Influence of plasma induced by radionuclide layer on the radar cross section of spherical objects (Postprint)

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Abstract

The influence of the α-decay radionuclide layer (the energy of α-particles are 5.45 MeV) on the radar cross section (RCS) of sphere objects was calculated under different radioactivities, frequencies, and sphere radii. When the sphere radius is smaller than 50 cm, the tendency of the electron densities of the plasma slab is to ascend first and then descend, and the typical maximum electron densities with a radioactivity of 10 Ci/cm2 raises from 7.02\$×1010*to*1.76×\$1011 when the sphere radii increases from 10 to 300 cm. The average data of a normalized RCS of a sphere with radius of 12.5 cm, which is coated with a radionuclide layer with different radioactivities are -0.35, -0.50, -0.79 and -1.13 dB when the radioactivity is, per-mode=symbol 1, 2, 5 and 10 Ci/cm2, respectively.

Full Text

Preamble

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Abstract: The influence of an α-decay radionuclide layer (α-particle energy of 5.45 MeV) on the radar cross section (RCS) of spherical objects was calculated under different radioactivities, frequencies, and sphere radii. When the sphere radius is smaller than 50 cm, the electron density of the plasma slab exhibits a tendency to first increase and then decrease. The typical maximum electron density for a radioactivity of 10 Ci/cm^2 rises from 7.02×10^{10} to 1.76×10^{11} cm^{-3} as the sphere radius increases from 10 to 300 cm. The average normalized RCS values for a sphere with radius 12.5 cm coated with a radionuclide layer at different radioactivities are -0.35, -0.50, -0.79, and -1.13 dB for radioactivities of 1, 2, 5, and 10 Ci/cm^2, respectively.

Keywords: Electromagnetic radiation; Plasma; α-particles; Radar cross section; Sphere object

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Introduction

In recent years, plasma stealth technology has attracted increasing attention due to its minimal impact on object shape and superior adaptability across a wide frequency band [1-3]. Plasma can be generated through various techniques, including arc discharge, laser excitation, electron guns, or radioactive isotopes [4-7]. When the plasma frequency produced by radioactive isotopes matches the frequency of electromagnetic waves (EMWs), the damping loss resulting from EMW excitation in the plasma slab reaches its maximum. Consequently, plasma stealth technology based on radioactive isotopes offers particular advantages, especially in ultra-high frequency (UHF) and super-high frequency (SHF) bands.

Spherical metal objects are most commonly used as calibration bodies in radar cross section (RCS) measurement facilities [8, 9]. In recent years, many research groups have investigated the influence of RCS on different plasma densities and geometries, but most studies were conducted under self-defined density or shape parameters [10-17]. While these works serve as verification of plasma theory, a significant gap remains for practical applications. This paper aims to calculate the influence of plasma induced by a radionuclide layer (RNL) coated on the surface of a spherical metal object on the RCS under different radioactivities and ratios of sphere radius to electromagnetic wavelength (RRW).

Theoretical Principle and Research Methods

A. Model

[Figure 1: see original paper] presents a schematic diagram of the simulation. A thin RNL is coated on the surface of a spherical metal object. Common α-decay radioactive isotopes include Po-210 (5.304 MeV, 138.4 d), Pu-238 (5.456 and 5.499 MeV, 87.7 a), and Am-241 (5.443 and 5.485 MeV, 432.6 a). The α-particle energies from these three isotopes are similar, meaning the energy loss per unit distance for these α-particles is also comparable. In this work, all calculations assume an α-particle energy of 5.45 MeV as a representative value, which shows no significant difference in energy loss in air compared to the three aforementioned isotopes. We assume the spherical metal object material is a perfect electric conductor (PEC) because the skin depth of most metals is much smaller than typical sphere radii. When EMWs propagate into the plasma slab created by the ionization effect of α-particles, damping loss from charged particles reduces EMW energy and refracts the spatial distribution of EMWs, both of which influence the RCS of the spherical metal objects.

B. Electron Density Distribution in Plasma Slab Induced by α-Particles

Since the velocity of α-particles is much less than the speed of light, we can determine the average number of newly created ions and ionization electrons produced by a single α-particle using the non-relativistic Bethe-Bloch formula and an average ionization energy of 36.08 eV in air [18]:

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4 NZ}{m_0 v^2} \ln\left(\frac{2m_0 v^2}{I}\right)$$

The plasma frequency is primarily determined by electron density because the electron mass is much smaller than that of ions. Consequently, in the simulation we only need to track these ionization electrons. In air, newly created ionization electrons undergo three main physical processes: diffusion, recombination with positive ions, and attachment to neutral molecules. During these processes, negative oxygen ions formed by attachment dissociate rapidly under ultraviolet radiation when the ionized electrons reach a specific energy [19]. In our calculations, we neglected the attachment process, as its omission does not introduce any substantive effects on the results.

The diffusion velocity of electrons is related to the gradient of electron density (n_e), and considering ambipolar diffusion effects in the plasma slab, the diffusion coefficient is $D_{\text{dif}} = 3.7 \times 10^2$ cm^2/s:

$$\left(\frac{dN}{dt}\right)_{\text{dif}} = D_{\text{dif}} \nabla n_e$$

The recombination velocity is proportional to the concentrations of both positive and negative ions. The entire plasma slab system is nearly neutral, so we can consider the numbers of positive ions and electrons to be approximately equal, with a recombination coefficient of $\alpha = 1.5 \times 10^{-6}$ cm^3/s (both coefficients validated experimentally):

$$\left(\frac{dn_e}{dt}\right)_{\text{rec}} = \alpha n_+ n_e \approx \alpha n_e^2$$

The final electron density is determined by diffusion, recombination, and ionization by α-particles. [Figure 2: see original paper] shows the simulation flow chart. The time step for each cycle is the average time interval between adjacent ejected α-particles per square centimeter, which is determined by the radioactivity of the RNL.

C. The Interaction Between EMW and Plasma

In the plasma slab, four types of collisions occur: electron-molecule, electron-ion, ion-molecule, and electron-electron collisions. In the troposphere, collisions predominantly occur between electrons and molecules. Ginzburg defined a coefficient called effective collision frequency [20]; when the EMW frequency is much smaller than the effective collision frequency, the latter can be formulated as:

$$\nu \sim \nu_{\mathrm{eff},l} \approx 1.5 \times 10^{11} \frac{N_m}{2.7 \times 10^{19}} \sqrt{\frac{T}{273}}$$

where N_m is the number of molecules per unit volume. However, the effective collision frequency impacts the EMW frequency. The relationship between the relative dielectric constant and effective collision frequency is:

$$\varepsilon_r = 1 - \frac{K_1 \omega_p^2}{\omega^2 + \nu_{\mathrm{eff},l}^2} - j \frac{K_2 \omega_p^2 \nu_{\mathrm{eff},l}}{\omega(\omega^2 + \nu_{\mathrm{eff},l}^2)}$$

where K_1 and K_2 are coefficients related to the ratio of EMW frequency to effective collision frequency [20], and:

$$\omega_p \approx \omega_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

The plasma slab induced by the RNL coated on the spherical object surface is isotropic, meaning the density distribution depends only on radial distance r. Therefore, the plasma slab can be divided into m layers, with the radius of the boundary between the $(i-1)$th and ith layer set as a_i: when $0 \leq r \leq a_1$, the material is a perfect electric conductor (PEC); the relative dielectric constant of the ith layer is $\varepsilon_{r,i}$ and the relative permeability is approximately 1. The relationship between RCS and scattering coefficients b_n and c_n is:

$$\sigma = \frac{\lambda_0^2}{\pi} \left(|A_c|^2 \cos^2 \phi + |A_s|^2 \sin^2 \phi \right)$$

$$|A_c|^2 = |A_s|^2 = \left| \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[b_n \sin\theta P_n^{1\prime}(\cos\theta) - c_n \frac{P_n^1(\cos\theta)}{\sin\theta} \right] \right|^2 + \Bigg| \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \Bigg[b_n \frac{P_n^1(\cos\theta)}{\sin\theta} - c_n \sin\theta P_n^{1\prime}(\mathrm{co}$$

The scattering coefficients b_n and c_n are calculated by:

$$b_n = -\frac{\hat{J}_n'(k_0 a_m) - R_{b,m}\hat{J}_n(k_0 a_m)}{\widehat{H}_n^{(2)'}(k_0 a_m) - R_{b,m}\widehat{H}_n^{(2)}(k_0 a_m)}$$

$$c_n = -\frac{\hat{J}_n(k_0 a_m) - R_{c,m}\hat{J}_n'(k_0 a_m)}{\widehat{H}_n^{(2)}(k_0 a_m) - R_{c,m}\widehat{H}_n^{(2)'}(k_0 a_m)}$$

where:

$$a_n = j^{-n}\frac{2n+1}{n(n+1)}$$

And the recurrent relationship of the coefficients $R_{b,m}$ and $R_{c,m}$ is:

$$R_{b,i} = \frac{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n'(k_i a_i) + \chi_{b,i}\hat{Y}_n'(k_i a_i)}{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n(k_i a_i) + \chi_{b,i}\hat{Y}_n(k_i a_i)}$$

$$R_{c,i} = \frac{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n(k_i a_i) + \chi_{c,i}\hat{Y}_n(k_i a_i)}{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n'(k_i a_i) + \chi_{c,i}\hat{Y}_n'(k_i a_i)}$$

$$\chi_{b,i+1} = -\frac{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n'(k_{i+1} a_i) - R_{b,i}\hat{J}_n(k_{i+1} a_i)}{\sqrt{\varepsilon_{r,i+1}}\hat{Y}_n'(k_{i+1} a_i) - R_{b,i}\hat{Y}_n(k_{i+1} a_i)}$$

$$\chi_{c,i+1} = -\frac{\sqrt{\varepsilon_{r,i+1}}\hat{J}_n(k_{i+1} a_i) - R_{c,i}\hat{J}_n'(k_{i+1} a_i)}{\sqrt{\varepsilon_{r,i+1}}\hat{Y}_n(k_{i+1} a_i) - R_{c,i}\hat{Y}_n'(k_{i+1} a_i)}$$

Because the sphere core material is PEC:

$$\chi_{b,2} = -\frac{\hat{J}_n'(k_2 a_1)}{\hat{Y}_n'(k_2 a_1)}, \quad \chi_{c,2} = -\frac{\hat{J}_n(k_2 a_1)}{\hat{Y}_n(k_2 a_1)}$$

The monostatic RCS is a special case ($\theta = \pi$), so the RCS can be simplified as:

$$\sigma = \frac{\lambda_0^2}{\pi}\left|\sum_{n=1}^{\infty}(-j)^n\frac{2n+1}{n(n+1)}(b_n - c_n)\right|^2$$

All RCS values are presented as normalized results, $10\log(\sigma/\pi r^2)$, where r is the radius of the spherical object.

Results and Discussion

A. Electron Density Distribution in Plasma Slab

The average range of 5.45 MeV α-particles is 3.84 cm in air at normal pressure and temperature; the track of a single α-particle is almost straight along the ejection direction. By simulating the average energy loss along the radial direction, taking into account the surface curvature of the spherical metal objects and the randomness of ejection direction, we obtain the average electron density per unit volume ionized by a single α-particle, shown in [Figure 3: see original paper]. The solid angle per square centimeter on the surface increases as the sphere radius decreases, so the average electron densities ionized by a single α-particle decrease. When the sphere radius is smaller than 50 cm, the results show that the electron density tends to first increase and then decrease. This can be attributed to the effect of sphere curvature for relatively small radii, which causes the effective RNL surface area to decrease with distance in the region proximal to the surface. Under the combined interaction of the effective RNL surface and the volume corresponding to a unit solid angle, the radial electron densities exhibit characteristic trends with distance from the sphere.

Based on the average radial electron density and the flow chart shown in [Figure 2: see original paper], we calculated the actual electron density at different radii and radioactivities. In the calculation, we set the plasma slab thickness at 50 cm, which is much larger than the α-particle range. The diffusion effects were considered, and the results are shown in [Figure 4: see original paper]. The electron density increases with radius when the RNL radioactivity is 1 µCi/cm^2; the maximum density values are 2.42×10^7, 3.52×10^7, 4.48×10^7, and 5.17×10^7 cm^{-3} corresponding to sphere radii of 10, 25, 50, and 100 cm, respectively, with results approaching 5.76×10^7 cm^{-3} for an infinitely large plate ($r \to \infty$).

When radioactivity increases by a factor of 10, the ratios of electron density data at a certain radioactivity to data at ten times that radioactivity are basically consistent for the same sphere radii. This ratio, expressed as $a(x)$ and termed the activity coefficient, is shown in [FIGURE:4(b)] at different sphere radii. We summarized an empirical formula to describe the electron density in the plasma slab induced by 5.45 MeV α-particles as a function of distance from the sphere surface:

$$n(x) = n_0(x)a(x)\lg A$$

where $n_0(x)$ represents the electron density data at 1 µCi/cm^2 from [FIGURE:4(a)], x is the distance to the sphere surface, and A is the surface radioactivity in units of µCi/cm^2. When radioactivity is in the range of 1 µCi/cm^2 to 10 Ci/cm^2, the differences between the empirical equation and simulation results are less than 10%.

Using the empirical formula, we can conveniently obtain the electron density distribution under different radii and radioactivities. [Figure 5: see original paper] shows the electron densities for different sphere radii at a radioactivity of 10 Ci/cm^2 calculated using the empirical formula. When sphere radii are small, the regions of maximum electron density are not close to the sphere surface, and the electron density exhibits a tendency to first increase and then decrease. For example, when the sphere radius is 10 cm and the RNL radioactivity is 10 Ci/cm^2, the distance between the region of maximum electron density and the sphere surface is about 1 cm.

B. The Influence on Monostatic RCS of α-Decay RNL

One of the most important parameters in monostatic RCS research on spherical objects is the RRW. Normally, normalized RCS data are completely consistent for the same RRWs due to spatial scale relativity. However, in our model, the distributions of electron density in the plasma slab outside the spherical object change with radius and radioactivity, so differences exist in normalized RCS data even when RRWs are identical. [Figure 6: see original paper] shows monostatic RCS data for radioactivities ranging from 1 Ci/cm^2 to 10 Ci/cm^2 at a radius of 12.5 cm. The oscillation amplitudes decrease with increasing RRW, and when $r/\lambda_0 > 1$, the average monostatic RCS of spherical objects without RNL is 0 dB. The average values decrease with increasing RNL radioactivity: the average data are -0.35, -0.50, -0.79, and -1.13 dB for radioactivities of 1, 2, 5, and 10 Ci/cm^2, respectively. Additionally, oscillation amplitudes decrease with increasing radioactivity, and deviations exist in the positions of peaks and valleys. The reason is the refraction of incident and scattered waves caused by the inhomogeneous plasma distribution. Higher electron density associated with higher radioactivity results in more pronounced refraction.

[Figure 7: see original paper] shows monostatic RCS data at different sphere radii for a radioactivity of 10 Ci/cm^2, revealing differences in these curves for different sphere radii at the same radioactivity. Similarly, oscillation amplitudes decrease with increasing RRW or decreasing sphere radius. Certain deviations also exist in peak and valley positions. The average values of normalized monostatic RCS are -1.13, -0.62, -0.26, and -0.09 dB for sphere radii of 12.5, 25, 100, and 300 cm, respectively, when $r/\lambda_0 > 1$. A smaller radius means a shorter wavelength for the same RRWs, so the ratio of plasma slab thickness to EMW wavelength increases as radius decreases, resulting in more EMW refraction for the same RRW, even though electron density also decreases under those conditions.

Conclusion

The influence of plasma induced by an α-decay RNL on the RCS of spherical metal objects was simulated. First, we calculated the electron density in the plasma slab at different radioactivities and sphere radii. The maximum electron density is about 1.62×10^{11} cm^{-3} for an RNL radioactivity of 10 Ci/cm^2 and sphere radius of 1 m. The maximum electron density can increase with sphere radius for the same RNL radioactivity. When $r/\lambda_0 > 1$, the average monostatic

RCS values are -0.35, -0.50, -0.79, and -1.13 dB for radioactivities of 1, 2, 5, and 10 Ci/cm^2, respectively. Additionally, when radioactivity is 10 Ci/cm^2, the average normalized monostatic RCS values are -1.13, -0.62, -0.26, and -0.09 dB for sphere radii of 12.5, 25, 100, and 300 cm, respectively. Generally, the effects on monostatic RCS increase with increasing radioactivity or decreasing sphere radius for the same RRWs. The simulation results demonstrate that coating with an RNL can effectively reduce the RCS of spherical objects.

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