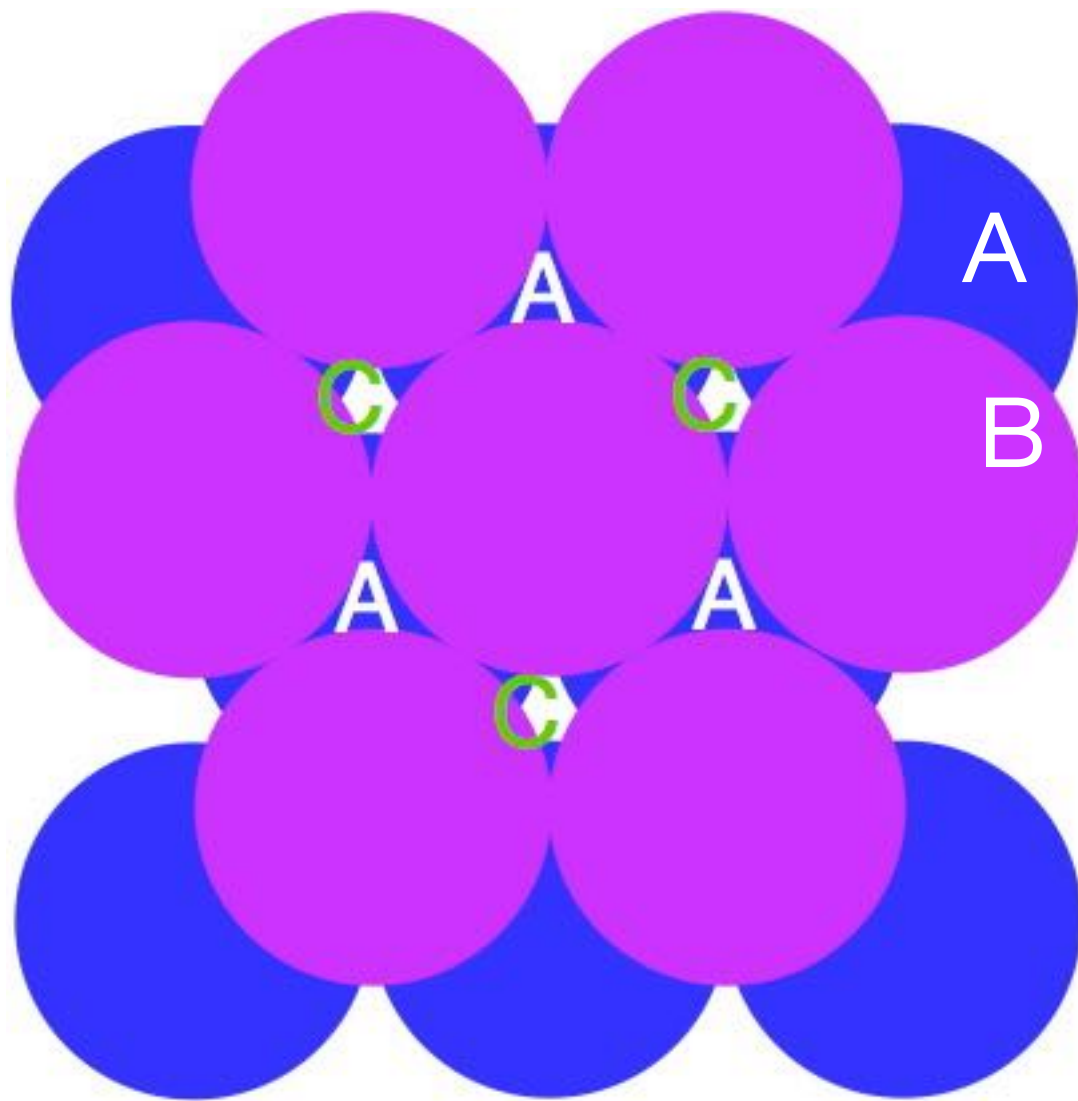


*Eis - H<sub>2</sub>O*

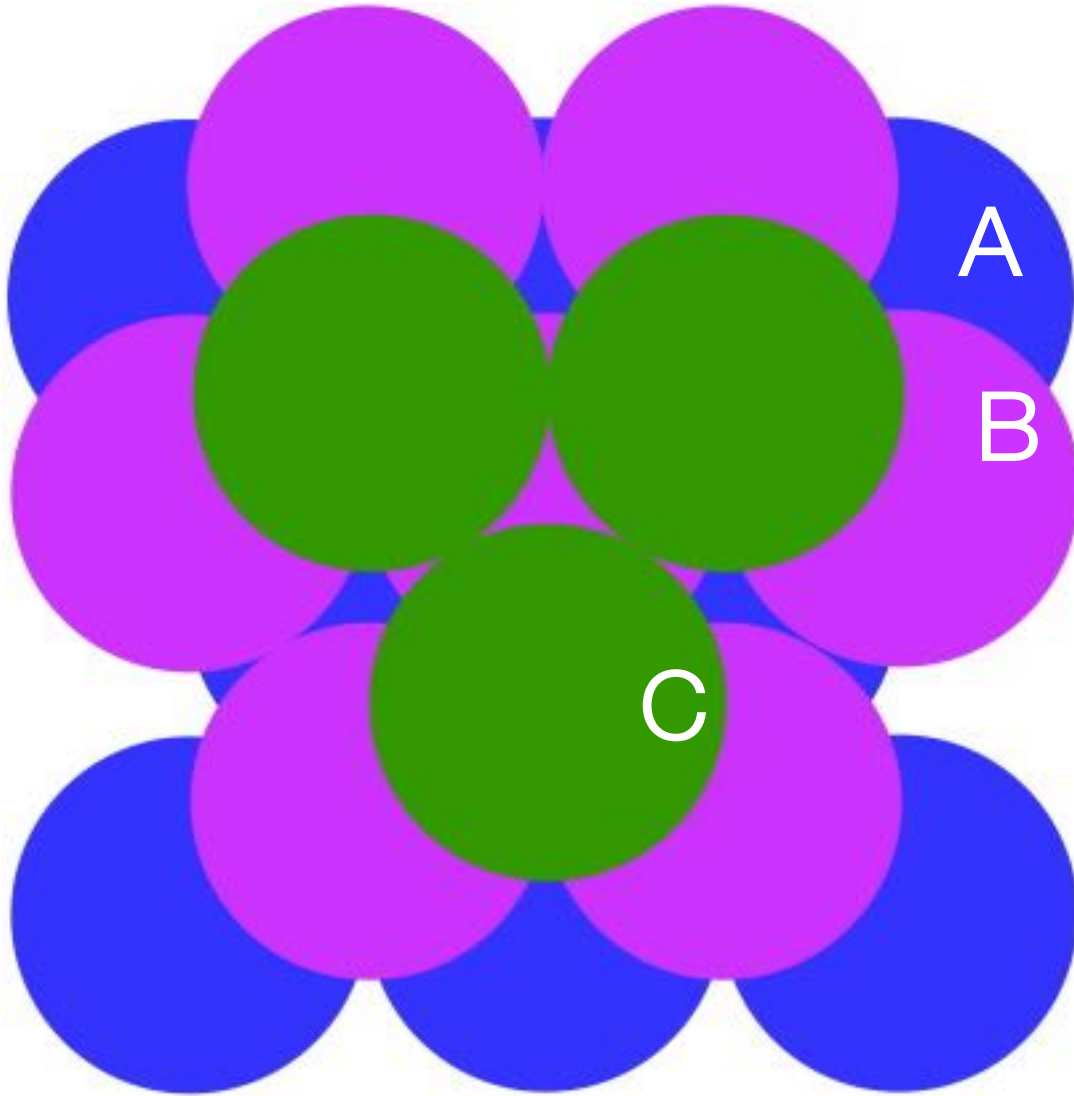
*(H-Atome ungeordnet über  
zwei mögliche Plätze verteilt)*

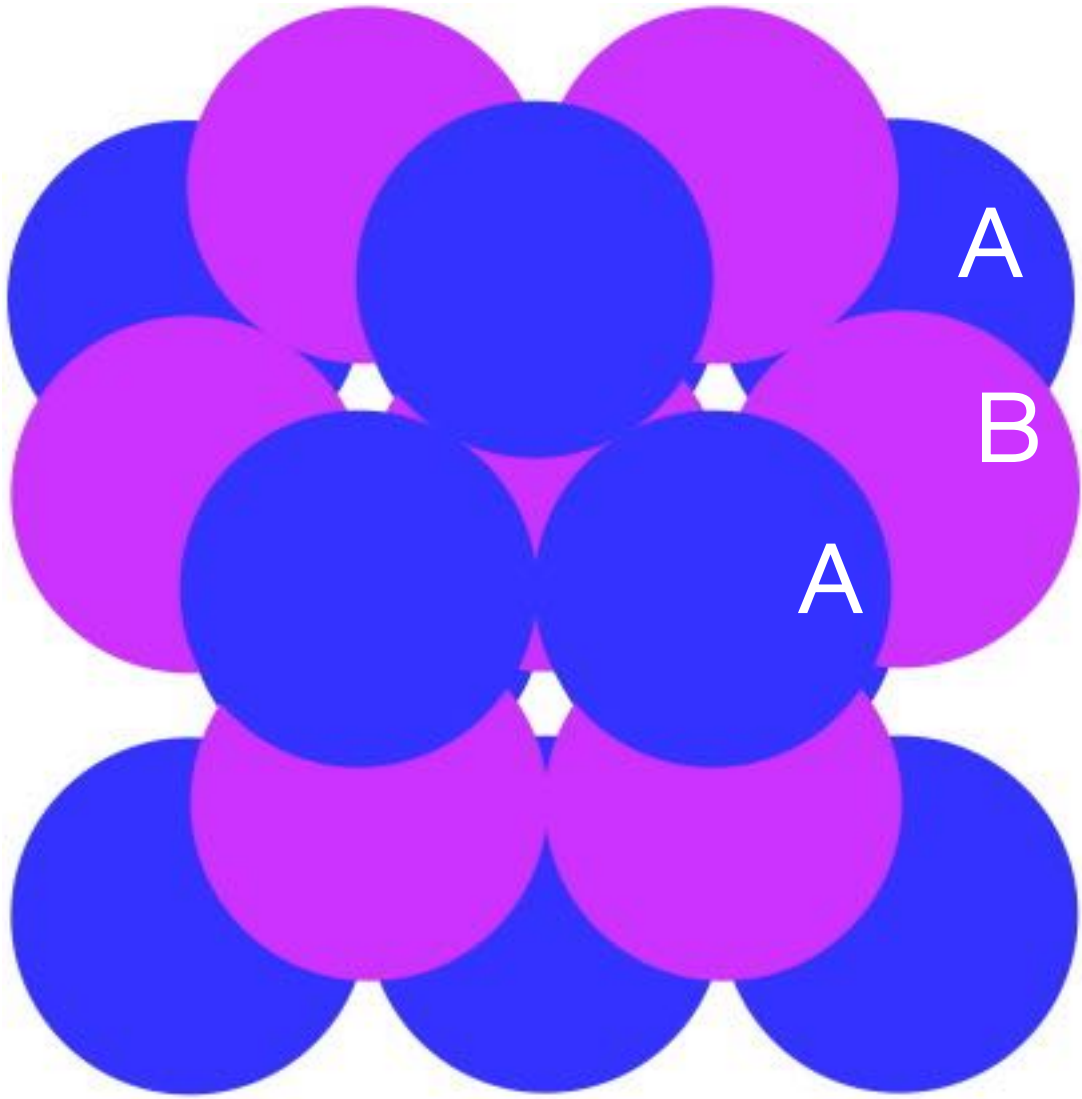


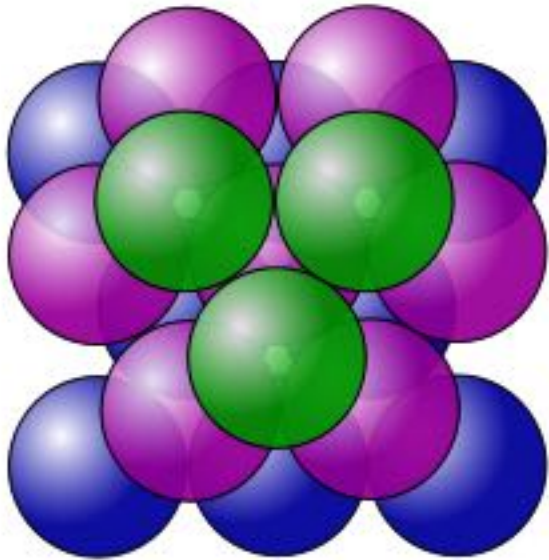
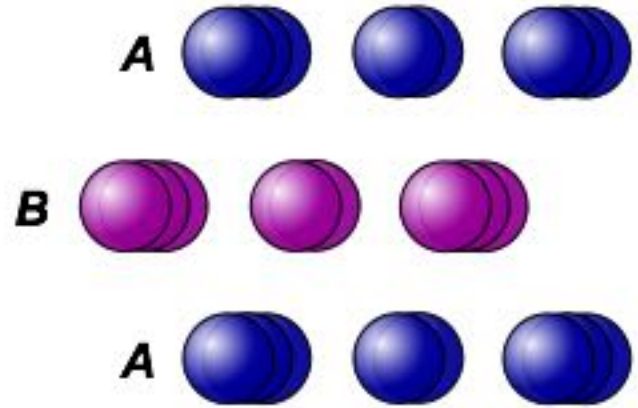
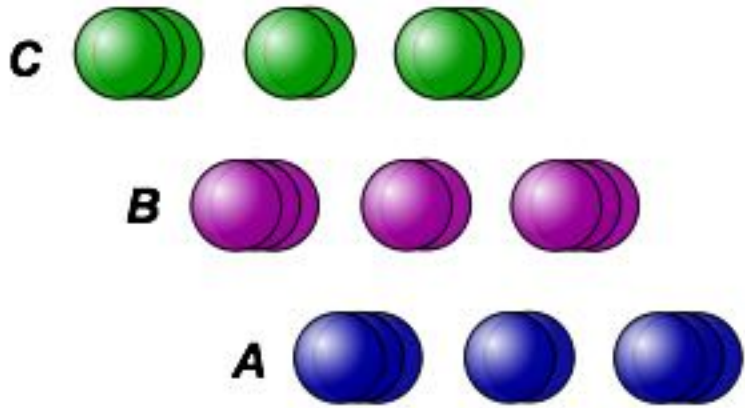




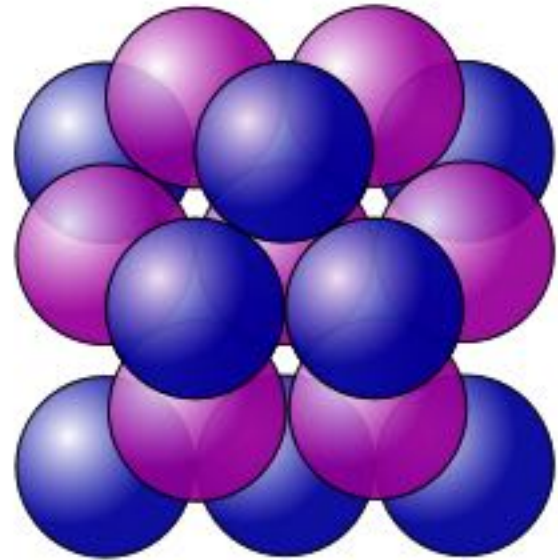






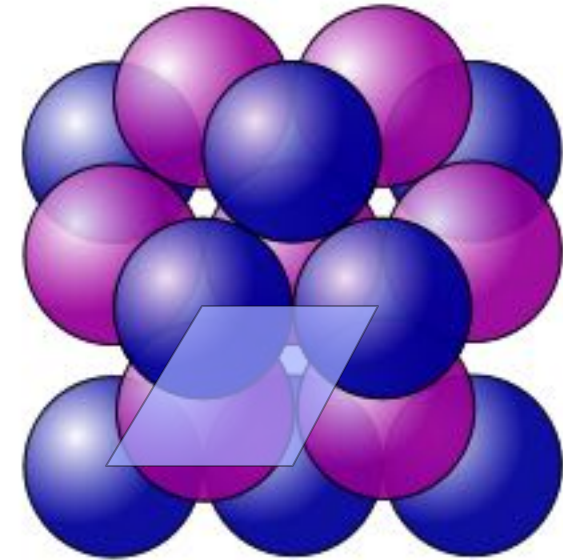
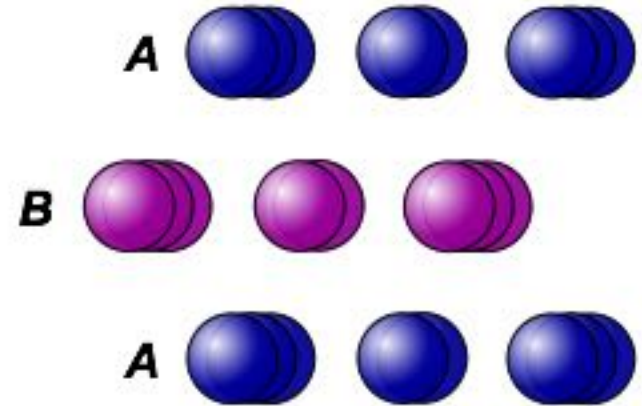
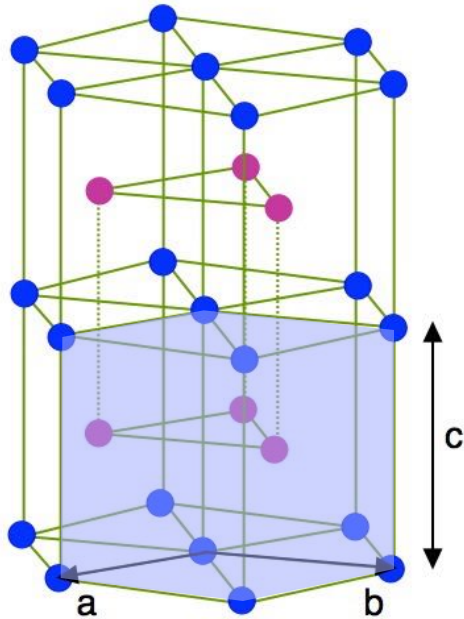


*ABCABC*



*ABABAB*

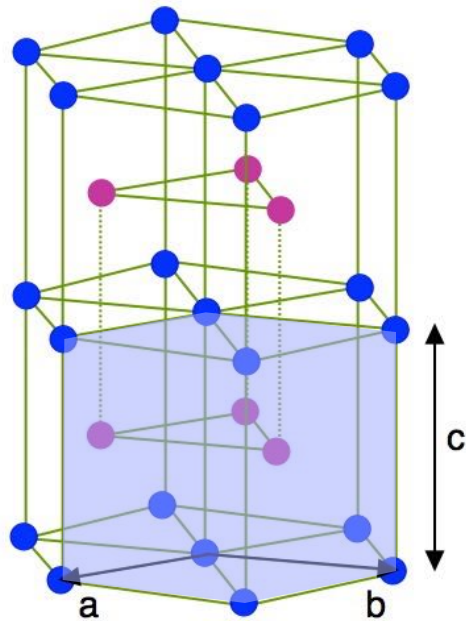
*Hexagonal dichteste Kugelpackung (HCP)*



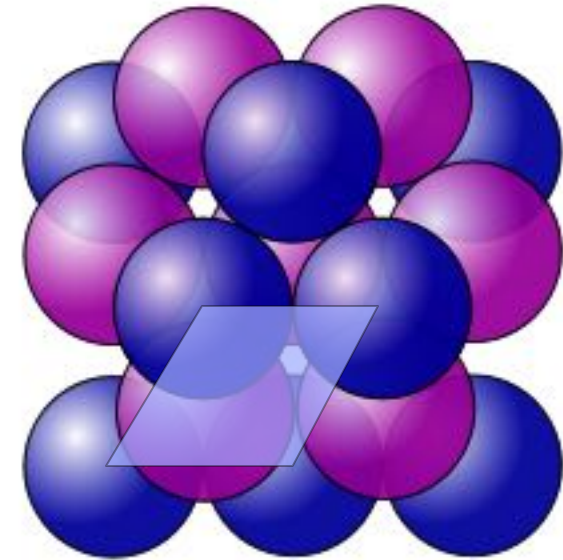
*ABABAB*

0      0      0  
 1/3    2/3    1/2

***Hexagonal dichteste Kugelpackung (HCP)***



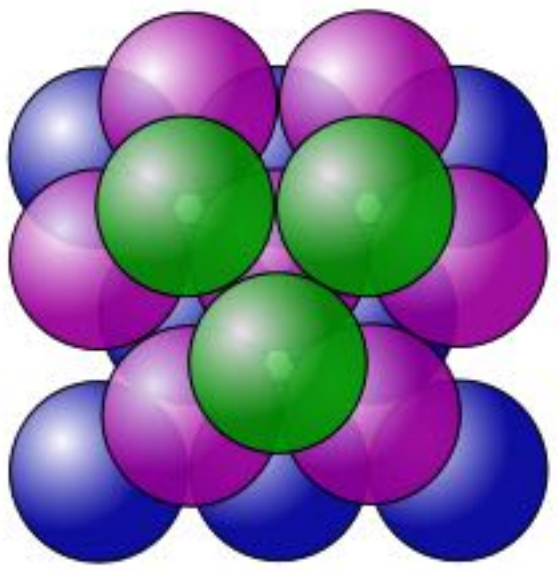
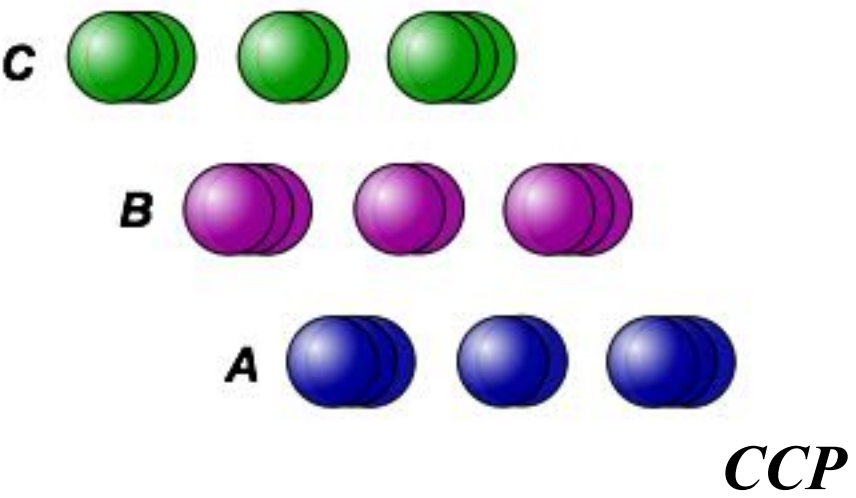
Element	$a$ (nm)	$c$ (nm)	$c/a$
Be	0.229	0.358	1.56
Cd	0.298	0.562	1.89
Ce	0.365	0.596	1.63
$\alpha$ -CO	0.251	0.407	1.62
Gd	0.364	0.578	1.59
He (2K)	0.357	0.583	1.63
La	0.375	0.607	1.62
Mg	0.321	0.521	1.62
Pr	0.367	0.592	1.61
Zn	0.266	0.495	1.86
Zr	0.323	0.515	1.59



***ABABAB***

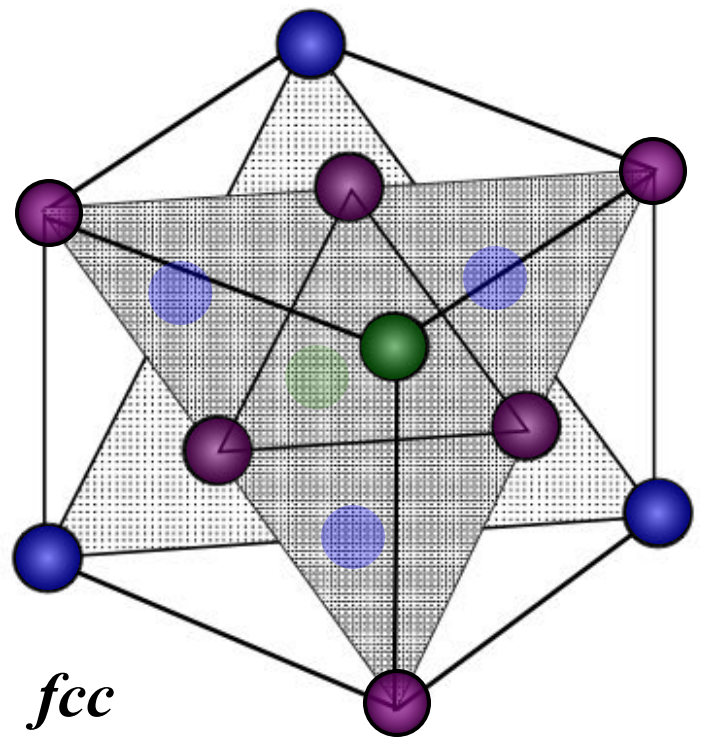
0      0      0  
1/3    2/3    1/2





*ABCABC*

*Kubisch dichteste  
Kugelpackung (CCP)*



*fcc*

**0      0      0**  
**1/2    0      1/2**

**& zyklisch**