## HYDROGEN ATOM - RADIAL FUNCTION EXAMPLES

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References: Griffiths, David J. (2005), Introduction to Quantum Mechanics, 2nd Edition; Pearson Education - Problem 4.10.

In solving the radial equation for the hydrogen atom, we used the following notation:

$$\psi_{nlm}(r,\theta,\phi) = R_{nl}(r)Y_l^m(\theta,\phi) \tag{0.1}$$

$$u_{nl}(\rho) = \rho^{l+1}e^{-\rho}v_{nl}(\rho) \tag{0.2}$$

$$u_{nl}(r) \equiv rR_{nl}(r) \tag{0.3}$$

$$\rho = \kappa r \tag{0.4}$$

$$\rho_0 = \frac{me^2}{2\pi\varepsilon_0\hbar^2\kappa} \tag{0.5}$$

$$\kappa = \frac{\sqrt{-2mE}}{\hbar} \tag{0.6}$$

The solution was expressed as a series:

$$v_{nl}(\rho) = \sum_{j=0}^{\infty} c_j\rho^j \tag{0.7}$$

with the coefficients $c_j$ satisfying a recursion relation:

$$c_{j+1} = \frac{2(j+l+1)-\rho_0}{(j+1)(j+2(l+1))}c_j \tag{0.8}$$

The series must terminate by requiring $\rho_0 = 2n$, and the initial constant $c_0$ is determined by normalization. This condition gives the quantization of energy, since from above

$$\kappa = \frac{me^2}{2\pi\varepsilon_0\hbar^2\rho_0} \tag{0.9}$$

$$= \frac{me^2}{4\pi\varepsilon_0\hbar^2 n} \tag{0.10}$$

Thus the original radial function is given by

$$R_{nl}(r) = \frac{1}{r}u_{nl}(r) \tag{0.11}$$

$$= \frac{1}{r}\rho^{l+1}e^{-\rho}v_{nl}(\rho) \tag{0.12}$$

As an example, for $l=0$, $n=3$ the recursion formula is

$$c_{j+1} = \frac{2(j-2)}{(j+1)(j+2)}c_j \tag{0.13}$$

so $c_1 = -2c_0$, $c_2 = 2c_0/3$ and all higher coefficients are zero.

The radial wave function is, from above:

$$R_{30}(r) = \frac{1}{r}\rho e^{-\rho}c_0(1-2\rho+2\rho^2/3) \tag{0.14}$$

$$= \frac{1}{3a}e^{-r/3a}c_0\left(1-\frac{2r}{3a}+\frac{2r^2}{27a^2}\right) \tag{0.15}$$

where $a$ is the Bohr radius:

$$a = \frac{4\pi\varepsilon_0\hbar^2}{me^2} \tag{0.16}$$

$$\kappa = \frac{1}{an} \tag{0.17}$$

$$\rho = \frac{r}{an} \tag{0.18}$$

We can find $c_0$ by normalizing the function. Since we are dealing with the radial function (the angular parts of the wave function are included in the spherical harmonic $Y_l^m$), the normalization integral is

$$\int_0^\infty r^2\left|R_{nl}(r)\right|^2 dr = 1 \tag{0.19}$$

Working out the integral (using software), we get

$$c_0 = \frac{2}{\sqrt{3a}} \tag{0.20}$$

For $l=1$, $n=3$ the recursion formula is

$$c_{j+1} = \frac{2(j-1)}{(j+1)(j+4)}c_j \tag{0.21}$$

so $c_1 = -c_0/2$, and all higher coefficients are zero.

The radial wave function is:

$$R_{31}(r) = \frac{1}{r}\rho^2 e^{-\rho} c_0 (1-\rho/2) \tag{0.22}$$

$$= \frac{r}{9a^2} e^{-r/3a} c_0 \left(1 - \frac{r}{6a}\right) \tag{0.23}$$

Normalizing gives

$$c_0 = \frac{4}{3}\sqrt{\frac{2}{3a}} \tag{0.24}$$

For $l=2$, $n=3$ the recursion formula is

$$c_{j+1} = \frac{2j}{(j+1)(j+6)} c_j \tag{0.25}$$

so and all coefficients above $c_0$ are zero.

The radial wave function is:

$$R_{32}(r) = \frac{1}{r}\rho^3 e^{-\rho} c_0 \tag{0.26}$$

$$= \frac{r^2}{27a^3} e^{-r/3a} c_0 \tag{0.27}$$

Normalizing gives

$$c_0 = \frac{2}{3}\sqrt{\frac{2}{15a}} \tag{0.28}$$

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