

Week 5 Worksheet

Symmetries!

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Exercise 1. In this problem, you will construct the 2×2 matrix corresponding to a finite rotation which places the \hat{z} axis along an arbitrary direction \hat{r} .

- A rotation can be specified by the Euler angles (α, β, γ) , or by (θ, φ) . The Euler angles represent first a rotation about \hat{z} by an angle α , then a rotation *about the new* y -axis by an angle β , and then a rotation about the *new* z -axis again. Convince yourself that this works.
- Now, suppose given a rotation specified by the Euler angles (α, β, γ) . This is given in quantum mechanics by the matrix

$$e^{-i\gamma S_{z'}/\hbar} e^{-i\beta S_u/\hbar} e^{-i\alpha S_z/\hbar},$$

where the u -axis is the new y -axis after rotating about z , and the z' -axis is the new z -axis after rotating about \hat{z} and \hat{u} . Show that this is the same matrix as

$$e^{-i\alpha S_z/\hbar} e^{-i\beta S_y/\hbar} e^{-i\gamma S_z/\hbar}.$$

Hint: Denoting a rotation about the axis r by an angle ζ as $R_r(\zeta)$, we have that $S_u = R_z(\alpha) S_y R_z(-\alpha) = e^{-i\alpha S_z/\hbar} S_y e^{i\alpha S_z/\hbar}$. Now, try to write a similar expression for $R_{z'}(\gamma) = e^{-i\gamma S_{z'}/\hbar}$.

- Use part (b) with $S_i = \frac{\hbar}{2} \sigma_i$ to calculate the rotation matrix corresponding to placing the \hat{z} axis along \hat{r} , where \hat{r} is specified by the two angles (θ, φ) .
Hints: The idea is to Taylor expand each exponential. Think about a simple expression for σ_i^n , where σ_i is the Pauli matrix you need. Finally, one of the results you should get along the way is

$$e^{-i\beta \sigma_y/2} = \cos(\beta/2) \mathbb{1} - i \sigma_y \sin(\beta/2).$$

- Calculate the matrix corresponding to a rotation by π about \hat{x} .
- Calculate the matrix corresponding to a 2π rotation about \hat{z} . Comment on the answer.

Exercise 2. Another symmetry is called **dilation** symmetry. Dilations are given by the transformation $\mathbf{x} \rightarrow \mathbf{x}' = e^c \mathbf{x}$, where $c \in \mathbb{R}$. Call its generator D , so that e^{-icD} is the corresponding unitary operator.

Remark. In conformal field theory, the convention is to absorb the factor of $-i$ into D , so that e^{cD} is the dilation operator.

- a) Show that the *infinitesimal* transformation

$$e^{i\mathbf{a}\cdot\mathbf{p}} e^{icD} e^{-i\mathbf{a}\cdot\mathbf{p}} e^{-icD}$$

is given by $\mathbb{1} - ic\mathbf{a} \cdot [D, \mathbf{p}]$.

- b) Calculate $[D, \mathbf{p}]$.