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Thermal Properties of Alpha Decay in Magnetic Field Medium

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ABSTRACT

An analytical study of alpha decay in the presence of an imposed magnetic field and some of its thermodynamic properties was considered. The study used the JWKB method to determine the allowed energy eigenvalues and mean lifetime of the decay process with the understanding that the two expressions will enable us to determine the impact of the imposed magnetic field and the select thermodynamic properties. The study reveals that the solution admits a discrete energy spectrum and the radial wave function decreases exponentially as the imposed magnetic field decreases and is square integrable with zero point energy and the presence of the imposed magnetic field, enhanced the decay rate of the particles as well as partially removed the degeneracy of the process. The four thermodynamic properties considered as shown in the graphs plotted also laid credence by enhancing the entropy and the Helmholtz free energy, while the internal energy and the specific heat at constant volume of the decay process, depreciated as the magnetic field increases as well as attainment of saturation point. Generally, the shape of the wave function plot confirmed the radioactive decay curve.

INTRODUCTION

The radioactive process is statistical, one cannot tell when a particular atom will disintegrate. Radioactivity can be natural or anthropogenic. However, this paper is primarily concerned with the former. Radioactivity is the spontaneous emission of radiation from an unstable nucleus or the spontaneous nuclear transformation that results in the formation of new elements. There are three types of decay, namely alpha decay, beta decay, and gamma decay. The different radioactive decay can also be distinguished by subjecting them to an imposed constant magnetic field, with the assumption that the induced magnetic field is neglected. This simple experiment reveals that the alpha decay deflects upward while the beta decay is downward and the gamma decay is not deflected. Alpha particle is a highly energetic helium nucleus that is emitted from the nucleus of a radioactive isotope when the neutron and proton ratio is low. It is a positively charged massive particle, consisting of an assembly of two protons and two neutrons.

A general radioactive alpha emission takes the form as follow Eq. (1).

$$ {}^{A}_{Z}D \rightarrow {}^{A-4}_{Z-2}F + {}^{4}_{2}He + Energy \tag{1}$$

where A is mass number of the radioactive element, Z is the atomic number, D is the parent element and F is the daughter element.

Generally, for an alpha decay or emission or transformation to occur, the conservation equation as shown in Eq. (2) must be satisfied.

$$E_d = (\mu_p - \mu_d - \mu_\alpha)x931.50\,\frac{MeV}{amu} \tag{2}$$

where E_d is the disintegration energy, μ_P is the mass of the parent nucleus, μ_d is the mass of the daughter nucleus and μ_α is the mass of the alpha particle.

The radioactive decay process and its products are useful in nuclear studies and medicine,

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mainly for both diagnostic and therapeutic purposes [1]. Alpha decay, which is a radioactive transformation, resulting in the formation of helium elements and energy, is essential in the study of nuclear chemistry, energy production, and chemical separation processes of tons of pitchblende [2].

Magnetic field presence in the universe is well known, therefore, its effect on virtually all human interactions and study cannot be overemphasized. McPatterson [3] reported that magnetic field is seriously considered for the control of heat generated in nuclear power plants. Several studies also reported the magnetic field effects on chemical and biological reactions [4,5]. The results are unanimous that magnetic fields alter the rate and yield of chemical reactions. Rogers [6] opined that product distribution, yield, and rate of chemical reactions are influenced by magnetic fields. Filip [7] reported that magnetic field disturbance is useful in the study of spin-orbit coupling in organic-inorganic hybrid perovskites. Studies such as [8,9] also made useful contributions to the effect of magnetic field in the alteration of the behavior of diatomic molecules and alpha decay. Ikhdair et al. [10] examined an analytical study of the effect of magnetic field and other parameters in non-relativistic molecular models and made useful deductions.

In 1933, Meissner discovered that a conductor when entering the superconductivity state in an external magnetic field will repel the latter outside it. Ni and Chen [11] reported that the superconductivity state of a given element or compound can be destroyed by gradually enhancing the external magnetic field. They further explained that when the imposed magnetic field (H) is greater than a critical magnetic field value (H_c) (H >H_c), the magnetic field pierces through it suddenly, and the superconductivity state is destroyed and turned into a normal state. Ghatak and Lokanathan [12] used the Jeffreys, Wentzel, Kramers, and Brillouin (JWKB) method to determine alpha decay, and the results when compared with experimental data showed remarkable difference in the mean lifetime of the decayed particles. However, they were quick to adopt the expression of the mean lifetime of [13] and [14] whose equation is dependent on the emitted energy and the atomic number of the daughter nucleus and is a good fit for the experimental data. Ngiangia et al. [15] tackled the presence of an imposed magnetic field on alpha decay and the results showed that a remarkable difference is observed in the mean lifetime of the alpha decay elements considered. Though the centrifugal term in the radial Schrödinger wave equation was ignored, the approximate results showed the influence of the repulsive effect of the magnetic field. Palffy and Poprelzhenko [16], Stovbun et al. [17], Volpe [18], Tofani et al. [19], and Salimi et al. [20], all reported that magnetic fields alter or trigger chemical and biological processes. It is a common knowledge that thermodynamic properties are important in quantum analysis and nuclear studies [21]. Several works, describing the thermodynamic properties of parameters and potentials are abounded [22-27]. This present study incorporated the centrifugal term and in addition some thermodynamic properties, which are new, and an extension of the work of [15] and [28].

Review of JWKB method

The Phase - Integral method or the JWKB method to solutions in quantum mechanics is useful for approximate treatments of systems with slowly varying potentials, that is, potentials that remain almost constant over a region of the order of the de Broglie wavelength [28].

Consider the motion of a particle in a time-independent potential V(r), the Schrödinger equation or indeed any homogeneous second-order differential equation can be transformed into the expression Eq. (3).

$$\frac{d^2\varphi(r)}{dr^2} + k^2(r)\varphi(r) = 0 \tag{3}$$

where $k^2 = \frac{2\mu}{\hbar^2}(E - V(r))$ At the classical turning point as follows Eq. (4),

$$k^2 = 0 \quad r_1 = \beta_1, \quad r_2 = \beta_2 \tag{4}$$

The bound states for potential wells with no rigid walls, the quantization of the energy levels is given as follows Eq. (5).

$$\left(n + \frac{1}{2}\right)\pi = \int_{\beta_1}^{\beta_2} K(r)dr \tag{5}$$

n = 0, 1, 2, ………

For potential wells with one rigid wall, the quantization of the energy levels results to the following Eq. (6).

$$\left(n + \frac{3}{4}\right)\pi = \int_{\beta_1}^{\beta_2} k(r)dr \tag{6}$$

$$\left(n + \frac{3}{4}\right)\pi = \int_{\beta_1}^{\beta_2} k(r)\, dr$$

n = 0, 1, 2, ………

Also, for potential wells with two rigid walls, the quantization of the energy levels is stated as follows Eq. (7).

$$n\pi = \int_{\beta_1}^{\beta_2} k(r)dr \qquad (7)$$

n = 0, 1, 2, ………

In essence, if the particle is moving in a region where V(r) is constant, the solution of Eq. (1) is of the following form Eq. (8).

$$\varphi(r) = AExp \pm kr \qquad (8)$$

where A is a constant.
However, V(r) is slowly varying and the approximate solution to Eq. (1) is the following Eq. (9).

$$\varphi(r) = \frac{c}{\sqrt{k(r)}} Exp \int_{\beta_1}^{\beta_2} k(r)dr \qquad (9)$$

where C is a constant and can be determined by the normalization relation as follows Eq. (10).

$$\int_{-\infty}^{\infty} /\varphi(r)/^2 dr = 1 \qquad (10)$$

METHODOLOGY

To consider the effect of magnetic field potential for our study and for spherically symmetric potential V(r), the radial part of the wave function R(r) satisfies the Eq. (11).

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dR(r)}{dr}\right) + \frac{2\mu}{\hbar^2}\left[E + \frac{zZq^2}{4\pi\varepsilon_0 r} + \frac{qBm\hbar}{2\mu} - \frac{l(l+1)\hbar}{2\mu r^2}\right]R(r) = 0 \qquad (11)$$

where E is the energy, r is the radius of the nucleus, zq and Zq are the charges of the alpha particle and the daughter nucleus respectively, m is the magnetic quantum number, B is the magnetic induction, l is the angular quantum number, $\hbar$ is the Planck's constant divided by 2π, and μ is mass of alpha particle.

JWKB solutions for spherically symmetric potentials

To solve Eq. (11), the transformation of the following form is suggested.

$$u(r) = rR(r) \qquad (12)$$

Equation (12) is put into Eq. (11) and the resulting expression takes the form of Eq. (1), with Eq. (13).

$$\mathrm{k}^2 = \frac{2\mu}{\hbar^2}\left[E + \frac{zZq^2}{4\pi\varepsilon_0 r} + \frac{qBm\hbar}{2\mu} - \frac{l(l+1)\hbar}{2\mu r^2}\right]R(r) \qquad (13)$$

For simplicity, we set $\hbar = \mu = 1$ [29-32] and assume that z = 2 [12]. Then, Eq. (13) is reduced to Eq. (14).

$$K^2(r) = \left(2E + \frac{Zq^2}{\mu\varepsilon_0 r} + qBm - \frac{l(l+1)}{r^2}\right) \qquad (14)$$

The potential well has no rigid wall; therefore, following Eq. (5), the quantization relation is expressed as follows Eq. (15).

$$\left(n + \frac{1}{2}\right)\pi = \int_{r_1}^{r_2}\left(2E + \frac{Zq^2}{\mu\varepsilon_0} + qBm - \frac{l(l+1)}{r^2}\right)^{0.5} \qquad (15)$$

Equation (15) can be put in the following form.

$$\left(n + \frac{1}{2}\right)\pi = \sqrt{-(2E + qBm)}\int_{r_1}^{r_2}\frac{\sqrt{-r^2 + A_1 r + A_2}}{r}dr \qquad (16)$$

where $A_1 = \frac{Zq^2}{(2E+qBm)\pi\varepsilon_0}$, $\quad A_2 = \frac{l(l+1)}{(2E+qBm)}$

If r_1 and r_2 are the symmetric roots of the polynomial $-r^2 + A_1 r + A_2$, according to the standard integral by [33], the right-hand side of Eq. (16) can be written as follows Eq. (17).

$$\sqrt{-(2E + qBm)}\int_{r_1}^{r_2}\frac{\sqrt{(r - r_1)(r + r_2)}}{r}dr = \sqrt{-(2E + qBm)}\frac{\pi}{2}\left(\sqrt{r_2} - \sqrt{r_1}\right)^2 \qquad (17)$$

It therefore follows that Eq. (18).

$$2\left(n + \frac{1}{2}\right) = \sqrt{-(2E + qBm)}\left(r_2 + r_1 - 2\sqrt{r_2 r_1}\right) \qquad (18)$$

And it leads to the following Eq. (19).

$$2\left(n + \frac{1}{2}\right) = \sqrt{-(2E + qBm)}\left(\frac{Zq^2}{(2E+qBm)\pi\varepsilon_0} - 2\sqrt{\frac{-l(l+1)}{2E+qBm}}\right) \qquad (19)$$

By simplification, the allowed energy eigenvalues become the following Eq. (20).

$$E_{n.l} = \frac{-zq^2}{8(\pi\varepsilon_0)^2\left((l(l+1)) + \left(n+\frac{1}{2}\right)^2\right)} - 2qBm$$
$$n, l = 0,1,2,3 \qquad (20)$$

Following Eqs. (9,10,12), the radial part of the wave function can be written as follows Eq. (21).

$$R(r) = \frac{1}{\sqrt{(2E+qBm)r^2+\frac{Zq^2}{\mu\varepsilon_0}r-l(l+1)}} \qquad (21)$$

Mean lifetime of alpha decay

When the energy is bigger than the potential (E > V), the particle gets transmitted through a barrier. However, according to the theory of quantum mechanics, even if E < V, there exist finite probability of the particle tunneling through the barrier. This phenomenon, is entirely a quantum mechanical effect and field emission of electrons as well as of alpha particles from the nucleus are some of the examples.

To determine the lifetime of nuclei emitting alpha particles, the tunneling probability is given by Eq. (22).

$$T \approx Exp(-2J) \qquad (22)$$

where

$$J = \int_{r_1}^{r_2} \sqrt{-(2E+qBm) + \frac{Zq^2}{\mu\varepsilon_0 r} - \frac{l(l+1)}{r^2}}\, dr$$

r_2 represent the turning point and R the radius of the nucleus.

$$r_2 = \frac{\sqrt{\left(\frac{Zq^2}{\mu\varepsilon_0}\right)^2 - 4(qBm+2E)(-l(l+1)}}{-2l(l+1)}$$

Following Eq. (23),

$$J = \frac{\pi}{2}\sqrt{-(2E+qBm)\left(r_2 + R - 2\sqrt{r_2 R}\right)} \qquad (23)$$

The speed of the alpha particles inside the nucleus is approximately v, and then the rate of hitting the barrier is $\approx \frac{v}{R}$ .This implies that the probability per second of escape or the reciprocal of the mean lifetime is given as Eq. (24).

$$\frac{1}{\tau} \approx \frac{v}{R} Exp(-2J) \qquad (24)$$

Recall that $v = \sqrt{\frac{2E_d}{\mu}} \approx \sqrt{2E_d}$ and take the natural logarithm of Eq. (24), yields the following Eq. (25).

$$In\tau = -In\frac{\sqrt{2E_d}}{R} + 2J \qquad (25)$$

Using the numerical data as follows,

$\pi = 3.142$, $q = 1.602x10^{-19}C$,

$B = 0.5T, \varepsilon_0 = 8.854x10^{-12}F/m$

$$In\tau = -In5.403\sqrt{E_d}$$
$$+2\Big[-1.1x10^{-20}E\big(9.2x10^{-29}Z - 2.9x10^{-37}z$$
$$+ 6.4x10^{-20}\sqrt{E}\big) + 6.3x10^{-15}$$
$$- \sqrt{(-5.8x10^{-43}z) - 1.8x10^{-71}z + \left(4.4x10^{-34}\sqrt{E}\right)}\Big] \qquad (26)$$

The radioactive decay of polonium (Po) is given as follows:

$${}^{212}_{84}Po \rightarrow {}^{208}_{82}Pb + {}^{4}_{2}He(8.9MeV).$$

Thus Z = 82, E_d= 8.9MeV and $\tau = 0.0430s$, the experimental value [12] is $\approx 3x10^{-7}s$. Also, the radioactive decay of Uranium (U) is given as follows:

$${}^{238}_{92}U \rightarrow {}^{234}_{90}Pb + {}^{4}_{2}He(4.2MeV).$$

Thus Z = 90, E_d= 4.2MeV and $\tau = 0.0639s$, the experimental value [12] is $\approx 10^{17}s$. Similarly, the radioactive decay of Radium (Ra) is given as:

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He(2.4219MeV).$$

Thus Z = 86, E_d = 2.4219MeV and = $0.118929s$ $\tau = 0.118929s$, the experimental value is $-$ (not available). In the same manner, the radioactive decay of an isotope of Plutonium (Pu) is given as follows:

$${}^{239}_{94}PU \rightarrow {}^{235}_{92}U + {}^{4}_{2}He(5216MeV).$$

Thus Z = 92, E_d = 5.2164MeV and $\tau = 0.0810361s$, the experimental value is $-$ (not available).

Further, the theoretical work of [13] and [14] on alpha decay in the absence of magnetic field and which was described as in substantial agreement with experimental data is given as follows Eq. (27).

$$log_{10}\frac{1}{\tau} \approx (28.9 + 1.6\sqrt[3]{Z} - \frac{1.61Z}{\sqrt{E_d}} \quad (27)$$

The values of $\tau$for the alpha decay of ${}^{212}_{84}Po$ and ${}^{238}_{92}U$ are $\approx 10^{-15}$ and $\approx 10^{-10}s$, respectively.

Thermodynamic properties

According to [34], in a given microscopic or nuclear systems, its statistical physics nature makes it imperative to analyze some thermodynamic properties. To tackle some of the thermodynamic properties, a consideration of the ensemble of systems given by **t**he grand partition function is given as follows Eq. (28).

$$Z_{n,l} = \sum Exp\left(\frac{E_{n,l}}{K_B T}\right) \quad (28)$$

where K_B is the Boltzmann constant and T is the system temperature. Some of the thermodynamic properties to be considered include Helmholtz free energy F(T), internal energy U(T), entropy S(T), and specific heat at constant volume $C(T)$.

The Helmholtz free energy is given as follows Eq. (29).

$$F(T) = \frac{1}{T}InZ(T) = \sum_{n,l=0}^{\infty}\left[\left(\frac{-Zq^2}{8(\pi\varepsilon_0)^2\left(\left(n+\frac{1}{2}\right)^2 + l(l+1)\right)}\right) - 2qBm\right|\frac{1}{K_B T^2} \quad (29)$$

The internal energy also transform into the following Eq. (30).

$$U(T) = -\frac{\partial InZ(T)}{\partial T} = \sum_{n,l=0}^{\infty}\left[\left(\frac{-Zq^2}{8(\pi\varepsilon_0)^2\left(\left(n+\frac{1}{2}\right)^2 + l(l+1)\right)}\right) - 2qBm\right|\frac{1}{K_B T^2} \quad (30)$$

Similarly, the entropy takes the following form Eq. (31).

$$S(T) = -K_B\frac{\partial F}{\partial T} = \sum_{n,l=0}^{\infty}\left[\left(\frac{-Zq^2}{8(\pi\varepsilon_0)^2\left(\left(n+\frac{1}{2}\right)^2 + l(l+1)\right)}\right) - 2qBm\right|\frac{1}{K_B T^2} \quad (31)$$

And lastly, the specific heat at constant volume boils down to the following Eq. (32).

$$C_V(T) = K_B\frac{\partial U}{\partial T} = \sum_{n,l=0}^{\infty}\left[\left(\frac{Zq^2}{8(\pi\varepsilon_0)^2\left(\left(n+\frac{1}{2}\right)^2 + l(l+1)\right)}\right) + 2qBm\right|\frac{1}{T^2} \quad (32)$$

RESULTS AND DISCUSSION

Table 1. Energy (eV) of the alpha decay of U and Po in the presence of imposed magnetic field $q = 1.602 \times 10^{-16}, B = 0.5T, m = 0.5$.

n	l	En,l (Z=82)	En,l (Z=90)
0	1	1191.74201	-1295.264357
0	2	-484.3392634	-518.8467541
0	3	-307.4886288	-324.7423533
0	4	-285.8122971	-247.100593
1	1	-629.981038	-678.697437
1	2	-387.8752998	-412.9716264
1	3	-279.5648378	-294.09429
1	4	-226.0180926	-235.323472
2	1	-387.8752998	-412.9716264
2	2	-303.8792066	-320.781039
2	3	-261.3164352	-258.2682434
2	4	-211.483976	-219.3713929

The Mathematica 12.3 plot shows the relationship between the mean energy and the temperature for polonium decay with different values of the imposed magnetic field (Fig. 1).

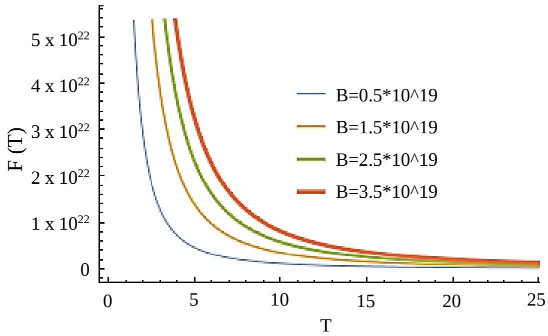

Fig. 1. Helmholtz free energy dependence on temperature with magnetic field varying for polonium decay.

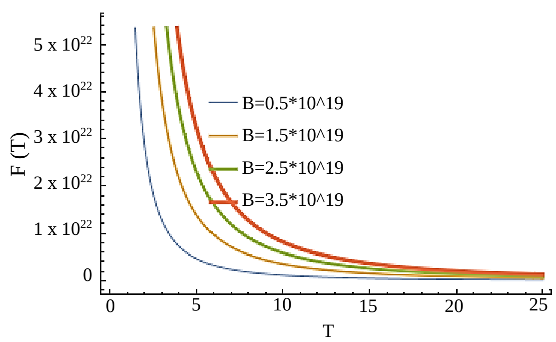

Fig. 2. Helmholtz free energy dependence on temperature with magnetic field varying for uranium decay.

The Mathematica 12.3 plot shows the relationship between the mean energy and the temperature for uranium decay with different values of the imposed magnetic field (Fig. 2).

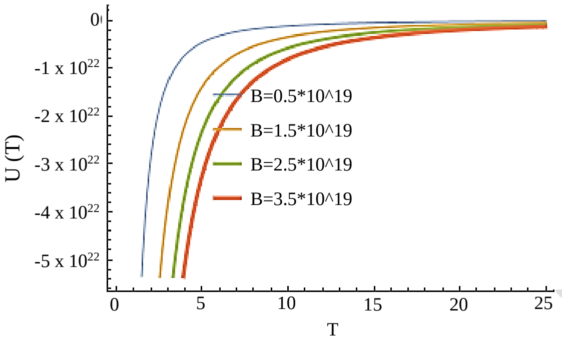

Fig. 3. Internal energy dependence on temperature with varying magnetic field for polonium decay.

The Mathematica 12.3 plot, shows the relationship between the internal energy and the temperature for polonium decay with different values of the imposed magnetic field (Fig. 3).

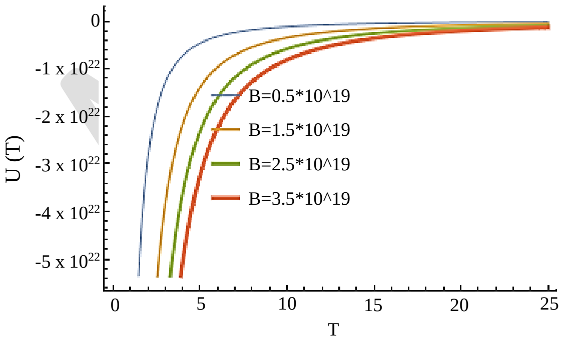

Fig. 4. Internal energy dependence on temperature with varying external magnetic field for uranium decay.

The Mathematica 12.3 plot shows the relationship between the internal energy and the temperature for uranium decay with different values of the imposed magnetic field (Fig. 4).

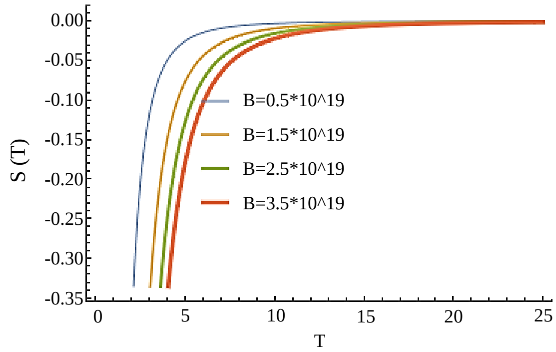

Fig. 5. Entropy dependence on temperature with varying magnetic field for polonium decay.

The Mathematica 12.3 plot shows the relationship between the entropy and the temperature for polonium decay with different values of the imposed magnetic field (Fig. 5).

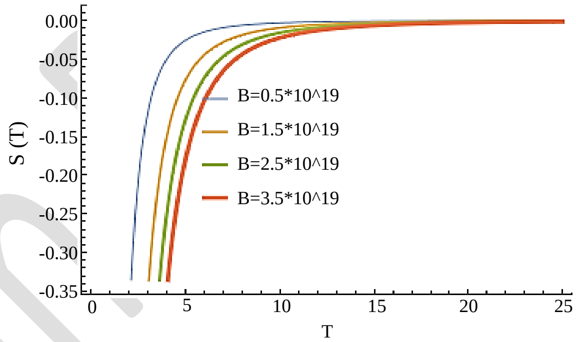

Fig. 6. Entropy dependence on temperature with varying magnetic field for uranium decay.

The Mathematica 12.3 plot shows the relationship between the entropy and the temperature for uranium decay with different values of the imposed magnetic field (Fig. 6).

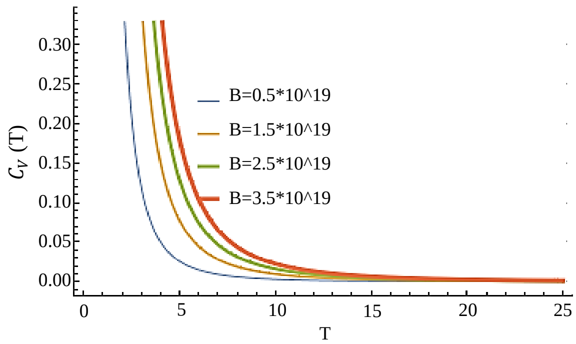

Fig. 7. Specific heat at constant volume dependence on temperature with magnetic field varying for polonium decay.

The Mathematica 12.3 plot shows the relationship between the specific heat at constant volume and the temperature for polonium decay with different values of the imposed magnetic field (Fig. 7).

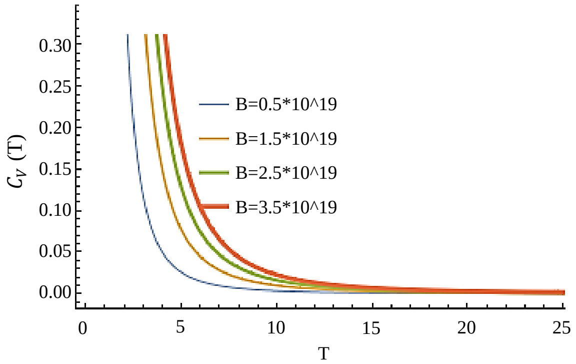

Fig. 8. Specific heat at constant volume dependence on temperature with magnetic field varying for uranium decay.

The Mathematica 12.3 plot, shows the relationship between the specific heat at constant volume and the temperature for uranium decay with different values of the imposed magnetic field (Fig. 8).

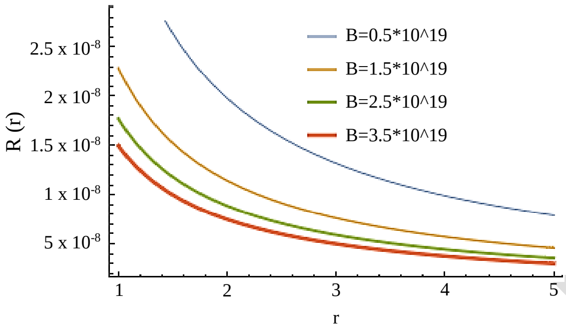

Fig. 9. Radial wave function dependence on radius of nucleus with magnetic field varying for polonium decay.

The plot shown is the radial wave function plotted against the radius of the nucleus of polonium decay for different values of the external magnetic field (Fig. 9).

Discussion

An analytical study of the repulsive influence of the magnetic field on the decay of alpha particles was examined. Analysis of Eq. (20) showed that the alpha decay in the vicinity of the imposed magnetic field admits a discrete energy spectrum. It is also shown that the radial wave function with a discrete energy level is square integrable with the presence of zero point energy. These observations are consistent with the works of [1,3].

Equations (26) and (27) reveal that in the alpha decay process, the character of the decayed species is described mainly by the atomic number and the energy released and the mean lifetime of the alpha particle is proportional to the energy released and the atomic number. Table 1 depicts the behavior of the energy of the transformed elements under consideration. It is observed that, as the orbital quantum and magnetic quantum numbers are increased in the presence of the external magnetic field, the energies eigenvalues of the alpha decay elements increases. Also, if we ignore the spin of the electron, it showed that degeneracy is partially removed owing to the exposure of the decay process to constant external magnetic field.

For instance, the following energy levels are still degenerate $E_{1,2} = E_{2,1}$. However, the appearance of degeneracy in some cases is bound state changed and possible. This observation is consistent with the study of hydrogen atom placed in a uniform magnetic field, which reveals that the degeneracy with respect to l remains and the atom's spherical symmetry is broken resulting in the equidistant splitting of the energy levels often referred to as the normal Zeeman effect [3]. The calculated value of the mean lifetime of the radioactive alpha decay is substantially different from the experimental values and that from Eq. (27) in which the magnetic field is absent.

The difference is expected because the presence of an imposed magnetic field altered the lifetime of the alpha decay thereby hastening the decay rate. It is observed that the higher the atomic number, the shorter the mean lifetime of the radioactive transformed element. This effect was also corroborated by [16], in which they stated that extreme electromagnetic fields accelerate the alpha decay nuclei. The work of [35] also corroborated it that the rate of deoxyribonucleic acid synthesis monotonously decreased with external magnetic field.

Equation (21) showed that as the magnetic field strength increases, the wave function becomes less bounded, which also explains that the deflection of alpha particle is quasi-proportional to the strength of the imposed magnetic field. This observation is in agreement with the work of [17]. A Similar observation was also reported by [18]. Figures 1-8 explained the behavior of some thermodynamic properties under the influence of varying external magnetic field. As the magnetic field strength increases, it results in corresponding increase in the Helmholtz free energy displayed in (Figs. 1 and 2) and the entropy seen in (Figs. 3 and 4) which is consistent with the work of [15] and emphasis was made on the agreement of the additive property of entropy, while a decrease is observed in the internal energy shown in (Figs. 5 and 6) and the specific heat at constant volume displayed also in (Figs. 7 and 8).

Similar observations have also been reported by [22-27] in the absence of the external magnetic field but were consistent with the work of [15] though the stability term was ignored. It is also established that the saturation point was reached as the external magnetic field was applied to the select thermodynamic functions. Finally, it is shown in Fig. 9 that an increase in the imposed magnetic field, results in an exponential decrease in the radial wave function, which conforms with the radioactive decay curve and confirms the report of the well-known concept including [1].

CONCLUSION

This theoretical work within the limits of reasonable approximation reveals that the decay rate of radioactive alpha particle is enhanced by the introduction of the external magnetic field into the vicinity of the decay process. Other studies cited including the experimental works, agreed with the observation that indeed the decay rate is faster than calculated values of the mean lifetime of the decayed nucleus. It implies that the magnetic field acts as a catalyst in the decay process. The thermodynamic properties of the new alpha decay also confirmed the additive property of entropy.

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AUTHOR CONTRIBUTION

Peter O. Nwabuzor and Alalibo T. Ngiangia: Conceived and designed the study, acquired, analyzed, and interpreted the data, and handled the review. Frimabo Jim - George: Handled the computational analysis, review, and editing.

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