

Exercise walk-through

35.1

Partition derivatives, energy fluctuations and heat capacity

GRE · GRE Subject Test · GRE Physics

35.1 Partition derivatives, energy fluctuations and heat capacity

Name: _____ Class: _____ Date: _____

Total: 11 marks

KEY WORDS energy fluctuation • Helmholtz free energy

Objective

Obtain canonical mean energy and free energy from a fixed energy spectrum; Relate energy variance to constant-volume heat capacity with fixed-spectrum conditions; Evaluate entropy and low/high-temperature limits for an original finite-level model. Original public practice; not an ETS paper.

1 Key knowledge and worked examples

Canonical $\beta=1/(kBT)$, $Z=\sum g_i e^{(-\beta E_i)}$, $U=-\partial \ln Z / \partial \beta$. Hold the energy spectrum fixed during derivatives; independent distinguishable subsystems have $Z_{\text{total}}=z^N$.

$F=-kBT \ln Z$ and $S=kB(\ln Z + \beta U)$. A constant common energy offset shifts U/F but

preserves probabilities, S and C. Mean energy and heat capacity have different units.

$\text{Var}(E) = \partial^2 \ln Z / \partial \beta^2$. With fixed spectrum at fixed N,V, $C_V = \text{Var}(E) / (k_B T^2)$, or C_V / k_B . Independent variances add; relative fluctuations decrease for large N.

For nondegenerate levels 0, Δ , $x = \Delta / (k_B T)$: $p_{\text{exc}} = 1 / (1 + e^x)$, $u = \Delta p_{\text{exc}}$, $C / k_B = x^2 e^x / (1 + e^x)^2$. C vanishes at both temperature extremes; S tends from zero to $k_B \ln 2$.

■ **Worked method**

Hold the two energy levels 0 and Delta fixed when differentiating the partition function

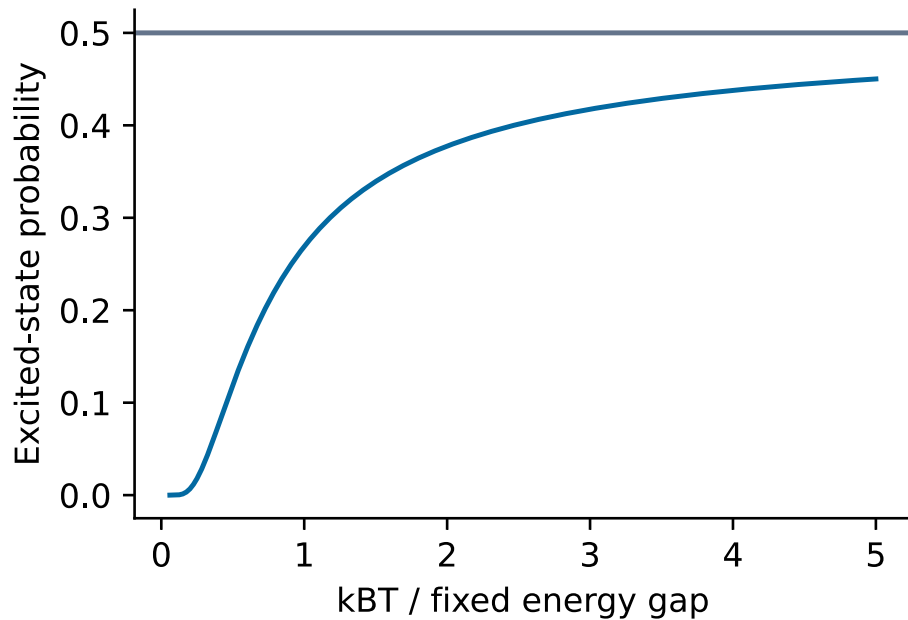
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$$Z = 1 + e^{-\beta \Delta}, \quad U = -\partial_\beta \ln Z = \frac{\Delta}{1 + e^{\beta \Delta}}.$$

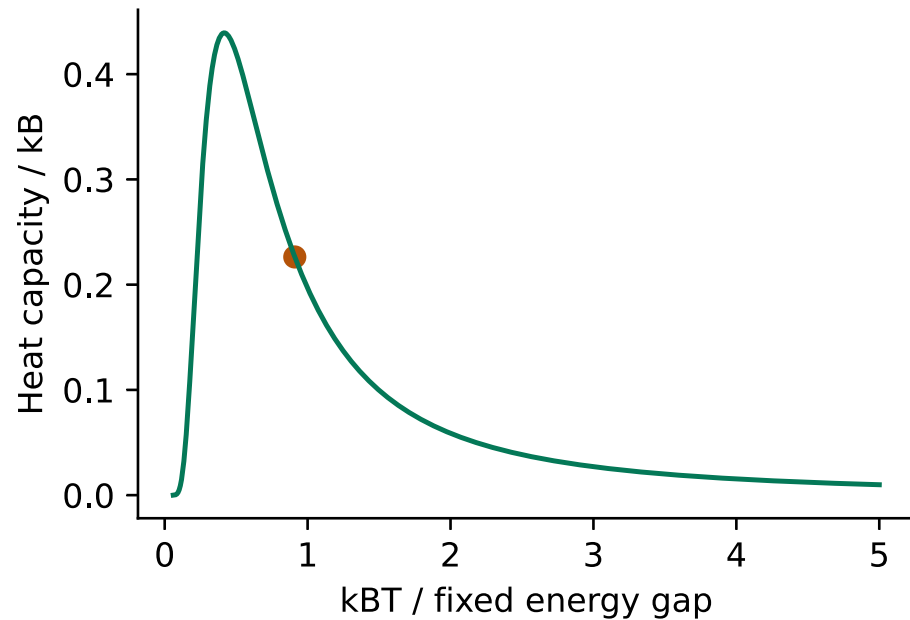
$$\text{Var}(E) = \partial_\beta^2 \ln Z = \frac{\Delta^2 e^{\beta \Delta}}{(1 + e^{\beta \Delta})^2}, \quad C_V = \text{Var}(E) / (k_B T^2).$$

At $\beta\Delta = \ln 3$, excited probability is $1/4$, mean energy $\Delta/4$, variance $3\Delta^2/16$ and $C_V/k_B = 3(\ln 3)^2/16 = 0.2263$. Degeneracy, if present, belongs in Z before differentiation.

Two nondegenerate levels
Excited probability saturates



Finite-level heat capacity
Low and high $T \rightarrow 0$



Exercise 2.1

2.1 Two nondegenerate levels have energies 0 and fixed Δ . At $\Delta/(kBT)=\ln 4$, excited probability is: [1]

- A. $1/4$
- B. $1/5$
- C. $4/5$
- D. $\ln 4$
- E. $1/2$

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- D. $\ln 4$
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2.1 Answer: B. $p_{\text{exc}}=1/(1+e^x)=1/(1+4)=1/5$.

Compare the rejected options: $1/4$; $4/5$; $\ln 4$; $1/2$. Use the stated model and conditions.

Exercises 2.2·2.3

2.2 A constant temperature-independent energy ε is added to every state. Which quantity stays unchanged? [1]

- A. Mean energy U
- B. Free energy F
- C. Entropy S
- D. Every energy eigenvalue
- E. Z itself

2.3 For equally probable energies 0 J and 2 J, energy variance is _____ J^2 . Show your relation and units. [2]

Exercises 2.2·2.3

2.2 A constant temperature-independent energy ε is added to every state. Which quantity stays unchanged? [1]

- A. Mean energy U
- B. Free energy F
- C. Entropy S
- D. Every energy eigenvalue
- E. Z itself

2.2 Answer: C. All probabilities are unchanged. U and F shift by ε and Z gains $e^{(-\beta\varepsilon)}$, but entropy and heat capacity remain the same.

Compare the rejected options: Mean energy U ; Free energy F ; Every energy eigenvalue; Z itself. Use the stated model and conditions.

2.3 For equally probable energies 0 J and 2 J, energy variance is _____ J^2 . Show your relation and units. [2]

2.3 1. Mean=1 J and second moment= $2 J^2$, so variance= $2-1^2=1 J^2$.

Exercises 2.4·3.1

2.4 Decide whether this claim is true. Justify it: For a fixed two-level nondegenerate spectrum, canonical heat capacity tends to zero as T becomes arbitrarily high. [2]

3.1 N independent distinguishable two-level units have ground energy zero and excited energy Δ with degeneracy g . Derive total U and C at fixed spectrum, and the high-temperature entropy. Check both heat-capacity limits. [5]

Exercises 2.4-3.1

2.4 Decide whether this claim is true. Justify it: For a fixed two-level nondegenerate spectrum, canonical heat capacity tends to zero as T becomes arbitrarily high. [2]

2.4 True. Energy approaches $\Delta/2$ and its temperature derivative tends to zero; a finite spectrum saturates.

3.1 N independent distinguishable two-level units have ground energy zero and excited energy Δ with degeneracy g . Derive total U and C at fixed spectrum, and the high-temperature entropy. Check both heat-capacity limits. [5]

3.1 Write $x = \beta\Delta$, $w = ge^{-x}$, $z = 1 + w$ and $Z = z^N$. $U = N\Delta w/(1 + w)$; $\text{Var}(E) = N\Delta^2 w/(1 + w)^2$. $C = Nk_B x^2 w/(1 + w)^2$. At high T every complete state is equally likely, so $S \rightarrow Nk_B \ln(1 + g)$. C tends to zero at low T and at high T . Award Z , U , variance/ C , entropy and limits. This is not a quantum-gas state-counting model.