

Problem 1. Let \mathcal{V} be a bounded region of space and let ϕ be an electrostatic potential that is source free in this region, so that $\nabla^2\phi = 0$ throughout \mathcal{V} . Suppose that for all \mathbf{x} lying on the boundary $S = \partial\mathcal{V}$, we have

$$\phi(\mathbf{x}) = -f(\mathbf{x})\hat{\mathbf{n}} \cdot \nabla\phi(\mathbf{x}), \quad (1)$$

where f is a positive function ($f(\mathbf{x}) \geq 0$) and $\hat{\mathbf{n}}$ is the outward pointing normal. Show that $\phi = 0$ throughout \mathcal{V} .

Solution. Maxwell's equations for electrostatics are

$$\nabla \cdot \mathbf{E} = 4\pi\rho, \quad (2)$$

$$\mathbf{E} = -\nabla\phi. \quad (3)$$

Substituting (3) into (1), we have

$$\phi(\mathbf{x}) = f(\mathbf{x})\hat{\mathbf{n}} \cdot \mathbf{E}(\mathbf{x}).$$

Then, taking the gradient of both sides,

$$\begin{aligned} \nabla\phi(\mathbf{x}) &= (\nabla f)(\hat{\mathbf{n}} \cdot \mathbf{E}) + f\nabla(\hat{\mathbf{n}} \cdot \mathbf{E}) \\ &= (\nabla f)(\hat{\mathbf{n}} \cdot \mathbf{E}) + f[(\hat{\mathbf{n}} \cdot \nabla)\mathbf{E} + (\mathbf{E} \cdot \nabla)\hat{\mathbf{n}} + \hat{\mathbf{n}} \times (\nabla \times \mathbf{E}) + \mathbf{E} \times (\nabla \times \hat{\mathbf{n}})] \\ &= (\nabla f)(\hat{\mathbf{n}} \cdot \mathbf{E}) + f(\hat{\mathbf{n}} \cdot \nabla)\mathbf{E} + f(\mathbf{E} \cdot \nabla)\hat{\mathbf{n}}, \end{aligned}$$

where we have used the fact that the curl of \mathbf{E} is zero (ME) and that the curl of the outward-pointing normal vector must also be zero for a closed boundary. Then taking the divergence of both sides,

$$\begin{aligned} \nabla^2\phi &= \nabla \cdot [(\nabla f)(\hat{\mathbf{n}} \cdot \mathbf{E}) + f(\hat{\mathbf{n}} \cdot \nabla)\mathbf{E} + f(\mathbf{E} \cdot \nabla)\hat{\mathbf{n}}] \\ &= 0 \end{aligned}$$

Problem 2. Consider the following classical model of a hydrogen atom. The proton is taken to be a uniformly charged ball of radius $R = 10 \times 10^{-13}$ cm and total charge $e = 4.8 \times 10^{-10}$ esu. The electron is taken to have charge density $\rho = -e|\psi|^2$, where ψ is the ground state wave function, $\psi(r) = e^{-r/a}/\sqrt{\pi a^3}$, with $a = \hbar/me^2 = 5.3 \times 10^{-9}$ cm.

2.a What is the electromagnetic energy of the proton? Compare this with the mass of the proton.

Solution. From elementary electrostatics, the electric field due to the proton is given by

$$\mathbf{E}(\mathbf{x}) = \begin{cases} \frac{er}{R^3} \hat{\mathbf{r}} & r < R, \\ \frac{e}{r^2} \hat{\mathbf{r}} & r > R, \end{cases}$$

where $\hat{\mathbf{r}}$ is the unit vector in the radial direction and r is the radial spherical coordinate. Then the electrostatic potential is given by

$$\phi(\mathbf{x}) = -\int_{\infty}^{\mathbf{r}} \mathbf{E} \cdot d\mathbf{r}' = \begin{cases} \frac{e}{2R^3}(3R^2 - r^2) & r < R, \\ \frac{e}{r} & r > R. \end{cases}$$

Let ρ_p be the charge density, which is given by

$$\rho(\mathbf{x}) = \begin{cases} \frac{3e}{4\pi R^3} & r < R, \\ 0 & r > R. \end{cases}$$

The total electrostatic energy is then given by Eq. (2.25) in the lecture notes. For the proton,

$$\begin{aligned} \mathcal{E} &= \frac{1}{2} \int \phi(\mathbf{x}) \rho_p(\mathbf{x}) d^3x \\ &= \frac{1}{2} \int_0^R \frac{3e}{4\pi R^3} \frac{e}{2R^3} (3R^2 - r^2) 4\pi r^2 dr = \frac{3e^2}{4R^6} \int_0^R (3R^2 r^2 - r^4) dr = \frac{3e^2}{4R^6} \left[R^2 r^3 - \frac{1}{5} r^5 \right]_0^R = \frac{3e^2}{4R^6} \left(R^5 - \frac{R^5}{5} \right) \\ &= \frac{3e^2}{5R}. \end{aligned}$$

Plugging in numbers, we have

$$\mathcal{E} = \frac{3(4.8 \times 10^{-10} \text{ esu})^2}{5(10 \times 10^{-13} \text{ cm})} = 1.4 \times 10^{-7} \text{ erg}.$$

The mass of the proton is $m_p = 1.673 \times 10^{-24} \text{ g}$, so the fraction of the proton mass due to electromagnetic energy is

$$\frac{\mathcal{E}}{m_p c^2} = \frac{1.4 \times 10^{-7} \text{ erg}}{(1.673 \times 10^{-24} \text{ g})(3.00 \times 10^{10} \text{ cm s}^{-1})^2} = 9 \times 10^{-5}.$$

This makes sense, because the proton's mass is primarily due to the strong interactions that bind its constituent quarks.

2.b What is the electromagnetic interaction energy of the proton and electron? (Since $R \ll a$, you may treat the proton as a point charge located at the origin.) Compare this with the ground state energy of hydrogen.

Solution. For this model, the electrostatic potential due to the proton is simply

$$\phi_p(\mathbf{x}) = \frac{e}{r}.$$

Let ρ_e denote the charge density of the electron. The electromagnetic interaction energy between two charged bodies is given by Eq. (2.30) in the course notes. For the proton and electron, this is

$$\begin{aligned} \mathcal{E}_{\text{int}} &= \int \rho_e \phi_p d^3x \\ &= \int_0^\infty -e \left| \frac{e^{-r/a}}{\sqrt{\pi a^3}} \right|^2 \frac{e}{r} 4\pi r^2 dr = -\frac{4e^2}{a^3} \int_0^\infty r e^{-2r/a} dr = -\frac{4e^2}{a^3} \frac{a^2}{4} \left[e^{-2r/a} \right]_0^\infty \\ &= -\frac{e^2}{a}. \end{aligned}$$

Plugging in numbers, we have

$$\mathcal{E}_{\text{int}} = -\frac{(4.8 \times 10^{-10} \text{ esu})^2}{5.3 \times 10^{-9} \text{ cm}} = -4.35 \times 10^{-11} \text{ erg}.$$

The ground state energy of hydrogen is $E = 13.6 \text{ eV}$, which is equivalent to $2.18 \times 10^{-11} \text{ erg}$. Then the fraction of the ground state energy due to the electromagnetic interaction is

$$\frac{\mathcal{E}_{\text{int}}}{E} = \frac{-4.35 \times 10^{-11} \text{ erg}}{2.18 \times 10^{-11} \text{ erg}} = -2,$$

so we see that the interaction energy has twice the magnitude of the ground state energy. This makes sense when we consider the virial theorem $T = -U/2$, where T is the electron's kinetic energy and U its potential energy. If we consider \mathcal{E}_{int} as the electron's potential energy, then its kinetic energy is equal in magnitude to the ground state energy of hydrogen.

Problem 3. The potential of an electrostatic dipole of dipole moment \mathbf{p} located at \mathbf{x}' is given by

$$\phi(\mathbf{x}) = \frac{\mathbf{p} \cdot (\mathbf{x} - \mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|^3}.$$

Suppose a dipole \mathbf{p}_1 is located at \mathbf{x}_1 and another dipole \mathbf{p}_2 is located at \mathbf{x}_2 .

3.a What is the electrostatic force on the second dipole?

Solution. Let Q_1, Q_2 be the charges of the dipoles and let $\mathbf{d}_1, \mathbf{d}_2$ be their displacement vectors, so $\mathbf{p}_1 = Q_1 \mathbf{d}_1$ and $\mathbf{p}_2 = Q_2 \mathbf{d}_2$. Let $\mathbf{r} = \mathbf{x}_2 - \mathbf{x}_1$ and assume $d_1, d_2 \ll r$. Let ϕ_1 be the potential of \mathbf{p}_1 ; that is,

$$\phi_1(\mathbf{x}) = \frac{\mathbf{p}_1 \cdot (\mathbf{x} - \mathbf{x}_1)}{|\mathbf{x} - \mathbf{x}_1|^3}. \quad (4)$$

The potential energy of \mathbf{p}_2 due to the field of \mathbf{p}_1 is then

$$\begin{aligned} U &= Q_2 \phi_1(\mathbf{r}) - Q_2 \phi_1(\mathbf{r} - \mathbf{d}_2) \\ &= Q_2 \left(\frac{\mathbf{p}_1 \cdot \mathbf{r}}{r^3} - \frac{\mathbf{p}_1 \cdot (\mathbf{r} - \mathbf{d}_2)}{|\mathbf{r} - \mathbf{d}_2|^3} \right) \approx Q_2 \left[\frac{\mathbf{p}_1 \cdot \mathbf{r}}{r^3} - \mathbf{p}_1 \cdot (\mathbf{r} - \mathbf{d}_2) \left(\frac{1}{r^3} + \frac{3\mathbf{d}_2 \cdot \mathbf{r}}{r^5} \right) \right] \\ &= Q_2 \left(\frac{\mathbf{p}_1 \cdot \mathbf{r}}{r^3} - \frac{\mathbf{p}_1 \cdot (\mathbf{r} - \mathbf{d}_2)}{r^3} + \frac{3\mathbf{p}_1 \cdot (\mathbf{r} - \mathbf{d}_2)(\mathbf{d}_2 \cdot \mathbf{r})}{r^5} \right) \approx Q_2 \left(\frac{\mathbf{p}_1 \cdot \mathbf{d}_2}{r^3} - \frac{3(\mathbf{p}_1 \cdot \mathbf{r})(\mathbf{d}_2 \cdot \mathbf{r})}{r^5} \right) \\ &= \left(\frac{\mathbf{p}_1 \cdot \mathbf{p}_2}{r^3} - \frac{3(\mathbf{p}_1 \cdot \mathbf{r})(\mathbf{p}_2 \cdot \mathbf{r})}{r^5} \right), \end{aligned} \quad (5)$$

where we have used the Taylor series expansion

$$\frac{1}{|\mathbf{r} - \mathbf{d}_2|^3} = \frac{1}{r^3} + \frac{3\mathbf{d}_2 \cdot \mathbf{r}}{r^5} + \dots$$

and neglected terms of $\mathcal{O}(d^2)$. The electrostatic force on the second dipole is then given by

$$\mathbf{F} = -\nabla U = -\nabla \left(\frac{\mathbf{p}_1 \cdot \mathbf{p}_2}{|\mathbf{x}_2 - \mathbf{x}_1|^3} - \frac{3[\mathbf{p}_1 \cdot (\mathbf{x}_2 - \mathbf{x}_1)][\mathbf{p}_2 \cdot (\mathbf{x}_2 - \mathbf{x}_1)]}{|\mathbf{x}_2 - \mathbf{x}_1|^5} \right).$$

3.b What is the electrostatic interaction energy of the two dipoles?

Solution. Equation (2.30) in the course notes gives the interaction energy of two charge distributions:

$$\mathcal{E}_{\text{int}} = \int \rho_2 \phi_1 d^3x, \quad (6)$$

where ρ_2 is the charge distribution of \mathbf{p}_2 and ϕ_1 is given by (4). Since \mathbf{p}_2 consists of two point charges,

$$\rho_2(\mathbf{x}) = Q_2[\delta(\mathbf{x}_2) - \delta(\mathbf{x}_2 - \mathbf{d}_2)],$$

where we are placing the positive end of \mathbf{p}_2 at \mathbf{x}_2 and the negative end at $\mathbf{x}_2 - \mathbf{d}_2$. Then (6) becomes

$$\mathcal{E}_{\text{int}} = Q_2 \int [\delta(\mathbf{x}_2) - \delta(\mathbf{x}_2 - \mathbf{d}_2)] \frac{\mathbf{p}_1 \cdot (\mathbf{x} - \mathbf{x}_1)}{|\mathbf{x} - \mathbf{x}_1|^3} d^3x = Q_2 \left(\frac{\mathbf{p}_1 \cdot (\mathbf{x}_2 - \mathbf{x}_1)}{|\mathbf{x}_2 - \mathbf{x}_1|^3} - \frac{\mathbf{p}_1 \cdot (\mathbf{x}_2 - \mathbf{d}_2 - \mathbf{x}_1)}{|\mathbf{x}_2 - \mathbf{d}_2 - \mathbf{x}_1|^3} \right) = U,$$

where U is the potential energy in (5). So the force on the second dipole may be found by $F = -\nabla \mathcal{E}_{\text{int}}$.

In writing up these solutions, I consulted Griffiths's *Introduction to Electrodynamics* and David Tong's lecture notes on electrodynamics.