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ISOTOPE-DEPENDENT Zn(n,α) REACTION CHANNELS IN NEUTRON-IRRADIATED ZnO NANOPARTICLES

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Abstract: This study investigates neutron-induced (n,α) nuclear reaction channels in ZnO nanoparticles with emphasis on the stable isotopes of zinc and their transmutation products. Natural zinc consists primarily of ^{64}Zn, ^{66}Zn, ^{67}Zn, and ^{68}Zn, which can undergo neutron-induced alpha-emission reactions to form different nickel isotopes. The analyzed reaction channels include ^{64}Zn(n,α)^{61}Ni, ^{66}Zn(n,α)^{63}Ni, ^{67}Zn(n,α)^{64}Ni, and ^{68}Zn(n,α)^{65}Ni. The cross-section data demonstrate that each isotope has a distinct neutron-energy-dependent behavior, indicating that the transmutation yield is governed by both isotopic abundance and neutron energy spectrum. In ZnO nanoparticles, these reactions may contribute to local Ni formation, alpha-particle-induced damage, recoil effects, oxygen-related defects, and lattice distortion. Therefore, neutron-induced (n,α) reactions should be considered an important mechanism for isotope-dependent transmutation, radiation damage accumulation, and possible nuclear-assisted modification of ZnO nanomaterials.

Keywords: ZnO nanoparticles, zinc activation, Zn(n, α)Ni reactions, Ni radionuclides.

1. Introduction

Zinc-based oxide nanoparticles are important functional materials because their structural, optical, electrical, and surface properties are strongly influenced by intrinsic defects, impurity centers, and external irradiation conditions [1–5]. Among these materials, ZnO nanoparticles are of interest due to their nanoscale morphology, high surface-to-volume ratio, and sensitivity to radiation-induced modification [6–8]. When such nanoparticles are exposed to neutron fields, their properties may change not only through conventional displacement damage, but also through nuclear reactions involving the stable isotopes of zinc. Natural zinc consists of several stable isotopes, mainly ^{64}Zn, ^{66}Zn, ^{67}Zn, and ^{68}Zn. Under neutron irradiation, these isotopes can undergo alpha-emission nuclear reactions. As a result, zinc nuclei are converted into nickel isotopes, while energetic alpha particles and recoil nuclei are produced. The main reaction channels considered in this study are ^{64}Zn(n,α)^{61}Ni, ^{66}Zn(n,α)^{63}Ni, ^{67}Zn(n,α)^{64}Ni, and ^{68}Zn(n,α)^{65}Ni. These reactions are important because they may cause isotope-dependent transmutation, formation of Ni-related impurity centers, and local radiation damage in the nanoparticle structure.

The probability of each (n,α) reaction is determined by its neutron-energy-dependent cross section. Therefore, the final transmutation yield in ZnO nanoparticles depends on both the natural abundance of each Zn isotope and the neutron energy spectrum. For example, ^{64}Zn is the most abundant stable zinc isotope and can be an important source of stable ^{61}Ni formation, while ^{66}Zn is significant from the activation viewpoint because it produces long-lived radioactive ^{63}Ni. In

contrast, the $^{68}Zn(n,\alpha)^{65}Ni$ reaction becomes more relevant under fast-neutron irradiation conditions.

In nanoparticles, the consequences of these nuclear reactions can be different from those in bulk materials [9–14]. The emitted alpha particles and recoil nickel nuclei can contribute to the formation of localized defects, oxygen-related vacancies, lattice distortion, and near-surface disorder. At the same time, transmutation-produced nickel atoms may modify the local electronic structure and chemical environment of ZnO. Thus, neutron-induced (n,α) reactions provide a possible pathway for nuclear-assisted modification and defect engineering of ZnO nanoparticles [15–21]. The aim of this article is to analyze the neutron-induced (n,α) reaction channels of stable zinc isotopes in ZnO nanoparticles using the available cross-section data. Special attention is given to the isotope-specific behavior of ^{64}Zn, ^{66}Zn, ^{67}Zn, and ^{68}Zn, their corresponding nickel products, and the possible role of these reactions in radiation-induced structural and compositional changes.

2. Radiation effects in ZnO nanoparticles and cross-section behavior of stable Zn isotopes

The (n,α) reaction in ZnO nanoparticles may influence the material through several mechanisms. First, the emitted alpha particle deposits energy locally, producing ionization and displacement damage. Second, the residual Ni nucleus receives recoil energy and may become incorporated into the ZnO lattice in a substitutional or interstitial configuration. Third, the local chemical environment around the transmutation site changes because a Zn atom is converted into a Ni atom. This process can generate Ni-related defect complexes, oxygen vacancy centers, and local lattice distortion. In nanoparticles, these effects may be enhanced because the particle size is comparable to the range of some secondary particles and recoil events. As a result, part of the alpha-particle energy may be deposited inside the nanoparticle, while another part may escape to the surrounding medium. This can create a non-uniform defect distribution between the nanoparticle core and surface region.

Because ^{64}Zn is the most abundant stable isotope, the $^{64}Zn(n,\alpha)^{61}Ni$ reaction is expected to be one of the most important stable-Ni-producing channels in natural ZnO. The ^{66}Zn isotope is also abundant, but its product, ^{63}Ni, is radiologically important because it is a long-lived beta-emitting isotope. Although ^{67}Zn has low natural abundance, its cross-section behavior may still be important under specific neutron-energy conditions. The ^{68}Zn channel becomes increasingly relevant in the fast-neutron region. Their contribution to neutron-induced transmutation depends on both natural abundance and neutron-energy-dependent reaction cross section.

3. Results and discussion

Figure 1 shows the neutron-induced $^{64}Zn(n,\alpha)^{61}Ni$ reaction cross section as a function of incident neutron energy. This reaction is one of the most important (n,α) channels in natural ZnO nanoparticles because ^{64}Zn is the dominant stable isotope of zinc, with an abundance of about 49%. As shown in Fig. 1, the cross section strongly depends on neutron energy. At low neutron energies, the cross section is relatively higher and gradually decreases with increasing energy. In the intermediate energy region, the reaction probability becomes very small. At higher energies, resonance-like fluctuations and step-shaped changes appear, indicating the influence of compound-nucleus processes and nuclear-level structure. For ZnO nanoparticles, this reaction has two main effects. First, it produces stable nickel atoms inside the nanoparticle matrix through nuclear transmutation. These Ni atoms act as impurity centers and modify the local electronic

structure and defect distribution. Second, the emitted alpha particle and recoil ^{61}Ni nucleus can generate localized radiation damage, including atomic displacements and oxygen-related defects. Therefore, the ^{64}Zn(n,α)^{61}Ni reaction can contribute to both compositional modification and defect formation in neutron-irradiated ZnO nanoparticles.

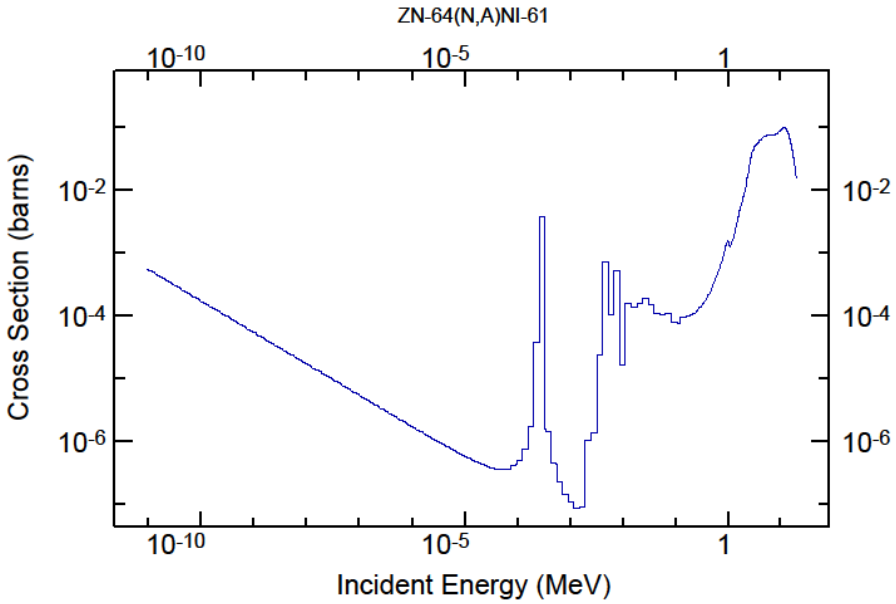

Fig. 1. Neutron-induced ^{64}Zn(n,α)^{61}Ni reaction cross section as a function of incident neutron energy in ZnO nanoparticles.

Figure 2 presents the neutron-induced ^{66}Zn(n,α)^{63}Ni reaction cross section as a function of incident neutron energy. This reaction is important for ZnO nanoparticles because ^{66}Zn is the second most abundant stable isotope of natural zinc, with an abundance of about 27.7%. As shown in Fig. 2, the cross section of the ^{66}Zn(n,α)^{63}Ni reaction remains very low over most of the investigated neutron-energy range. A gradual decrease is observed from the low-energy region toward intermediate energies, followed by a small increase at higher energies. Compared with the ^{64}Zn(n,α)^{61}Ni channel, the reaction probability for ^{66}Zn is considerably weaker. The main significance of this reaction is related to the formation of ^{63}Ni. Unlike ^{61}Ni, ^{63}Ni is a radioactive isotope with a long half-life. Therefore, even a low reaction cross section can be important under high neutron fluence or long irradiation period. In neutron-irradiated ZnO nanoparticles, this channel may contribute to low-level activation and the formation of Ni-related defect centers. The emitted alpha particle and recoil ^{63}Ni nucleus can also generate localized displacement damage, oxygen-related defects, and lattice distortion. Thus, the ^{66}Zn(n,α)^{63}Ni reaction should be considered mainly from the viewpoint of activation, transmutation-induced impurity formation, and radiation damage accumulation in ZnO nanoparticles.

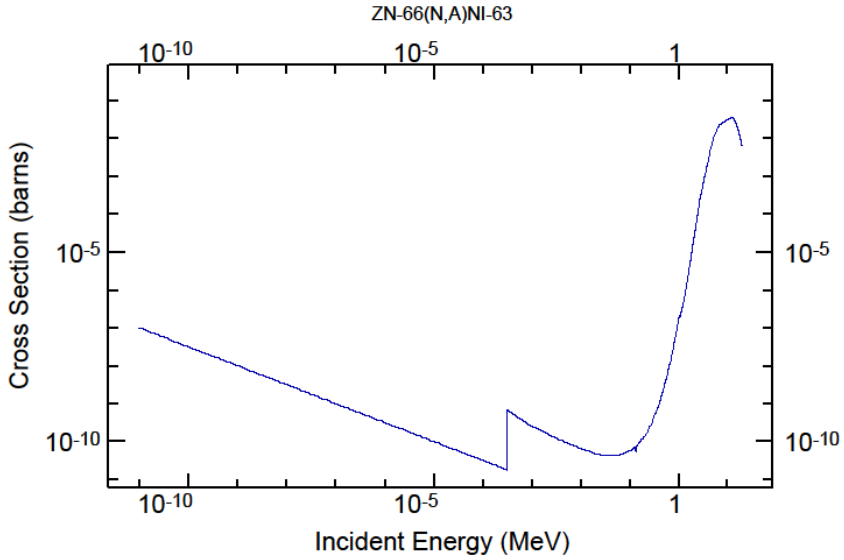

Fig. 2. Neutron-induced $^{66}Zn(n,\alpha)^{63}Ni$ reaction cross section as a function of incident neutron energy in ZnO nanoparticles.

Figure 3 shows the neutron-induced $^{67}Zn(n,\alpha)^{64}Ni$ reaction cross section as a function of incident neutron energy. This reaction converts the stable zinc isotope ^{67}Zn into stable ^{64}Ni isotope. Although ^{67}Zn has a relatively low natural abundance of about 4%, this channel is still important because the produced ^{64}Ni is a stable nickel isotope.

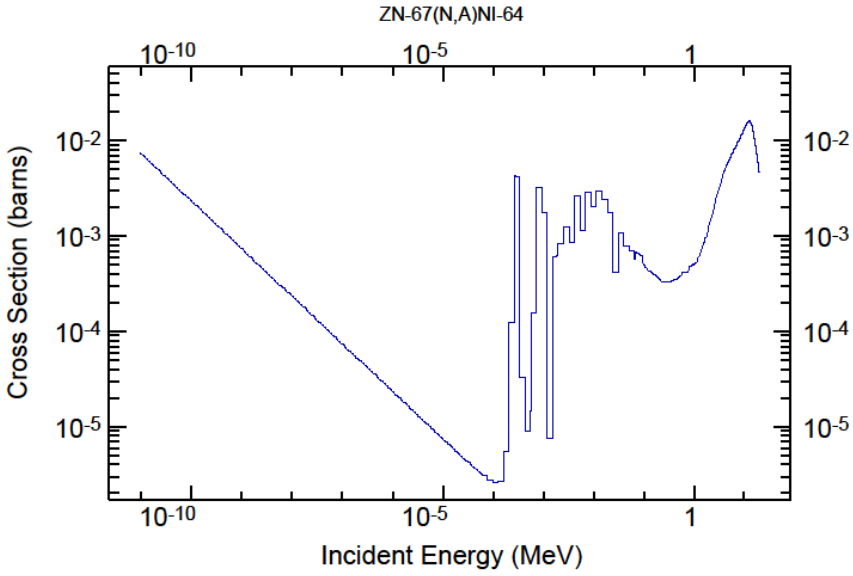

Fig. 3. Neutron-induced $^{67}Zn(n,\alpha)^{64}Ni$ reaction cross section as a function of incident neutron energy in ZnO nanoparticles.

As seen in Fig. 3, the cross section decreases from the low-energy region toward intermediate neutron energies, where the reaction probability becomes very small. At higher neutron energies, distinct resonance-like fluctuations and sharp changes are observed. These features indicate that the reaction show strong dependence on neutron energy and compound-nucleus excitation processes. In ZnO nanoparticles, the $^{67}Zn(n,\alpha)^{64}Ni$ reaction may contribute to local nickel formation and radiation-induced defect generation. The emitted alpha particle and recoil ^{64}Ni nucleus may produce localized displacement damage, oxygen-related defects, and lattice distortion. Therefore, even with the low abundance of ^{67}Zn, this reaction can play a role in neutron-induced compositional and structural modification of ZnO nanoparticles, especially under neutron spectra containing suitable fast or resonance-energy components.

Figure 4 shows the neutron-induced $^{68}Zn(n,\alpha)^{65}Ni$ reaction cross section as a function of incident neutron energy. This reaction converts the stable zinc isotope ^{68}Zn into radioactive ^{65}Ni isotope. The ^{68}Zn isotope has a relatively high natural abundance of about 18.5%, so this reaction can contribute noticeably to neutron-induced transmutation in natural ZnO nanoparticles.

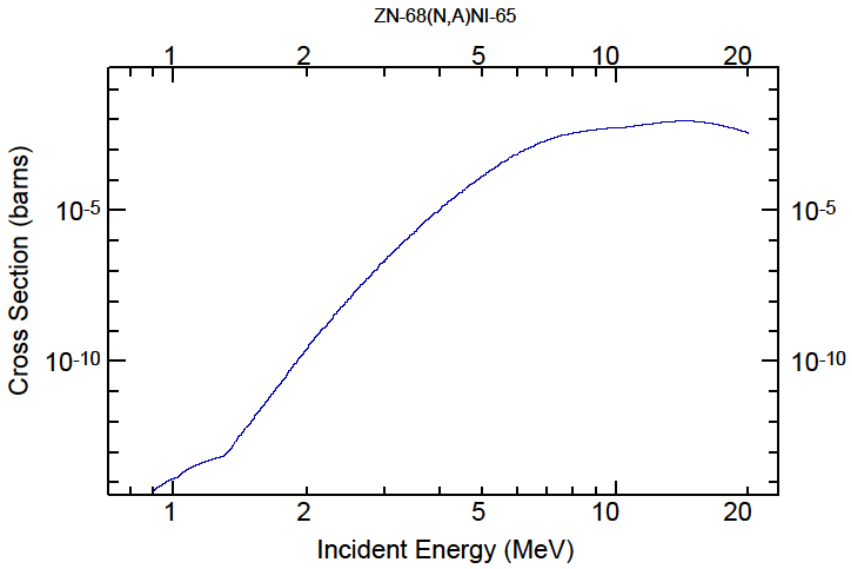

Fig. 4. Neutron-induced $^{68}Zn(n,\alpha)^{65}Ni$ reaction cross section as a function of incident neutron energy in ZnO nanoparticles.

As seen in Fig. 4, the cross section is very low at lower neutron energies, but it increases strongly in the MeV energy region. This indicates that the $^{68}Zn(n,\alpha)^{65}Ni$ reaction is primarily driven by fast neutrons rather than thermal or low-energy neutrons. For ZnO nanoparticles, this channel is important because it produces ^{65}Ni atoms together with energetic alpha particles. The recoil ^{65}Ni nucleus and emitted alpha particle can induce localized lattice disorder, oxygen-related defects, and near-surface damage. Since ^{65}Ni is radioactive but short-lived, this reaction may also contribute to temporary post-irradiation activation. Therefore, under fast-neutron irradiation, the $^{68}Zn(n,\alpha)^{65}Ni$ reaction can play an important role in both transmutation-induced Ni formation and defect accumulation in ZnO nanoparticles.

4. Conclusion

The neutron-induced (n,α) reactions of stable zinc isotopes represent an important nuclear transmutation pathway in ZnO nanoparticles. The evaluated cross-section data show that each zinc isotope has a different neutron-energy-dependent behavior, indicating that the final transmutation yield is governed not only by isotopic abundance but also by the neutron energy spectrum. The $^{64}Zn(n,\alpha)^{61}Ni$ reaction is particularly significant because ^{64}Zn is the dominant stable isotope of natural zinc and produces stable ^{61}Ni. The $^{66}Zn(n,\alpha)^{63}Ni$ reaction has a lower reaction probability but is significant from an activation point of view because it forms radioactive ^{63}Ni. The $^{67}Zn(n,\alpha)^{64}Ni$ channel contributes to stable nickel formation, while the $^{68}Zn(n,\alpha)^{65}Ni$ reaction becomes more relevant in the fast-neutron energy region. In ZnO nanoparticles, these reactions may lead to simultaneous compositional and structural modification. The formation of Ni isotopes inside the nanoparticle matrix may introduce impurity-related centers, while the emitted alpha particles and recoil nuclei can generate localized radiation damage, lattice distortion, and oxygen-related defects. Therefore, ZnO nanoparticles exposed to neutron irradiation may undergo isotope-dependent nuclear modification, defect accumulation, and transmutation-induced changes in their physicochemical properties. Overall, the Zn(n,α) reaction channels should be considered as an important mechanism for understanding radiation effects, activation behavior, and possible nuclear-assisted functionalization of ZnO-based nanomaterials.

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ИЗОТОПНО-ЗАВИСИМЫЕ КАНАЛЫ РЕАКЦИЙ Zn(n,α) В НЕЙТРОННО-ОБЛУЧЁННЫХ НАНОЧАСТИЦАХ ZnO

И.В. Иззатова

Резюме: В данном исследовании рассматриваются каналы ядерных реакций типа (n,α), индуцированных нейтронами в наночастицах ZnO_2, с акцентом на стабильные изотопы цинка и продукты их трансмутации. Природный цинк состоит преимущественно из изотопов ^{64}Zn, ^{66}Zn, ^{67}Zn и ^{68}Zn, которые могут вступать в реакции испускания α-частиц под действием нейтронов с образованием различных изотопов никеля. Проанализированы следующие каналы реакций: ^{64}Zn(n,α)^{61}Ni, ^{66}Zn(n,α)^{63}Ni, ^{67}Zn(n,α)^{64}Ni и ^{68}Zn(n,α)^{65}Ni. Данные по сечениям реакций показывают, что каждый изотоп характеризуется собственной зависимостью от энергии нейтронов, что свидетельствует о том, что выход продуктов трансмутации определяется как изотопным составом,

так и энергетическим спектром нейтронов. В наночастицах ZnO данные реакции могут способствовать локальному образованию никеля, возникновению радиационных повреждений, обусловленных α-частицами, появлению эффектов отдачи, формированию кислородсодержащих дефектов и искажению кристаллической решётки. Таким образом, нейтронно-индуцированные реакции типа (n,α) следует рассматривать как важный механизм изотопно-зависимой трансмутации, накопления радиационных повреждений и возможной ядерно-стимулированной модификации наноматериалов ZnO.

Ключевые слова: наночастицы ZnO, активация цинка, реакции Zn(n,α)Ni, радионуклиды никеля.

NEYTRONLA ŞÜALANMIŞ ZnO NANOZƏRRƏCİKLƏRİNDƏ İZOTOPDAN ASILI Zn(n,α) REAKSİYASI KANALLARI

İ.V. İzzətova

Xülasə: Bu tədqiqat sinkin stabil izotoplarına və onların transmutasiya məhsullarına xüsusi diqqət yetirməklə ZnO_2 nanozərrəciklərində neytronla induksiya olunan (n,α) nüvə reaksiya kanallarını araşdırır. Təbii sink əsasən ^{64}Zn, ^{66}Zn, ^{67}Zn və ^{68}Zn izotoplarından ibarətdir və bu izotoplar neytronla induksiya olunan alfa-emissiya reaksiyalarına məruz qalaraq müxtəlif nikel izotoplarını əmələ gətirə bilər. Təhlil edilən reaksiya kanallarına $^{64}Zn(n,\alpha)^{61}Ni$, $^{66}Zn(n,\alpha)^{63}Ni$, $^{67}Zn(n,\alpha)^{64}Ni$ və $^{68}Zn(n,\alpha)^{65}Ni$ daxildir. Kəsişən sahə məlumatları göstərir ki, hər bir izotop neytron enerjisindən asılı olaraq fərqli davranış nümayiş etdirir, bu da transmutasiya çıxımının həm izotopların çoxluğu, həm də neytron enerji spektri tərəfindən idarə olunduğunu göstərir. ZnO nanozərrəciklərində bu reaksiyalar yerli Ni yaranmasına, alfa-hissəciklərin yaratdığı zərərə, geriçəkilmə (recoil) effektlərinə, oksigenlə əlaqəli defektlərə və kristal qəfəsin deformasiyasına səbəb ola bilər. Buna görə, neytronla induksiya olunan (n,α) reaksiyaları izotopdan asılı transmutasiya, şüalanma zərərlərinin toplanması və ZnO nanomateriallarının mümkün nüvə-vasitəli modifikasiyası üçün mühüm mexanizm kimi nəzərə alınmalıdır.

Açar sözlər: ZnO nanozərrəcikləri, sinkin aktivləşməsi, Zn(n,α)Ni reaksiyaları, Ni radionuklidləri.