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A potential model for alpha decay

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We calculate the half-life and energy of alpha decay using a simple potential model consisting of the sum of the electrostatic Coulomb potential plus a Woods–Saxon form to represent the alpha-nucleus strong interaction. The calculation extends the standard treatment of alpha decay and gives students experience in fitting a theoretical model to experimental data. © *2010 American Association of Physics Teachers.*

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I. INTRODUCTION

Alpha decay is discussed in all undergraduate modern physics and introductory quantum mechanics courses, usually as the first example of tunneling in quantum systems. It has the historical significance of being one of the first tests of the nonrelativistic Schrödinger equation.[1] In this article, we present an extension of the textbook treatment of alpha decay to the modeling of experimental data: The calculation of the half-life τ and the energy of the emitted alpha particle E_α using an α-nucleus potential.

The use of computers has made it possible for undergraduate students to obtain numerical solutions to complicated mathematical problems and, in particular, to perform modeling of real data. By tackling a research-type problem, students experience the difficulty of reconciling theory with experiment.[2]

The quantitative analysis of alpha decay in undergraduate texts consists of treating the problem as barrier penetration in one dimension.[3] It is shown that the decay constant $\lambda = \ln 2/\tau$ varies approximately as $e^{-E_\alpha^{-1/2}}$. Some textbooks include a graph of $\log \lambda$ versus $E_\alpha^{-1/2}$ for a wide range of isotopes that undergo alpha decay.[3] The linear plot supports the barrier penetration model and the alpha-nucleus potential used in the calculation. In more advanced courses, a similar approach is done using the WKB approximation.[4]

In this article, we discuss a numerical calculation of τ and E_α for the even isotopes of uranium using a potential model for the interaction. The parameters of the potential are varied to fit the experimental data. To do this calculation, we will need to consider some details of alpha decay that are not part of the standard textbook treatment, such as the value of the radial quantum number of the decaying state, reasonable values for the size and strength of the potential, and the probability that neutrons and protons cluster to form an alpha particle in the decaying state. We start by describing the potential model and the methods used in calculating E_α. Then the more difficult calculation of the half-life is presented. This article is structured so as to provide a systematic analysis that can done by undergraduate physics majors.

II. POTENTIAL MODEL

For spin zero nuclei, the interaction between an alpha particle and the nucleus can be modeled by a spherically symmetric potential, $V(r) = V_{\text{em}} + V_{\text{strong}}$, where V_{em} is the electrostatic contribution and V_{strong} represents the strong interaction. The electrostatic contribution is taken to be the potential energy between a point particle of charge $2e$ and a uniformly charged sphere of radius w with total charge of $(Z-2)e$,

$$V_{\text{em}} = \begin{cases} 2(Z-2)e^2 \dfrac{3w^2 - r^2}{2w^3} & (r \le w) \\ \dfrac{2(Z-2)e^2}{r} & (r > w), \end{cases} \tag{1}$$

where w is the effective radius and Z is the atomic number of the nucleus. For the strong interaction, we use the Woods–Saxon form,[5] which is a common choice for the nucleon-nucleus potential,

$$V_{\text{strong}}(r) = \frac{V_0}{e^{(r-w)/a} + 1}, \tag{2}$$

where a is the "surface thickness." For the uranium isotopes, we fix the parameter a to be 0.8 fm. With a fixed, the potential $V(r)$ has two free parameters, V_0 and w, which can be adjusted so that the calculated values of E_α and τ agree with experiment.

There are two important radii which satisfy $V(r) = E_\alpha$. These are the radius r_1 where the "tunnel" begins and the radius r_2 where the tunnel ends: $V(r_1) = V(r_2) = E_\alpha$ with $r_1 < r_2$.

III. SOLVING THE SCHRÖDINGER EQUATION

To solve for the energies of the bound alpha particle states, we use the Schrödinger equation with the potential $V(r)$. We will also show that the energy of the quasibound decaying state of the alpha particle can be determined using the same method. We consider alpha decay transitions where the initial and final nuclear spins are zero, $J_i = J_f = 0$, and the decay takes place in the $\ell = 0$ channel. With the usual substitution $R(r) = u(r)/r$ for the radial coordinate, the Schrödinger equation becomes

$$-\frac{\hbar^2}{2m}\frac{d^2u(r)}{dr^2} + V(r)u(r) = Eu(r) \tag{3}$$

for $\ell = 0$. Because $R(0)$ is finite, $u(r=0) = 0$. To solve Eq. (3) numerically, we employ a simple finite difference approximation for the second derivative,[6]

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Table I. Experimental data for the even uranium isotopes. The width Γ (MeV) is related to the half-life τ(s) as $\Gamma=\ln(2)\hbar/\tau$.

Isotope	E_α	$\tau_{\exp}$	$\Gamma_{\exp}$
U^{238}	4.27	1.41×10^{17}	3.23×10^{-39}
U^{236}	4.57	7.39×10^{14}	6.21×10^{-37}
U^{234}	4.86	7.73×10^{12}	5.94×10^{-35}
U^{232}	5.41	2.17×10^{9}	2.16×10^{-31}
U^{230}	5.99	1.80×10^{6}	2.55×10^{-28}
U^{228}	6.80	3.28×10^{4}	1.40×10^{-26}
U^{226}	7.72	3.5×10^{-1}	1.3×10^{-21}
U^{224}	8.62	9×10^{-4}	5×10^{-19}
U^{222}	9.50	1×10^{-6}	5×10^{-16}

$$u[i+1]=2u[i]-u[i-1]+\Delta^2\frac{2m}{\hbar^2}(V[i]-E)u[i], \tag{4}$$

where $r[i]$, $u[i]$, and $V[i]$ are arrays for r, $u(r)$, and $V(r)$ with i an integer: $r[i]=i\Delta$, $u[i]=u(r[i])$, and $V[i]=V(r[i])$. The step size Δ is taken to be 0.01 fm. To solve Eq. (4) for a particular energy, we set $u[0]=0$ and $u[1]=1$. We can calculate $u[i]$ for arbitrary i by iteration because $u[i+1]$ is expressed in terms of $u[i]$ and $u[i-1]$ in Eq. (4).

The energy of a bound state alpha particle $E_\alpha<0$ can be calculated using the shooting method.[6] For $E_\alpha<0$, $u(r\to\infty)\to0$. We start with an energy E_0 slightly greater than V_0 and iterate Eq. (4) out to a radius r_0, where $r_0\gg r_1$. The value of $u(r_0)\equiv u_E$ is saved. Then the energy is incremented by ΔE and Eq. (4) is iterated again out to r_0. The new value of $u(r_0)\equiv u_{E+\Delta E}$ is compared to u_E. If the product $u_E u_{E+\Delta E}>0$, the process is repeated with the same value of ΔE. If $u_E u_{E+\Delta E}<0$, we know that E_α is between E and $E+\Delta E$ because $u(r_0)$ has changed sign. The process is continued with a value of ΔE equal to $\Delta E=-\Delta E/2$. As this energy stepping process is repeated, the energy converges to the value of E for which $|u(r_0)|$ has a minimum.

We can use this same method to find energies $E_\alpha>0$ for quasibound states. For a given energy $E>0$, the function $u(r\to\infty)$ equals the Coulomb wave function for $\ell=0$ shifted in phase due to the strong interaction. At the energy of the quasibound state E_α, the strong phase shift, which is the complete phase shift minus the Coulomb phase shift, equals $\pi/2$. In alpha-nucleus scattering, E_α is referred to as a resonance because the scattering phase shift is $\pi/2$. The width Γ of the resonance is determined by calculating the strong phase shift through the resonance energy. The strong phase shift is $\pi/4$ at the energy $E_\alpha-\Gamma/2$ and $3\pi/4$ at the energy $E_\alpha+\Gamma/2$. In terms of Γ, the half-life of the decaying quasibound state is given by $\tau=(\ln 2)\hbar/\Gamma$. The difficulty in determining E_α and τ by calculating the strong phase shift is that for a long half-life the width is very small compared to E_α.

If we use long double precision (C syntax) in standard 64 bit compilers, we can obtain a precision of 17 decimal places. Because the energies for alpha decay are a few MeV, the energy resolution using long double precision will be 10^{-17} times a few MeV. So we can expect Eq. (4) to have a precision of $\approx10^{-17}$ MeV for the energy E_α.

In Table I we list the alpha decay properties of the even isotopes of uranium. With a precision of 17 decimal places, only the half-life of U^{222} can be calculated by examining the phase shift through resonance. However, at the resonance energy E_α, the ratio $u(r_2)/u(r_1)$ is a minimum,[7] with the value of this ratio being as small as 10^{-20}. Thus, we can determine the resonance energy E_α by using the boundary condition that $u(r_2)$ is a minimum. In practice, we do not need to iterate out as far as r_2. We can iterate Eq. (4) out to a value of r_0 inside the tunnel between r_1 and r_2, which is appropriate for the desired accuracy of E_α. For the uranium series, a value of r_0 of 20 fm gives an accuracy of E_α of 10^{-17} MeV. This shooting method of calculating E_α for the quasibound states of the Schrödinger equation gives a value that is more accurate than the measured value.

Table II. The first quasibound alpha particle energy E_α in terms of the radial quantum number n for orbital angular momentum $\ell=0$. V_0 is the potential strength for the Woods–Saxon potential. A value of $w=8$ fm was used.

n	V_0 (MeV)	E_α (MeV)
2	−45.2	3.7
3	−49.2	3.9
4	−53.4	5.1
5	−59.2	6.2
6	−66.3	7.1
7	−74.9	7.9
8	−84.7	8.6
9	−95.8	9.2
10	−108.2	9.8

IV. RADIAL QUANTUM NUMBER AND ENERGY CALCULATION

An important consideration for the alpha decay calculation is the approximate strength of V_0 in Eq. (2), which determines the radial quantum number n of the quasibound $\ell=0$ state. As the magnitude of V_0 is increased, more bound states can be fitted into the well. The energy E_α of the decaying state is greater than zero, and we assume that the decaying state is the first state with energy greater than zero. The values of E_α for the uranium isotopes are listed in Table I. The energy difference between the last bound state and the first quasibound state must be at least E_α. For U^{222}, the difference in adjacent energy states must be greater than 9.5 MeV.

A crude estimate of the radial quantum number for the alpha particle in this nucleus can be found using a one-dimensional infinite square well. For a well radius of $a=8$ fm, the energy levels of the infinite square well are $E_n=(\hbar^2\pi^2/(2ma^2))n^2\approx0.8n^2$ MeV. If we equate the difference in adjacent levels to 9.5 MeV, $0.8(n^2-(n-1)^2)=9.5$, we obtain $n\approx6$.

A more accurate estimate can be made using $V(r)=V_{\text{em}}+V_{\text{strong}}$. In Table II we list the results of solving the Schrödinger equation such that the state with radial quantum number n has positive energy and the $(n-1)$ level has an energy that is just below zero and bound. For this calculation, we used $w=8$ fm, which is a typical value for the uranium nucleus. From Table II, we see that to have a value for $E_\alpha=9.5$ MeV for the first quasibound state of U^{222}, $|V_0|$ must be greater than 108 MeV. For $|V_0|=108$ MeV, the radial quantum number for the alpha particle is $n=10$. Because the

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difference in adjacent isotopes is only two neutrons, it is reasonable to assume that the radial quantum number is the same for the isotopes listed in Table II.

A value of $|V_0| \geq 108$ MeV is consistent with alpha-nucleus scattering data, which yields $V_0 \approx 120$ MeV.[8] This value corresponds to 30 MeV/nucleon, which is consistent with the nucleon-nucleus mean field potential.[6] For the rest of the calculations, we choose $n=10$ as the radial quantum number of the quasibound decaying alpha state. With n determined, V_0 can be adjusted to fit the experimental data of E_α.

V. HALF-LIFE CALCULATION

Although an accurate value for the energy of the alpha can be calculated from the Schrödinger equation, it is more challenging to calculate the half-life using the Schrödinger equation. The reason is that to determine τ we need to calculate the phase shift through the resonance. As mentioned in Sec. IV, standard compilers have a precision of 10^{-17}. From Table I, only U^{222} has a broad enough width to do this calculation numerically. However, we can obtain an approximate value for the half-life by following an approach covered in undergraduate quantum physics texts. The decay constant can be expressed in terms of the barrier penetration factor for the transmission probability times the number of times the alpha particle "hits" the barrier,[3,7]

$$\lambda_{BP} \equiv f_0 e^{-2\sigma}, \tag{5}$$

where f_0 is the frequency at which the particle hits the barrier and σ is the WKB transmission factor,

$$\sigma = \frac{1}{\hbar}\int_{r_1}^{r_2} \sqrt{2M(V(r)-E)}dr. \tag{6}$$

The frequency f_0 can be approximated as the classical speed, $p/m=\sqrt{2\epsilon/m}$, divided by the diameter of the nucleus, $2r_1$. We take the energy $\epsilon=E_\alpha-[V_0+V_{em}(0)]$, which is the approximate kinetic energy of the alpha particle inside the nucleus. With these substitutions, we have

$$\lambda_{BP} = \sqrt{\frac{2\epsilon}{mc^2}}\frac{c}{2r_1}e^{-2\sigma}. \tag{7}$$

Two corrections need to be made to compare τ_{BP} with experiment. We need to correct for the approximation made in using the barrier penetration approach, and we have assumed that there is exactly one alpha particle present in the decaying nuclear state at all times, an assumption that can be checked by comparing with experiment. Realistic calculations include the preformation factor P, which is the probability that an alpha particle is present in the nucleus at any particular time.[8] That is, P represents the fraction of the time two neutrons and two protons behave as a single alpha particle. We first estimate the accuracy of λ_{BP} and then compare our calculation with experiment.

The correct resonance width $\Gamma_{correct}$ can be determined by calculating the scattering phase shift $\delta(E)$ as a function of energy.[7] For narrow resonances, the phase shift has the energy dependence $\tan(\delta(E))=\Gamma_{correct}/2/(E_\alpha-E)$, where E_α is the resonance energy. The width Γ is related to the decay rate by $\Gamma=\hbar\lambda$. Using these relations, we determined the accuracy of the barrier penetration half-life calculation as follows. First, Eq. (4) and the shooting method were used to determine E_α to the maximum precision of the computer. Then we calculated $\Gamma_{BP}=\hbar\lambda_{BP}$. Next we calculated the scattering phase shift for energies near E_α. Because we assume that the resonance width is approximately Γ_{BP}, we calculate $\delta(E)$ for values of $E=E_\alpha \pm i\Gamma_{BP}/10$, where the integer i satisfies $|i| \leq 10$. By examining $\delta(E)$ through the resonance, we can determine $\Gamma_{correct}$ and compare it to Γ_{BP}.

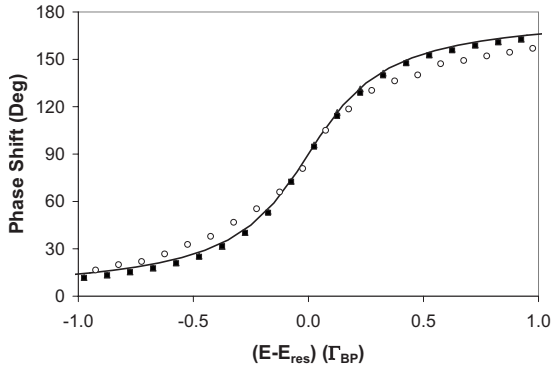

Fig. 1. Plot of the strong phase shift (in degrees) as a function of the difference in the energy of the alpha particle from the resonance energy E_{res}. The units in the horizontal axis are Γ_{BP}. That is, a value of ± 1 corresponds to alpha energies of $E_{res} \pm \Gamma_{BP}$. Results for three different potentials as discussed in the text are plotted. The curve corresponds to a phase shift that has $\Gamma=0.5\Gamma_{BP}$.

We show our results in Fig. 1. Note that for $E=E_{res}$, the phase shift is 90°. We have plotted the phase shift for three values of V_0. The solid dots and triangles, which overlap each other, are for $V_0=-113.4$ MeV and different values of w. The dots are for $E_\alpha=9.53$ MeV and the triangles are for $E_\alpha=10.2$ MeV. In both cases, $n=10$. The curve in Fig. 1 corresponds to a phase shift that has a width equal to $0.5\Gamma_{BP}$. To test the validity of the $\sqrt{\epsilon}$ factor in Eq. (6), we have also plotted the phase shift for a state with $V_0=-55$ MeV and $E_\alpha=9.72$ MeV in Fig. 1 (open circles). In this case, $n=5$ and the state is the second quasibound state with $E>0$. Even though ϵ is quite different than the other two cases, 16 MeV compared to 73 MeV, the width of the resonance is nearly the same fraction of Γ_{BP}. In this case, $\Gamma_{correct} \approx 0.7\Gamma_{BP}$. For the uranium isotopes, the value of ϵ is roughly the same because the magnitude of V_0 is large. Thus, we estimate that

$$\lambda_{correct} \approx 0.5\lambda_{BP} \approx 0.5\sqrt{\frac{2\epsilon}{mc^2}}\frac{c}{2r_1}e^{-2\sigma} \tag{8}$$

for the even isotopes of uranium. For the thorium isotopes, $\lambda_{correct} \approx 0.7\lambda_{BP}$.[8]

Before we fit the potential parameters to the data, we need to consider another aspect of the decay. What is the probability of having two neutrons and two protons cluster together to form an alpha particle in the quasibound state? This probability is referred to as the preformation factor P. Typical values for P for heavy nuclei are between 0.05 and 0.25.[8] The value of P is calculated from models for alpha formation or by comparing a calculation using a reliable potential, fitted to other alpha-nucleus properties, with experiments.

VI. FITTING THE DATA

At this stage of the analysis, there are three free parameters: P, w, and V_0. We can set $w=1.3A^{1/3}$ fm and determine

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Table III. Values of the potential parameters that fit the experimental data. Because the half-life is very sensitive to E_α and, consequently, V_0, we have listed V_0 to five significant figures. We have set A equal to 4 minus the atomic mass number because the alpha particle contains four nucleons.

Isotope (A)	$w=1.3A^{1/3}$ (fm)	V_0 (MeV)	E_α (calc) (MeV)	P
U^{238} (234)	8.01	−115.72	4.27	0.22
U^{236} (232)	7.99	−115.85	4.57	0.15
U^{234} (230)	7.96	−116.00	4.86	0.12
U^{232} (228)	7.94	−115.78	5.41	0.11
U^{230} (226)	7.92	−115.53	5.99	0.10
U^{228} (224)	7.89	−114.98	6.80	0.071
U^{226} (222)	7.87	−114.25	7.72	0.044
U^{224} (220)	7.85	−113.54	8.62	0.027

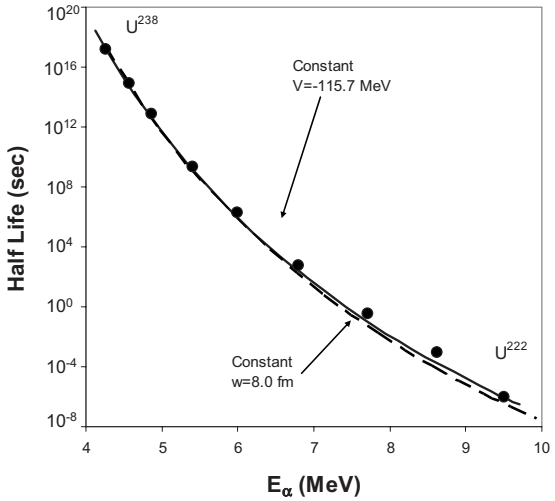

Fig. 2. Plot of the half-life versus the energy of the alpha particle. The solid line corresponds to $V_0=-115.7$ MeV with the parameter w varying from 8.0 to 7.7 fm. The dashed line has $w=8.0$ fm with $-116<V_0<-108$ MeV. The points are the experimental values for the even uranium isotopes: U^{238} to U^{222}.

P and V_0 by fitting the data. Another option is to set P equal to a value from the literature and determine w and V_0 from a fit to the data. We believe it is most useful for undergraduate students to take the former approach. It is a fairly good approximation to take $w=1.3A^{1/3}$ fm. With the range of the potential set, we can vary V_0 so that the state with a radial quantum number of $n=10$ has an energy E_α equal to the experimental value. With V_0 determined, λ_{BP} can be calculated and a good approximation to $\lambda_{correct}$ from Eq. (8) can be compared with the experimental value. To find P, we divide λ_{exp} by $\lambda_{correct}$: $P\equiv\lambda_{exp}/\lambda_{correct}$.

The results of the calculation are shown in Table III. It is interesting that the potential strength V_0 has roughly the same magnitude for the first six isotopes. Decreasing just the range parameter w increases E_α enough to match the experimental data. The preformation factor P changes from 0.22 to 0.027 as the atomic mass number decreases. These values are consistent with those in literature. In Ref. 9, $P=0.244$ for U^{238} and decreases monotonically to 0.05 for U^{224}. The reason for the decrease of P for the different isotopes of uranium is due to the closure properties of the nuclear shells.[9]

An interesting exercise is to plot the half-life τ of the quasibound state versus E_α. The shape of the graph is somewhat model independent because the shape of the Coulomb potential is the same for most nuclear models. We demonstrate this model independence in Fig. 2 where we have set P equal to its average value of $P=0.15$. In Fig. 2 the solid curve is for $V_0=-115.7$ MeV with w varied from 8.0 to 7.7 fm to produce values of E_α between 4.1 and 9.0 MeV. The dashed curve is for $w=8.0$ fm with the parameter V_0 varied from −116 to −108 MeV to produce values of E_α between 4.2 and 9.9 MeV. In Fig. 2 we have also plotted the data for the even uranium isotopes. The solid dots are the experimental values for the uranium series isotopes with even atomic numbers: U^{238} down to U^{222}.

In both cases, the calculations match the general trend of the data, with the constant V_0 curve being slightly better. The close fit to the data demonstrates the validity of the tunneling model and that the shape of the potential is fairly accurate. If we look at the details, the agreement is somewhat misleading because the half-life scale is logarithmic. If E_α and τ are fit at U^{238}, then at U^{226}, where $E_\alpha=7.715$ MeV, the half-life τ is low by a factor of 3.5 for constant V_0. For constant w, τ is low by a factor of 7 for U^{226}. Although the data suggest that V_0 varies less than the radius w for the uranium isotopes, it is not possible to find a satisfactory fit without changing P. In the model presented here, P needs to change by a factor of 5 from U^{238} to U^{222}, which is consistent with calculations in literature.[9]

VII. SUMMARY

Using a potential model to calculate the energy and half-life for the alpha decay of heavy nuclei is a practical undergraduate problem. The key to an accurate calculation of E_α is that the shooting method used to solve for bound states can also be used for quasibound states using a value of r_0 inside the tunnel. A determination of the half-life using long double precision is possible because the correction to the barrier penetration integral can be determined from states with half-lives shorter than a millisecond. The problem extends the usual textbook treatment of alpha decay by having the students perform a model calculation on nuclear data. The students solve for the radial quantum number of the decaying state and the preformation factor. Their results can be compared with more sophisticated treatments in literature. In this article, we treated the isotopes of uranium. The same methods can also be applied to the isotopes of other elements.

[1] See E. U. Condon, "Tunneling—How it all started," Am. J. Phys. **46** (4), 319–323 (1978) and references therein for an interesting historical account of tunneling in quantum mechanics.

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Ice Bomb. Water, when it goes through the transition from the liquid to the solid phase, expands. The ice bomb, sold by Cenco in 1937 for sixty cents, demonstrates this with a bang. The bomb, about 7.5 cm in diameter, is filled with water that has been boiled to remove any dissolved gases, sealed with the screw plug, and placed in a freezing mixture. Eventually the expanding ice is too much for the casing and it explodes. Presumably this is done outside with the students at a safe distance. This example, in the Greenslade Collection, is unused! (Photograph and Notes by Thomas B. Greenslade, Jr., Kenyon College)

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