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Opinion

Isomers in the Cosmos

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Abstract: The nucleosynthesis of chemical elements has been established to be the result of a variety of different types of nuclear reactions in stars. Under the extreme temperatures and densities encountered in such environments, nuclear isomers can be populated and thus complicate our understanding of these processes. In this paper, I have chosen to discuss five cases that illustrate how nuclear isomers can play important roles in the nucleosynthesis of chemical elements.

Keywords: nuclear isomers; nucleosynthesis

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1. Introduction

In their landmark paper "Synthesis of the Elements in Stars", Burbidge, Burbidge, Fowler, and Hoyle (B^2FH) laid out the basic framework for understanding how nuclear reactions provide the energy to power the stars and that the "ashes" of these reactions are the chemical elements we observe today in the universe [1]. Charged-particle-induced reactions involving protons, alpha particles, ^{12}C, and ^{16}O lead to the production of elements up to the iron region of the periodic table. These types of fusion reactions stop there because of the increasing Coulomb barriers and because the nuclear binding energy per nucleon reaches a maximum in this area, thus making further reactions endothermic. To explain how the heavier elements were formed, B^2FH proposed two different types of neutron capture mechanisms. In the s-process, (n,γ) reactions take place at rates that are "slow" compared to those of intervening beta decays. It is now thought that the s-process takes place in the helium-burning zones of red giant stars. The s-process produces about half of the isotopes between A = 56 and A = 209, and terminates at ^{209}Bi. To account for the origin of the other half of the isotopes below mass 209 and to explain how thorium and uranium are synthesized, the r-process was proposed. In the r-process (n,γ), reactions take place at rates that are "rapid" compared to intervening beta decay rates. Thus, during the r-process, very neutron-rich unstable nuclei are produced. Once the neutron source turns off, these nuclei beta decay, producing the stable isotopes we observe today. Possible sites for the r-process are still being debated, with supernova explosions and neutron star mergers being the leading candidates.

All of these nucleosynthesis reactions require extremely high temperatures and densities compared to those we normally encounter on Earth. As a result, nuclear isomers are often populated either directly through such reactions or indirectly through processes such as photoexcitation. In some cases, the presence of isomers presents challenges to understanding how certain isotopes are produced, but can also be utilized to gain information about the conditions under which these reactions take place. In this paper, five isotopes with isomers were chosen to illustrate these concepts: ^{26}Al, ^{99}Tc, ^{148}Pm. ^{176}Lu, and ^{180}Ta.

2. ^{26}Al

In 1977, Lee et al. reported ^{26}Mg/^{24}Mg excesses in grains from the Allende meteorite that correlated with the Al/Mg elemental ratios [2]. This was interpreted to mean that the observed ^{26}Mg was actually incorporated into the grains as live ^{26}Al, which decayed in situ to produce the present-day anomalies. Given the relatively short half-life of ^{26}Al, at 7.2×10^5 years, this implies that the nucleosynthetic event that produced the ^{26}Al must

have occurred very shortly before the formation of our solar system. This led to theories that perhaps a nearby supernova explosion produced this ^{26}Al and may have actually triggered the formation of our solar system. Subsequently, high-energy-resolution germanium detectors aboard NASA's High-Energy Astronomy Observatory, HEAO3, observed the 1.809 MeV gamma-ray line produced by the decay of ^{26}Al in the interstellar medium [3]. This demonstrated that the nucleosynthesis of ^{26}Al is an on-going activity in our galaxy. More recently, Diehl et al. utilized the INTEGRAL spectrometer's gamma-ray detectors to measure the intensity of this same line and determined the total mass of ^{26}Al present in our galaxy today to be 2.8 $\pm$ 0.8 solar masses. From this, they inferred that the rate of core collapse supernovas in our galaxy is 1.9 $\pm$ 1.1 per century [4].

As shown in Figure 1, the nuclear structure of ^{26}Al adds an interesting complication to understanding the nucleosynthesis of this isotope. The first excited state of ^{26}Al is a $J^{\pi} = 0^{+}$ isomer at an excitation energy of 228 keV that β^{+} decays to ^{26}Mg with a 6.3 s half-life. ^{26}Al is thought to be produced in stars via the ^{25}Mg (p,γ) reaction, which is known to populate both the ground state and isomer [5,6]. Recent measurements of lower-lying resonances in the ^{25}Mg (p,γ) reaction indicate that the net production of ^{26}Al^{g} is somewhat higher than previously thought [7]. Ward and Fowler [8] showed that, at low temperatures (<4 $\times$ 10^{8} K), the isomer and ground state can be treated as separate entities and that the beta decay of the isomer somewhat reduces the net production rate of ^{26}Al^{g}. However, at higher temperatures, namely T~(1–2) $\times$ 10^{9} K, these authors showed that photoexcitation reactions to states of intermediate spin (such as the states at 1759 and 2070 keV) can rapidly lead to thermal equilibration between the ground state and isomer. This then leads to a drastic reduction in the effective half-life of an ^{26}Al nucleus to only about 16.5 min for T = 1 $\times$ 10^{9} K. Nevertheless, a complete network calculation [8] shows that sufficient ^{26}Al^{g} can be produced and survive to explain the ^{26}Mg anomalies observed in the Allende meteorite and in the interstellar medium.

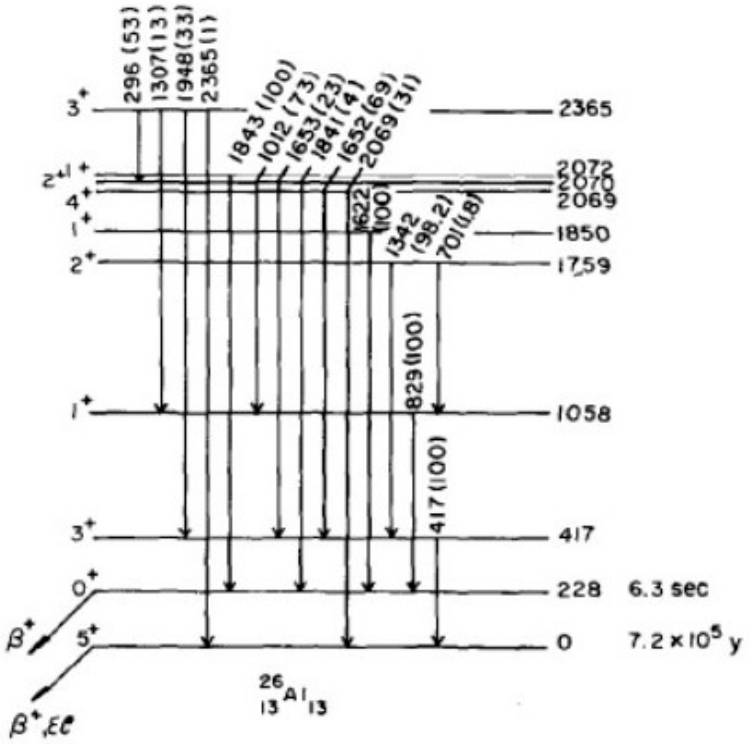

Figure 1. Partial level and decay scheme of ^{26}Al. Taken from Ref. [9].

3. ^{99}Tc

Technetium is one of only two chemical elements below uranium on the periodic table that have no stable isotopes (the other being promethium, one of whose isotopes is discussed later in this paper). In 1952, P. W. Merrill reported the observation of spectral

lines from the element technetium from the surfaces of some red-giant stars [10]. This observation provided strong evidence that nucleosyntheses in stars are still taking place throughout the universe. ^{99}Tc is believed to be produced in stars via the s-process from neutron captures on ^{98}Mo, followed by the beta decay of ^{99}Mo. The long-lived ^{99}Tc has a ground state with a half-life of 2.1 × 10^5 years and a $t_{1/2}$ = 6.0 h isomer, ^{99}Tc^m, at an excitation energy of 142.7 keV [11]. The s-process is thought to take place in the helium-burning zones of red-giant stars and at temperatures in the order of 3 × 10^8 K. Under such conditions, the half-life of this isotope can be drastically reduced via photo excitation reactions. A partial level and decay scheme of ^{99}Tc is shown in Figure 2.

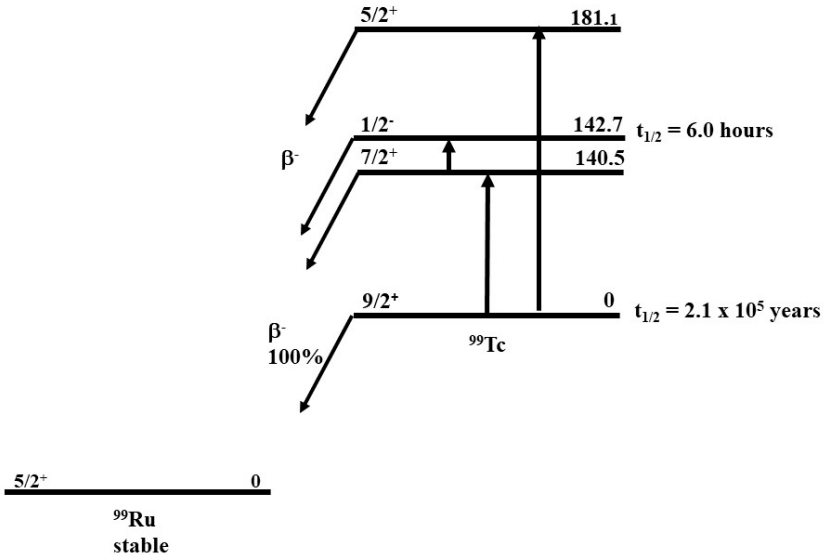

Figure 2. Partial level and decay scheme of ^{99}Tc. The possibility of photoexcitation from ^{99}Tc^g to some higher-lying levels, followed by beta decay to ^{99}Ru is shown.

At T= 3 × 10^8 K, the ground state and low-lying excited states of ^{99}Tc rapidly come into thermal equilibrium. Although the beta decays of the levels at 140.5 and 181.1 keV have not been experimentally observed, they allow Gamow–Teller transitions and therefore can provide potentially rapid decay pathways for ^{99}Tc. Takahashi et al. [12] carried out detailed shell model calculations and showed that the effective half-life of ^{99}Tc under expected s-process conditions could be in the order of only 20 years. At the surface of the star, however, where the temperature is much lower, the half-life of ^{99}Tc would be its known ground state value. Thus, if the technetium is dredged up from the interior of the star over a short time period, this could explain the presence of ^{99}Tc on the surfaces of red-giant stars.

Although unrelated to nuclear astrophysics, it is interesting to note that ^{99}Tc^m has very important practical applications. Because of its relatively short half-life, and its emission of low-energy betas and gammas, it has become the most widely used medical radioisotope in the world. Tens of millions of diagnostic procedures are performed annually worldwide utilizing this short-lived isomer.

4. ^{148}Pm

In the slow neutron capture process (s-process), neutron fluxes are relatively low and, as a result, if a radioactive isotope is produced, there is normally enough time between neutron captures for beta decay to occur. However, if the half-life of the unstable isotope is sufficiently long, then as a result of the competition between neutron capture and beta decay, a so-called "branch point" in the s-process path can occur. Thus, branch points offer the possibility of inferring the neutron density during the s-process. ^{148}Pm is an example of this phenomenon. The path of the s-process around A = 148 is shown in Figure 3.

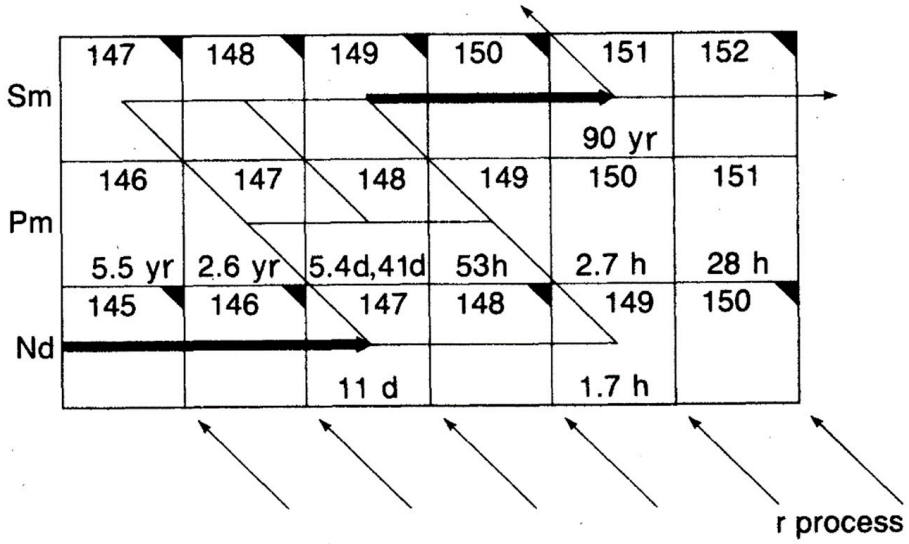

Figure 3. s-process path near A = 148 indicating the branches at ^{147}Pm and ^{148}Pm. Stable nuclei are indicated by shaded triangles. Diagonal lines indicate β^- decays. Taken from Ref. [13].

It has been observed that for s-process nuclei away from neutron magic numbers, $\sigma_{n\gamma}$N (Z,A − 1) = $\sigma_{n\gamma}$N (Z,A), where $\sigma_{n\gamma}$ is the neutron capture cross section and N (Z,A) is the isotopic abundance of the species. However, Winters et al. [14] showed that $\sigma_{n\gamma}$N (^{148}Sm)/$\sigma_{n\gamma}$N (^{150}Sm) = 0.91 ± 0.03, thus indicating a branch at ^{148}Pm. Once again, the nuclear structure adds an interesting complication to interpreting the results of the ^{148}Pm branch point. The ground state of ^{148}Pm has $J^\pi = 1^-$ and beta decays to ^{148}Sm, with a 5.4-day half-life. A $J^\pi = 6^-$, $t_{1/2}$ = 41 days isomer is located at a 137.2 keV excitation energy, and also beta decays 95% of the time. It has been estimated that neutron captures on ^{147}Pm ($J^\pi = 7/2^+$) would produce roughly equal amounts of ^{148}Pm^g and ^{148}Pm^m. Furthermore, calculations indicate that the neutron capture cross-section on the isomer is approximately 2.5 barns versus 1.5 barns for the ground state [14]. Putting all of this information together leads to the conclusion that, if the populations of ^{148}Pm^g and ^{148}Pm^m were equal, then the s-process neutron density would be 1×10^8/cm^3. On the other hand, if the ground state and isomer came into thermal equilibrium, then the isomer population would be much lower and the inferred neutron density would be 3×10^8/cm^3 (Ref. [15]).

To resolve this issue, Lesko et al. [13] performed a detailed study of gamma ray transitions in ^{148}Pm and found several levels below 500 keV excitation energy that decay to both the ground state and isomer. Such levels can serve as pathways for photoexcitation reactions to allow ^{148}Pm^g and ^{148}Pm^m to reach thermal equilibrium during the s-process. From their study, Lesko et al. concluded that such equilibration will take place for temperatures above approximately 0.9×10^8 K, which is lower than the temperature at which the s-process is believed to occur. Thus, the ^{148}Pm branch point suggests that the s-process neutron density is 3×10^8/cm^3, in agreement with that found from other branch point nuclei.

5. ^{176}Lu

Among the few long-lived naturally occurring radioisotopes is ^{176}Lu, with a ground state $J^\pi = 7^-$ and half-life of approximately 4×10^{10} years. Because of its long half-life and reasonably large natural isotopic abundance of 2.59%, ^{176}Lu is widely used as a geochronometer [16]. As can be seen in Figure 4, ^{176}Lu is produced in the s-process from neutron captures on ^{175}Lu and is shielded from the r-process by the stability of ^{176}Yb.

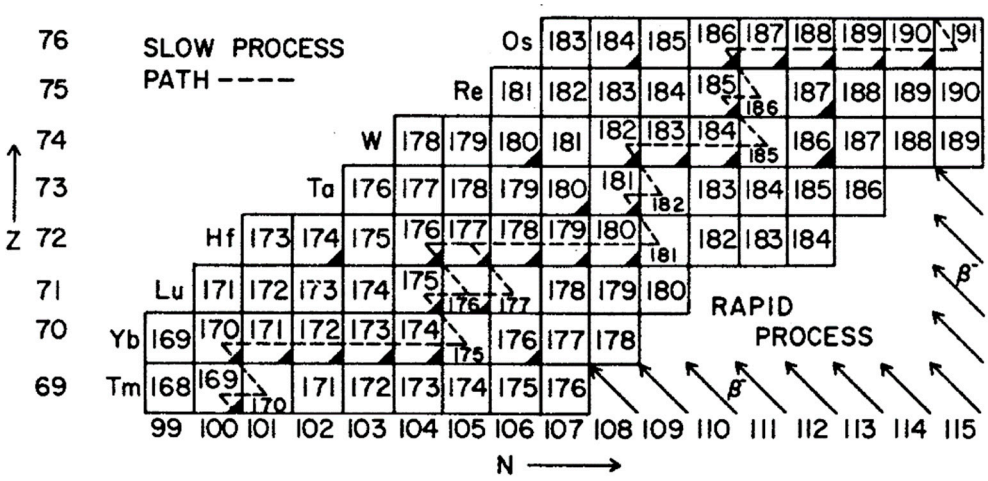

Figure 4. Region of the nuclear chart around A = 176 showing the path of the s-process and beta decays from the r-process. Taken from Ref. [17].

In the 1970s, it was suggested that ^{176}Lu could be used to determine the age of s-process nuclei [18,19]. However, the presence of a $J^{\pi} = 1^{-}$ isomer at an excitation energy of 123 keV that beta decays to ^{176}Hf with a 3.7-hour half-life but does not decay to ^{176}Lu^{g} calls the utility of this isotope as a chronometer into question. If ^{176}Lu^{g} and ^{176}Lu^{m} reached thermal equilibrium during the s-process, then the effective half-life of the nucleus would be drastically reduced. A possible mechanism by which this could happen is shown in Figure 5. Using very strong radioactive sources, Norman et al. [20] showed that ^{176}Lu^{m} was produced from ^{176}Lu^{g} with the gamma rays from ^{60}Co decay but not with those from ^{137}Cs decay. These observations suggested that a mediating level like that shown in Figure 5 exists above 662 keV and below a 1332 keV excitation energy in ^{176}Lu.

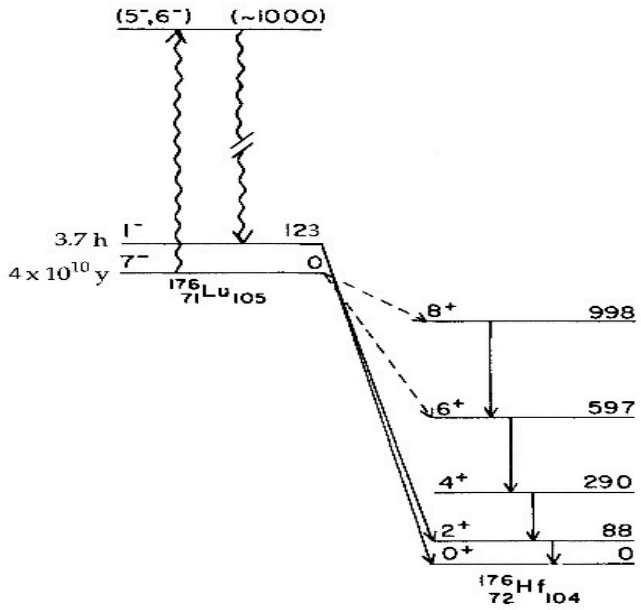

Figure 5. Decay schemes of ^{176}Lu^{g} and ^{176}Lu^{m}. The equilibration of these two levels during the s-process could occur via photoexcitation to a higher-lying level of intermediate spin, which subsequently decays both of these states. Taken from Ref. [17].

Subsequently, by performing detailed studies of gamma ray transitions in ^{176}Lu, two groups confirmed the existence of such a mediating level at an excitation energy of 838.5 keV [17,21]. This level guarantees that for s-process temperatures above 3×10^{8} K, ^{176}Lu^{g} and ^{176}Lu^{m} will be in thermal equilibrium. As a result, at such temperatures, the

effective half-life of ^{176}Lu would be less than 0.25 years [17]. Thus, the use of ^{176}Lu as an s-process chronometer has been ruled out. The fact that not all ^{176}Lu is destroyed by this mechanism has led to the idea that, instead of using it as an s-process chronometer, it could be used instead as a means to determine the temperature at which the s-process takes place [21].

6. ^{180}Ta

^{180}Ta bears the distinction of being the only naturally occurring isotope that is found in an isomeric state. As can be seen in Figure 6, the ground state of this nucleus has $J^{\pi} = 1^{+}$ and decays with an 8.1-hour half-life to ^{180}W and ^{180}Hf via beta minus and electron capture decays, respectively. The long-lived isomer is actually the second excited state of this nucleus at 77 keV and its decay has not yet been experimentally observed [22]. Another interesting feature of ^{180}Ta^{m} is that, despite its low natural isotopic abundance of 0.012%, the nucleosynthetic mechanism by which it is produced has yet to be positively identified. As can be seen in Figure 4, ^{180}Ta appears to be shielded from both the s- and r-processes. However, Beer and Ward suggested that ^{180}Ta^{m} could be produced via a one- or two-step branch off the s- and/or r-process paths [23]. They proposed that a small beta decay branch from the $J^{\pi} = 8^{-}$ isomer in ^{180}Hf (produced at some level in the s-process) could explain the abundance of ^{180}Ta^{m}. If that beta decay branch proved to be too small to account for all of the ^{180}Ta^{m}, then the r-process could potentially make up the difference through a beta decay branch of ^{180}Lu (produced in the r-process) to the ^{180}Hf isomer, followed by its decay to ^{180}Ta^{m}. The basic ideas of this model are shown in Figure 6.

Following the Beer and Ward proposal, a series of experiments were carried out to search for these previously unobserved beta decay branches. Kellogg and Norman performed careful measurements of the decay of ^{180}Hf^{m} that showed beta minus decay branches, but which were too small to account for the s-process production of ^{180}Ta^{m} (Refs. [24,25]). Searches for an r-process contribution to ^{180}Ta^{m} via the beta decay of ^{180}Lu were also negative [26–28].

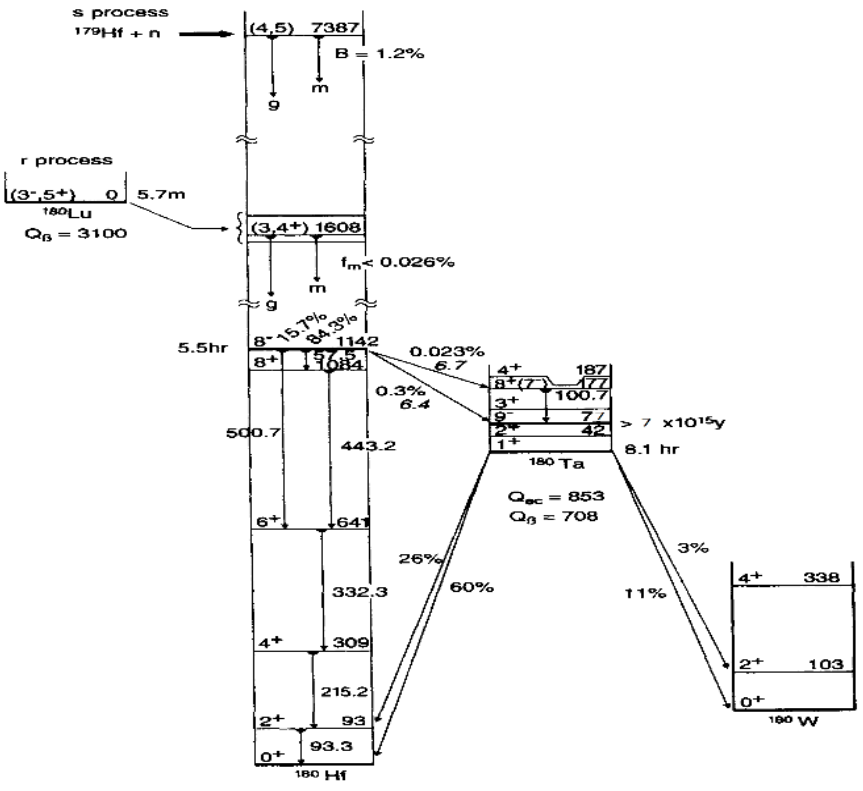

Figure 6. Partial level scheme of ^{180}Ta and the beta decays of ^{180}Lu and ^{180}Hf^{m} proposed by Beer and Ward to explain its nucleosynthesis. Taken from Ref. [25].

Another issue concerning the nucleosynthesis of ^{180}Ta is the question of its survivability in a stellar environment. Lakosi and Nguyen [29] showed that irradiations of ^{180}Ta^{m} using gamma rays from a strong ^{60}Co source produced the activity of the 8.1-hour ^{180}Ta^{g}. However, no such effect was observed when a ^{137}Cs source was used. This suggests that a "mediating level" that decays to both ^{180}Ta^{g} and ^{180}Ta^{m} exists above 662 keV and below 1332 keV. From this result, they inferred that the effective half-life of ^{180}Ta at a temperature of 3×10^8 K would be reduced to a maximum of 42 days. Two detailed experiments using multi-detector gamma-ray spectrometers were conducted to search for such mediating levels, but no conclusive evidence was found [30,31]. While there are alternative ideas on how ^{180}Ta is produced, the origin of nature's rarest isotope remains a mystery.

7. Conclusions

^{26}Al, ^{99}Tc, ^{148}Pm, ^{176}Lu, and ^{180}Ta all have isomers that influence the nucleosynthesis of these nuclei. In this paper, the specific effects for each of these isotopes have been discussed. Recently, other groups [32–35] have performed detailed theoretical studies on the influence of astronomical environments on the nuclear properties of these and other isotopes, including ^{34}Cl, and ^{85}Kr. New accelerator complexes, such as the Facility for Rare Ion Beams at Michigan State University, will enable ever more detailed studies of these and other isomers further from the valley of beta stability. Thus, the influences of nuclear structure and the harsh conditions in which these nuclei are produced combine to provide a rich area for past, present, and future research.

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