ABSTRACT: The nature of composite coal and rock fracture under load is the process of energy conversion inside it, and to explore the coupling mechanism of dissipated energy (DE) and electromagnetic radiation energy (ERE) during the deformation and fracture process of loaded composite coal and rock, based on theoretical mechanics, electromagnetics, and other subject theories, the stress-charge induction signal coupling relationship is deduced and established. On this basis, a coupled mathematical model of dissipated energy-electromagnetic radiation energy (DE-ERE) is established, and uniaxial loading experiments under different loading rates are carried out. The research results show that the energy of the composite coal and rock increases, and the internal free charge transitions from the high-concentration area to the low-concentration area, accumulating charges on the fractured surface, forming a regional electric field, and generating electromagnetic radiation. The change of the charge-induced signal on the surface of the loaded composite coal and rock is phased and has a corresponding relationship with each mechanical phase. Its peak appears earlier than the stress peak. There is a linear relationship between the charge induction signal and stress, and they have a strong correlation, which is consistent with the established mathematical model. The energy conversion characteristics of the composite coal and rock under load have stage characteristics. The elastoplastic period is mostly converted to dissipative energy release, and the increase of plastic deformation leads to rupture. ERE is one of the components of DE. In the early stage of elastoplasticity, the dissipated energy mainly exists in the form of electromagnetic radiation energy, and the change trends of the two are the same. After the peak value, it drops rapidly, and the DE is mainly composed of other destructive energy that causes deformation. The changes in ERE can be used to determine the DE and stress state, providing a new method for preventing coal and rock dynamic disasters.

1. INTRODUCTION
With the increase of coal mining depth, engineering disasters such as roadway deformation and instability, roof fall, and rock burst in underground mining projects occur frequently. Therefore, preventing coal and rock dynamic disasters has become an important research content of domestic and foreign scholars. The disasters in the deep mining process of coal mines are not only affected by the fractured structural surfaces of coal and rock themselves but the result of the combined structure of “roof rock mass—coal mass—floor rock mass”. Single coal and rock are two different media, and there are big differences in strength, material quality, heterogeneity, and microstructure. Therefore, many scholars have conducted a lot of research on composite coal and rock, and some progress has been made in the fields of electromagnetic radiation, charge induction signals, and energy conversion laws caused by coal and rock fractures.1–3 Zhao et al.4 studied the charge induction and microseismic law...
experiments of coal and rock with different combination ratios and showed that the microseismic and charge signals are low-frequency signals. The signal frequency spectrum is concentrated in 0–80 Hz, and the sudden change of stress has a good consistency with the generation and change of the microseismic signal and the charge signal. It provides theoretical support for the prediction of dynamic disasters. Ding et al.5 conducted uniaxial failure experiments on coal and rock, using the Fourier transform method to study the time–frequency domain characteristics and change laws of the charge signal at different loading stages. Wang et al.6 used a self-developed charge monitoring system to study the changes of charge signals under different types of coal and rock destruction. Li et al. used a self-made coal surface transient charge and microseismic signal test experimental system to conduct uniaxial compression experiments, which showed that the coal surface transient charge and microseismic signals have a strong correlation with stress changes. Lv et al.8 studied the frequency-domain characteristics of the charge signal during the early stage of loading and the later stage of destruction during the uniaxial compression of coal and verified that the Lilliefors test method can identify the effective charge induction signal at the initial stage of loading. He et al.9 studied the variation of electrical parameters such as the electric potential and charge density of coal and rock with different degrees of metamorphism, promoted the study of the microelectric characteristics of the coal surface to the micro–nanoscale, and further revealed the mechanism of coal–rock electromagnetic radiation from the micro level. Wang et al.10 analyzed electromagnetic radiation monitoring and early warning equipment and systems and proposed that electromagnetic radiation is an effective noncontact geophysical monitoring and early warning method for coal and rock dynamic disasters. Liu et al.11 conducted uniaxial compression experiments on coal and rock and analyzed the Hurst index of the electromagnetic radiation signal, which showed that there is a certain correlation between the electromagnetic radiation signal and coal rock fracture. Chang et al.12 designed an electromagnetic radiation signal acquisition and processing system to achieve the stability and accuracy of electromagnetic radiation signal acquisition. Yang et al.13,14 collected electromagnetic radiation signals and infrared radiation signals, established composite coal and rock deformation and a fracture force electrothermal coupling model, and obtained correlation coefficients through experiments. Zhao et al.15 studied rock-breaking acoustic emission and electromagnetic radiation characteristic tests under different loading rates and showed that the two signals are consistent during the rock-breaking process, and the signal gradually strengthens as the loading rate increases. Cao et al.16 used electromagnetic radiation monitoring technology to study the coal-breaking effect of coal under the action of high-pressure water and clarified that electromagnetic radiation monitoring technology can be used to monitor the internal fracture and creep of coal in the process of hydraulic punching coal. Yang and Chen17,18 conducted uniaxial experiments to study the energy evolution law of coal and rock with different strength ratios and effectively prevented coal mine dynamic disasters of different geology. Li et al.19 conducted shock compression experiments on coal and rock monomers and assemblages and revealed that composite coal and rock bodies have a higher degree of energy accumulation and lower energy required for dynamic disasters. Zhao et al.20 conducted uniaxial load experiments on samples with different coal thicknesses and showed that as the proportion of coal thickness increases, the failure type of the sample changes and the dissipation energy conversion rate decreases. Meng et al.21 conducted uniaxial cyclic loading and unloading experiments on rocks and revealed the evolution process and distribution law of elastic energy rebound density with stress. Liu et al.22 conducted uniaxial compression experiments on coal and rock under different strain rates and revealed the law of energy evolution of coal and rock under different strain rates and proposed a new method to determine the characteristic stress of uniaxial coal and rock using the energy dissipation rate curve and the lateral strain difference. Shan et al.23 studied the stage characteristics of the fractured coal and rock mass from damage to fracture under uniaxial compression load and its energy release law and determined the relationship between fracture strain energy and elastic strain energy (ESE) of fractured coal rock. Meng et al.24 studied the characteristics of energy accumulation and release in the process of rock damage and deformation under different loading and unloading modes, thereby revealing the evolution mechanism and distribution law of energy accumulation and dissipation before the peak. Chen et al.25 conducted uniaxial and triaxial compression tests on mudstone, etc., proposed damage coefficients based on the energy evolution mechanism, and analyzed rock mechanical properties and damage evolution process from the energy point of view. Zhang and Li26,27 conducted triaxial experiments on coal and rock under different confining pressures, based on theoretical analysis, established an energy dissipation coal and rock damage constitutive model, and studied the law of energy evolution. Hou et al.28 conducted triaxial compression experiments under different confining pressures, studied the compressive mechanical properties and energy evolution characteristics of soft coal, and revealed that there is no clear correlation between the dissipation energy and the confining pressure. Xu et al.29 studied the mechanism of energy evolution in the process of the fractured coal and rock and established a mechanical model of energy dissipation in the fractured coal seam, which showed that the energy dissipation of fracturing fracture expansion is proportional to the water pressure and the degree of coal seam damage.

In recent years, researchers have used the law of energy evolution to predict the rupture trend of composite coal and rock, and thus, the energy change is used as a way to judge whether a dynamic disaster has occurred. Among them, the trend of dissipated energy (DE) is mainly studied. However, due to the complex composition of dissipated energy (DE) and the difficulty of measurements, most studies are still in the preliminary stage. Electromagnetic radiation is one of the components of DE. This paper takes electromagnetic radiation energy (ERE) as the main research object and establishes a coupled model of DE–ERE during deformation and fracture of the loaded composite coal based on energy theory and electromagneticics, further analyzes and verifies through experiments, reveals the relationship between ERE and composite coal and rock mechanics, and provides new ideas for preventing coal and rock dynamic disasters.

2. THEORETICAL BASIS

2.1. Physical Mechanism. The coal and rock mass is essentially composed of atoms and electrons. When the coal rock is subjected to increasing external loads, macroscopically, the appearance of the coal rock can be seen to change, and microscopically, the internal chemical bonds of the coal rock are broken and free electric charges appear. The inhomogeneous structure and anisotropy and constant external pressure caused
the uneven distribution of the charge concentration. To regain the equilibrium state, the free charge will move, and the charged particles will diffuse from the high-concentration area to the low-concentration area. Figure 1 shows a schematic diagram of the movement of the charged particles.

Figure 1. Schematic diagram of the movement of charged particles.

Due to the diffusion movement of the charged particles, surface charges are accumulated on the fractured area to form a regional electric field, which accelerates the movement of charges and continuously radiates electromagnetic fields to the outside during the movement transfer process. As shown in Figure 2, the direction of the magnetic field rotates clockwise at this time.

Figure 2. Schematic diagram of the electromagnetic field generated by charged particles.

2.2. Stress—Charge Induction Signal Coupling Relationship. Electromagnetic radiation includes electrical energy and magnetic energy. The energy is generated by the movement of electric charges. The electric field generates a magnetic field, and the magnetic field generates an electric field. The two transform each other, so the intensity of the electric field can be used to characterize the electromagnetic radiation. To deeply study the coupling relationship between DE and ERE, the mathematical relationship between stress and electric field strength during the loading process of composite coal and rock should be clarified first.

There are many factors that produce electromagnetic radiation during the loading process of composite coal and rock. Therefore, the model is regarded as a stack of countless circular planes, as shown in Figure 3, for the circular plane of composite coal and rock.

Figure 3. Circular plane in composite coal rock mass.

It is assumed that the induced potentials of the fracture elements in each plane are the same and are evenly distributed on the plane. Since the boundary conditions of the composite coal and rock under load can be regarded as mechanical freedom and an electrical open circuit, the g-type piezoelectric formula is as follows

$$\begin{align*}
\varepsilon &= \varepsilon^0 \sigma + g^T D \\
E &= -g \sigma + \beta^T D
\end{align*}$$  (1)

$$D = d \sigma + \alpha^T E$$  (2)

In the formula, $\sigma$ is stress, MPa; $D$ is the electric displacement, C/m; $\varepsilon$ is the strain; $E$ is the electric field strength, N/C; $\beta$ is the free-dielectric constant; $g$ is the piezoelectric voltage constant; $g_t$ is the transformation of $g$ set; $d$ is the piezoelectric strain constant; $\beta^T$ is the isolation rate of the medium under constant stress; $\varepsilon^0$ is the constant electrical displacement compliance coefficient; and $\alpha$ is the dielectric constant.

Formula $\odot$ is the positive piezoelectric effect, and formula $\odot$ is the inverse piezoelectric effect. During the uniaxial loading of the composite coal and rock, its piezoelectric effect conforms to formula $\odot$, formula 2 shows the relationship among the electric displacement, stress, and electric field intensity, and the coupling model of the electric field intensity $E$ and stress $\sigma$ can be obtained by combining formula $\odot$ and formula 2

$$E = -\frac{\varepsilon^D + d g \sigma}{\alpha^T g_t} + \frac{\varepsilon}{\alpha^T g_t}$$  (3)

It can be seen from the above formula that stress $\sigma$ has a linear relationship with the electric field intensity $E$ during the loading process of the composite coal and rock.
The free charge moves on the plane of coal and rock to generate a voltage difference, forming a charge induction signal; according to the uniform electric field formula, it can be known as

$$E = \frac{U_{ab}}{d_{ab}}$$  \hspace{1cm} (4)

which is

$$U_{ab} = Ed_{ab} = -\frac{e^D + \frac{d}{\alpha g_t^2} \sigma + \frac{e}{\alpha g_t} d_{ab}}{2T}$$  \hspace{1cm} (5)

It can be seen that the charge induction signal has a linear relationship with the electric field intensity, that is, the same linear relationship with stress. Among them, $U_{ab}$ is the charge induction signal, $V$ and $d_{ab}$ is the distance between charges, mm.

### 2.3. DE–ERE Coupling Model

All objects whose temperature is greater than absolute zero can emit electromagnetic radiation, and the intensity of electromagnetic radiation is related to the state of the electromagnetic source and the intensity of the electric field. During the loading process of composite coal and rock, the charged particles move continuously, which makes the intensity of the electromagnetic radiation change. Based on this, the electromagnetic radiation intensity can be obtained by the noncontact electromagnetic radiation detector, and the ERE can be known, and then, the overall mechanical state of the coal and rock can be inferred.

The ERE density formula is

$$W_e = \frac{1}{2} ED$$  \hspace{1cm} (6)

Combining eqs 2, 3 and 6, a composite coal—rock stress—electromagnetic radiation energy coupling model can be obtained

$$W_e = a\sigma^2 - b\sigma + c$$

$$a = \frac{\varepsilon^2D + \frac{\varepsilon^D}{2g_t^2}\alpha}{2T}$$

$$b = \frac{(2\varepsilon\varepsilon^D + \frac{\varepsilon^D}{2g_t^2}\alpha)}{2T}$$

$$c = \frac{\varepsilon^2}{2g_t^2\alpha}$$  \hspace{1cm} (7)

The uniaxial loading experiment on composite coal and rock is actually the process of external work done by coal and rock, which includes energy accumulation and dissipation. Assuming that there is no energy exchange with the outside world in the coal and rock loading project, according to the law of conservation of energy, the strain energy of coal and rock mass will all be converted into elastic strain energy (ESE) and DE. The calculation formula of strain energy density $U$ is

$$U = U_d + U_e = \int_0^\sigma d\sigma$$  \hspace{1cm} (8)

In the formula, $U_d$ is the unit DE, which is composed of kinetic energy, thermal energy, infrared radiation energy, ERE, etc., J/m$^3$ and $U_e$ is the unit ESE, J/m$^3$.

The unit ERE $U_e$ is the area enclosed by the load curve and the strain axis. The calculation formula for the unit ESE $U_e$ of the composite coal under uniaxial loading is

$$U_e = \int_{\sigma_0}^\sigma d\sigma = \frac{1}{2E_t}\sigma^2$$  \hspace{1cm} (9)

In the formula, $E_t$ is the elastic modulus of loading in the elastic stage, so it can be known that the calculation formula of the unit DE $U_d$ of the composite coal under uniaxial loading is

$$U_d = \int_0^\sigma d\sigma = \frac{1}{2E_t}\sigma^2$$  \hspace{1cm} (10)

Combining eqs 7 and 10 together can obtain the coupling relationship between ERE and DE

$$\begin{cases}
\sigma = [b \pm (b^2 - 4a(c - W_e)^{1/2})]/2a \\
U_d = \int_0^\sigma d\sigma = \frac{1}{2E_t}\sigma^2 \\
a = \frac{\varepsilon^2D + \frac{\varepsilon^D}{2g_t^2}\alpha}{2T} \\
b = \frac{2\varepsilon\varepsilon^D + \frac{\varepsilon^D}{2g_t^2}\alpha}{2T} \\
c = \frac{\varepsilon^2}{2g_t^2\alpha}
\end{cases}$$  \hspace{1cm} (11)

It can be seen from formula 11 that there is a numerical relationship between the ERE $W_e$ and the DE $U_d$ during the loading process.

## 3. RESULTS AND DISCUSSION

### 3.1. Correlation Analysis of Stress and Charge Induction Signals

Table 1 shows the size of f1–f9 specimens and the results of mechanical experiments under uniaxial loading. Since the hardness of the top and floor sandstone of the composite coal sample is much larger than that of the coal sample, most of the samples are obviously fractured in the middle coal sample after the test, while the upper and lower sandstones only show microcracking.30,31 Because the fracture tendency of the 9 coal and rock samples is the same, the results of only one sample are shown, as shown in Figure 4.

In view of the fact that the components of the samples are basically the same and the change trend of the charge induction results during the deformation and rupture process is consistent, three groups of test data of composite coal and rock samples f1, f4, and f7 under different loading rates are selected for analysis. Figure 5 shows the stress—charge versus time curves of samples...


f1, f4, and f7, respectively, corresponding to loading rates of 0.1, 0.3, and 1.0 mm/min.

It can be seen from Figure 5 that the compressive strength of f1 under 0.1 mm/min loading condition is 28.57 MPa, the compressive strength of f4 under 0.3 mm/min loading condition is 23.34 MPa, and the compressive strength of f7 under 1.0 mm/min loading condition is 33.43 MPa. The four stages of compaction, elasticity, elastoplasticity, and rupture can be seen on the stress–time curves of each group under uniaxial loading. The charge change trend is basically the same at each loading rate. Taking Figure 5b as an example for analysis, in the compaction stage, the internal cracks in the sample are closed, and the charge induction signal is weak about 0.150 V. As stress continues to increase, after entering the elastic phase, the induced charge fluctuates slightly, and the charge-induced signal reaches 0.280 V when t is about 400 s. After the charge signal fluctuates, it gradually rises and enters the elastoplastic stage. At this stage, the coal and rock samples gradually produce cracks, and the charged particles move quickly. At t = 631 s, the charge induction signal reaches the maximum value of 0.851 V, and the coal and rock sample cracks gradually increase. When t = 641 s, stress reaches the peak value, and the coal and rock sample ruptures at this time. It can be seen that the charge induction signal has a maximum value before the stress reaches the peak value. It can be seen in Figure 5 that the change of the composite coal charge induction signal at different loading rates is consistent with the stress change trend, so there is a certain correlation.

To verify the correctness of the mathematical relationship established above and to further explore the coupling law between ERE and strain energy, the physical quantity corresponding to energy, namely, the correlation between stress and charge signals should be analyzed. Performing a linear fit to the stress and charge signals at the same time in Figure 5, the curve of the fitting result and the experimental data used in the fitting are shown in Figure 6, and the fitting result is shown in Table 2.

It can be seen from Figure 6 and Table 2 that the charge induction signal of the composite coal and rock samples under different loading conditions has a linear functional relationship with stress. As the mechanical parameters increase, the charge-induced signal on the surface of the sample increases at the same time. The correlation coefficients between the two are between 0.93 and 0.97. It can be seen that there is a strong correlation between the charge-induced signal and stress.

It can be seen from the fitting relationship equation in Table 2 that the fitting relationship between the sample charge induction signal $U_{ab}$ and stress $\sigma$ under different loading conditions is shown in eq 12

$$U_{ab} = A \cdot \sigma + B$$  \hspace{1cm} (12)

where $U_{ab}$ is the sample charge induction signal, $V$; $\sigma$ is the external force received, MPa; and $A$ and $B$ are two linear fitting coefficients.

The fitting formula 12 is consistent with formula 5 deduced above, and the correlation is high. It can be seen that the mathematical relationship between the charge induction signal and stress deduced above has certain accuracy and feasibility.

3.2. Variation Law of DE during Loading. The deformation of the composite coal and rock is closely related to the work–energy conversion. As shown in eq 8, in the absence of other exchanges, all external work is converted into ESE and DE. An analysis of the experimental results with the most obvious characteristics of each group of different loading conditions is made, and Figure 7 shows the respective total energy (TE), DE, ESE, and strain change curves and stress–strain curve of samples f1, f4, and f7 at uniaxial loading rates of 0.1, 0.3, and 1.0 mm/min, respectively. It can be seen from Figure 10 that the laws of TE conversion into each energy in different mechanical stages of composite coal and rock are different, but the change trend is the same under different loading rates. Specific analysis results of Figure 7a are as follows: During the compaction stage, most of the TE is converted into ESE, and the conversion of DE is extremely low; the TE of the sample increases slowly and the trend of stress changes is similar; the energy at this stage is mostly caused by elastic deformation, and the TE density reaches 0.0068 MJ/m³ at the end. In the elastic stage, the TE accelerates, and the later growth rate reaches 0.01657 MJ/m³. At this stage, most of the TE is still transformed into ESE, but the growth rate is significantly lower than the overall; its conversion rate gradually decreases, and the transformation DE increases significantly, but the total amount does not exceed the ESE; the energy density of the two at the end is the same as 0.01312 MJ/m³. At this time, the external work is still mostly used for elastic deformation; however, due to the complex internal structure of geotechnical materials, some areas have reached the elastic limit; load promotes the increased proportion of nonelastic deformation, and part of the TE is consumed as DE. In the elastoplastic stage, the TE maintains a high rate of growth, and the initial ESE and plastic properties continue to increase. The growth rate of DE is significantly greater than the rate of ESE, and the total amount is greater than that of ESE. When the strain reaches 0.0146, the ESE reaches the peak value of 0.0297 MJ/m³, which is earlier than the stress peak. After that, the TE conversion trend changes, and the ESE decreases rapidly, and finally, the energy density in the early stage of rupture stabilizes at 0.00546 MJ/m³. The DE density rapidly increases to 0.08 MJ/m³, and the TE and excess ESE are
almost all converted into DE. It can be seen from this that although the sample is still elastically deformed at the beginning of the elastoplastic stage, it will eventually reach its limit. The inelastic region will eventually become dominant as the load continues to increase, which causes most of the remaining energy to be converted into DE and released. At this time, the sample has a tendency to crack locally, and the cracking sound can be heard outside. In the rupture stage, the ESE of the sample remains stable, and the TE is almost completely converted to DE, which still maintains a high-speed growth, and finally reaches the peak energy of 0.08597 MJ/m³. The sample ruptures and the DE is released. In summary, the TE conversion trend of uniaxial loading affects the stress state of coal and rock, and there is a coupling relationship between the DE and ESE change trend and the conversion ratio as well as the stress states. The DE of the sample in the early stage of rupture increases obviously, but the ESE accounts for little.

3.3. Law of ERE Change and Coupling. The charge induction signal changes when the composite coal is loaded, it can be known from the conservation of energy that it is related to function conversion. DE refers to the general term for total energy converted into inelastic strain energy and other energy. ERE is a part of the DE, which directly affects the change law of the charge induction signal. The relationship between ERE and DE is shown in eq 13

\[
\begin{align*}
W_c & \propto U_c \\
U_d &= U_c + U_\Delta 
\end{align*}
\]

where \( W_c \) is the ERE, J; \( U_c \) is the ERE density, which is proportional to the ERE under the same volume, J/m³; and \( U_\Delta \) is the energy density of DE converted into nonelectromagnetic radiation, J/m³.

It can be seen from formula 13 that when the sample volume is constant, the external ERE of the object is proportional to the ERE density, and the change trend of ERE \( E_c \) is consistent with the change trend of the ERE density \( U_c \). Therefore, the law of energy density change can be obtained by analyzing the change of ERE, which is helpful for an in-depth analysis of the relationship among ERE, DE, and TE. Formula 6 can be used to

![Figure 5. Stress—charge—time curve.](https://doi.org/10.1021/acsomega.1c06511)
calculate the change law of the ERE of the composite coal during the loading process. Because each sample has the same change rule under the same loading conditions, only f1, f4, and f7 are analyzed. Figure 8 shows the energy density, ERE, and strain curves of composite coal and rock at loading rates of 0.1, 0.3, and 1.0 mm/min, respectively. From the previous analysis of Figure 5, we can see that the sample charge induction signal trend corresponds to each mechanical stage. It can be seen from Figure 8 that the change trend of coal and rock ERE under uniaxial loading is basically the same as the change trend of the charge induction signal.

Coal and rock fracture is a way to release DE, but the possibility of directly measuring DE is extremely low. ERE is one of the manifestations of DE, and its noncontact measurement is helpful to determine the mechanical state with energy characteristics. It can be seen from Figure 8 that there is a correlation between the ERE and the change trend of the DE and ESE. In the compaction stage, the growth of ESE is the main factor, the DE grows slowly, the ERE changes relatively smoothly, and there is no obvious growth trend overall, which is basically the same as the change trend of DE. In the elastic phase, the DE begins to grow, the growth rate of ESE slows down, which is less than the growth rate of DE, and the overall energy is still higher than the DE. At the beginning of the

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**Figure 6.** Stress—charge induction signal correlation curve.

**Table 2. Fitting Results and the Correlation Coefficient**

| sample no | fitting relation | correlation coefficient |
|-----------|------------------|-------------------------|
| f1        | $U_0 = 0.04734\sigma + 0.46726$ | 0.9354 |
| f4        | $U_0 = 0.03147\sigma + 0.16234$ | 0.9718 |
| f7        | $U_0 = 0.02884\sigma + 0.01559$ | 0.9682 |
elastoplastic stage, the DE continues to increase significantly, and the ESE grows slowly. At this time, the increase in ERE is obviously in line with the trend of DE. Near the intersection of ESE and DE, the DE grows rapidly under all loading conditions, and the ERE grows to a higher level, which has the characteristics of ERE peaks. According to the law of conservation of energy, the ERE can be considered to be converted from two parts at this time, one part is the DE converted by the external force, and the other part is the conversion of ESE. Therefore, the growth of ERE starts to accelerate at this time. In the late elastoplastic stage, the ESE decreases, and the TE is mainly converted into DE. The ERE falls significantly earlier than the stress peak and rupture stage. It can be seen from eq 13 that when the proportion of ERE in the DE begins to decrease significantly, the proportion of its nonelectromagnetic radiation energy density $U_{\Delta \theta}$ will increase significantly, that is, the proportion of energy such as kinetic energy and plastic deformation energy rises rapidly, and the composite coal and rock enter the deformation stage with a tendency to fracture. According to the previous analysis, the sample cracking sound can be heard outside, and the sample has cracks at this time until the rupture stage produces penetrating cracks. In the late elastoplastic stage and the rupture stage, the performance of the DE is mainly nonelectromagnetic radiation energy such as kinetic energy and plastic deformation energy. The ERE always maintains a low energy value and fluctuates steadily and no longer has a growing trend.

In summary, ERE and DE have a high degree of coupling. In the early stage of the elastoplastic stage, ERE, as one of the important components of DE, is consistent with the changing trend of DE, but after that, the DE is mainly composed of nonelectromagnetic radiation energy such as kinetic energy and plastic strain energy. ERE falls and the ERE peaks, and maintains relatively low energy stability, which is significantly earlier than the stress peak and rupture stage. Therefore, according to the ERE, the DE state of the composite coal can be grasped, which can assist in judging the precursor of composite coal and rock fracture. The method for judging the DE, TE, and fracture state of composite coal and rock using the characteristics of ERE change is shown in Figure 9. The number of round balls represents the amount of converted energy.

Figure 7. Energy change curve during loading.
4. CONCLUSIONS

(1) The energy of the loaded composite coal and rock increases, and the internal free charge transitions from the high-concentration area to the low-concentration area, breaking the internal balance, accumulating charges on the fractured surface, forming a regional electric field, and generating electromagnetic radiation. Based on the piezoelectric effect, a linear mathematical model of stress and the charge induction signal is established. Based on energy theory and electromagnetics, a coupling model of DE–ERE is further deduced and established.

(2) The change of the charge induction signal on the surface of the loaded composite coal rock has a phased relationship with each mechanical stage, and its peak appears earlier than the stress peak. There is a linear relationship between the charge induction signal and stress, which has a strong correlation, which is consistent with the established mathematical model.

The energy conversion characteristics of the composite coal and rock under load are staged. The elastoplastic period is mostly converted to the release of DE, and the increase in plastic deformation leads to rupture. ERE is a part of DE. In the early stage of elastoplasticity, it is consistent with the trend of DE. After the peak, the rapid fall is no longer the main component. The DE is mainly composed of other destructive energy that causes deformation. The changes in ERE can be used to determine the DE and stress state, providing a new method for preventing coal and rock dynamic disasters.

5. METHODOLOGY

5.1. Sample Preparation. The sample in this study was taken from a coal seam with typical coal and rock dynamic disaster characteristics in a coal mine in Datong. According to the standards of the International Society of Rock Mechanics, first, use a core drilling machine to drill coal and rock blocks into 50 and 100 mm cylindrical coal and rock specimens, respectively. Second, cut them into the required specimen height with a stone saw, and then, a surface grinder is used to
grind both ends of the specimens flat. The nonparallelism at both ends of each sample is required to be no more than 0.03 mm, and the diameter deviation at both ends is no more than 0.02 mm. Finally, the roof sandstone, coal, and floor sandstone are bonded with white latex at a height of 1:1:1 to form a cylindrical composite coal sample with a diameter of 50 mm and a height of 100 mm, as shown in Figure 10.

The 5E-MACIII infrared fast coal quality analyzer was used to measure various industrial analysis indexes of the collected coal samples. The measurement results are shown in Table 3.

In the literature,30,31 the stress−strain and other mechanical properties of coal samples taken from different regions were studied, revealing that the changes in the stress−strain curve of different coal samples were consistent. The coal samples in the literature26,31−33 were also taken from different places, and the results showed that the change trend of the dissipated energy in the process of coal rock fracture was consistent. Therefore, this paper selects a kind of coal sample for experimental research.

5.2. Experimental Equipment. To verify the coupling relationship between DE and ERE in the process of composite coal and rock fracture under load, in this study, a uniaxial loading experiment was performed on the prepared coal and rock samples, and the uniaxial loading experiment site is shown in Figure 11.

![Figure 9](https://doj.org/10121/acsomega.1c06511)

**Figure 9.** Judgment of the loading state of electromagnetic radiation energy.

![Figure 10](https://doj.org/10121/acsomega.1c06511)

**Figure 10.** Composite coal and rock sample.

![Figure 11](https://doj.org/10121/acsomega.1c06511)

**Figure 11.** Experimental site.

| number | moisture (%) | ash (%) | volatile (%) | fixed carbon (%) |
|--------|--------------|---------|--------------|-----------------|
| f1     | 1.78         | 12.56   | 11.77        | 73.89           |
| f2     | 1.82         | 11.87   | 12.87        | 73.44           |
| f3     | 1.69         | 12.07   | 12.45        | 73.79           |
| f4     | 1.74         | 11.93   | 12.69        | 73.64           |
| f5     | 1.73         | 12.58   | 11.98        | 73.71           |
| f6     | 1.81         | 12.24   | 12.32        | 73.63           |
| f7     | 1.67         | 12.20   | 12.23        | 73.90           |
| f8     | 1.72         | 12.45   | 12.13        | 73.70           |
| f9     | 1.78         | 12.16   | 12.10        | 73.96           |
| average| 1.75         | 12.23   | 12.28        | 73.74           |

![Table 3. Industrial Analysis of Coal Samples](https://doj.org/10121/acsomega.1c06511)

The experimental loading system consists of a SANS universal testing press (maximum load is 300KN), a computer, a control cabinet, and a data acquisition system. A self-developed charge meter is used for charge collection, and its charge−voltage conversion ratio is 80−100 mV/pC. The test was carried out in a self-made electromagnetic shielding chamber. The experimental equipment is shown in Figure 12.
5.3. Experimental Steps. To study the coupling relationship between DE and ERE during composite coal and rock loading, by collecting and analyzing the stress, strain, and charge data of the composite coal and rock sample during the uniaxial loading process, the mathematical relationship between DE and ERE can be revealed, and the correctness and rationality of the theoretical derivation relationship can be verified. To ensure the universality and accuracy of the experimental results, a total of 9 specimens were made in this study, which was denoted as f1−f9, divided into 3 groups equally, and tested with 3 different loading rates. The loading rate and the corresponding sample groups are 0.1 mm/min (f1−f3), 0.3 mm/min (f4−f6), and 1.0 mm/min (f7−f9).

(1) Each layer of the sample with tape is fixed, the sample is placed in the shielding cover, the shielding cover is put on the test bench of the press, and the charge meter probe is placed in the shielding cover in the middle part of the coal body, 5 mm from the surface of the sample.

(2) Before starting the test, the electrical equipment that is not related to the experiment and other equipment that requires power are switched off, and the doors and windows of the laboratory are closed to avoid unnecessary movement of personnel, so as not to affect the data results.

(3) The power is turned on, and the loading rate is set to 0.1, 0.3, and 1.0 mm/min; first, the load and charge sensing acquisition system is started, then the press and loading are started, and the stress, strain, and charge data are recorded.

(4) The loading conditions of the coal and rock samples are monitored. After the charge induction signal reaches the peak value, the sample ruptures. The experimental system is closed and the data are saved.

AUTHOR INFORMATION

Corresponding Author
Zhen Yang* — College of Electrical and Engineering Control, Liaoning Technical University, Huludao 125105, China; Email: yangzhen1980219@163.com

Authors
Xin Li — College of Electrical and Engineering Control, Liaoning Technical University, Huludao 125105, China

Hui Zuo — College of Electrical and Engineering Control, Liaoning Technical University, Huludao 125105, China; orcid.org/0000-0002-3100-7702

Hao Li — College of Electrical and Engineering Control, Liaoning Technical University, Huludao 125105, China; orcid.org/0000-0002-8020-9220

Weiman Sun — College of Electrical and Engineering Control, Liaoning Technical University, Huludao 125105, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c06511

Notes
The authors declare no competing financial interest.

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