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THE EFFECT OF INELASTIC NEUTRON ACCELERATION BY ISOMERIC NUCLEI ON THE *s*-PROCESS NUCLEOSYNTHESIS

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ABSTRACT

We show that the recently discovered reaction of inelastic neutron acceleration by isomeric nuclei (INNA-reaction) can cause a considerable change in the abundances of elements produced by the pulsed *s*-process. We have chosen ^{85m}Kr branching to demonstrate this effect in more detail.

Subject headings: nuclear reactions — nucleosynthesis

I. INTRODUCTION

If a neutron strikes a long-lived excited (isomeric) nucleus, the inelastic neutron acceleration (INNA) reaction becomes possible in which the neutron carries away the excitation energy. Such a reaction was predicted theoretically long ago (Petrov 1959) but only recently has been discovered experimentally (Kondurov, Korotkikh, and Petrov 1979, 1981). Here we show that one should take the INNA reaction into account when calculating the abundances of elements produced by the pulsed *s*-process.

At temperatures of about $T_8 \approx 3$ ($kT \approx 30$ keV) which are usual for the *s*-process, a noticeable fraction of nuclei appear in their excited states. If transition to the stable ground state is the main decay mode, then after some time period thermal equilibrium occurs so that the Boltzmann distribution is achieved (the isomer is "thermalized"). However, if the main mode is nuclear destruction (β-decay, depletion, etc.), the stationary distribution may differ considerably from the equilibrium one (Ward and Fowler 1980). If the isomer is thermalized, one can use an effective temperature-dependent rate of nuclide destruction in the *s*-process calculation. Otherwise, the ground and isomeric states should be separately included in the nuclide inventory for network calculations. The abundances of nuclides following some key isomers in the *s*-process chain may change by an order of magnitude depending on whether they are thermalized or not (Cosner, Iben, and Truran 1980). While considering different paths of thermalization, Ward and Fowler (1980) have mentioned that the INNA reaction (they called it the "superelastic scattering") could enhance the transitions to the ground state, thus facilitating the thermalization (though they did not perform any estimates). When no thermalization occurs, the INNA reaction can be still important because it diminishes the lifetime of the isomeric state and the relative probability of its decay. Important examples of the isomers which are not thermalized are ^{85m}Kr and ^{180m}Hf (Beer and Käppeler 1981).

II. CALCULATIONS

A considerable fraction of isomeric nuclei will have enough time to transfer their energy to the neutrons only if the condition

$$\sigma_{in}\phi\tau_m \gtrsim 1 \qquad (1)$$

is satisfied. Here σ_{in} is the INNA cross section (in what follows, it is for 30 keV neutrons), ϕ is the neutron flux, and τ_m is the lifetime of the isomer ($\tau_m \equiv T_{1/2}/\ln 2$). One must bear in mind that even heavy atoms are highly ionized under *s*-process conditions so that conversion is hindered. Thus, τ_m may considerably exceed its laboratory value if the conversion coefficients for the isomeric transition are big enough (Beer and Macklin 1982). The value of σ_{in} depends on the energy of the isomeric transition and on its type. Earlier we have calculated the energy-dependent INNA cross sections for a number of M4 isomers (^{85m}Kr, ^{87m}Sr, ^{91m}Nb, ^{113m}In, and ^{115m}In) using the optical model (OM) and the Hauser-Feshbach-Moldauer (HFM) formulae (Petrov and Shlyakhter 1976, 1977). In the 20–50 keV region, σ_{in} is about 10–100 millibarns. For $\tau_m = 10^4$ s, the neutron flux required by equation (1) is $\phi = 10^{20}$–10^{21} neutrons cm^{-2} s^{-1} (the corresponding density of free neutrons is $n = 5 \times 10^{11}$ to 5×10^{12} neutrons cm^{-3}). Such high fluxes may occur, for example, in the helium-shell flashing intermediate mass stars, as suggested by Iben (1977). The explicit time dependence of the free-neutron density obtained by Cosner, Iben, and Truran (1980) was used

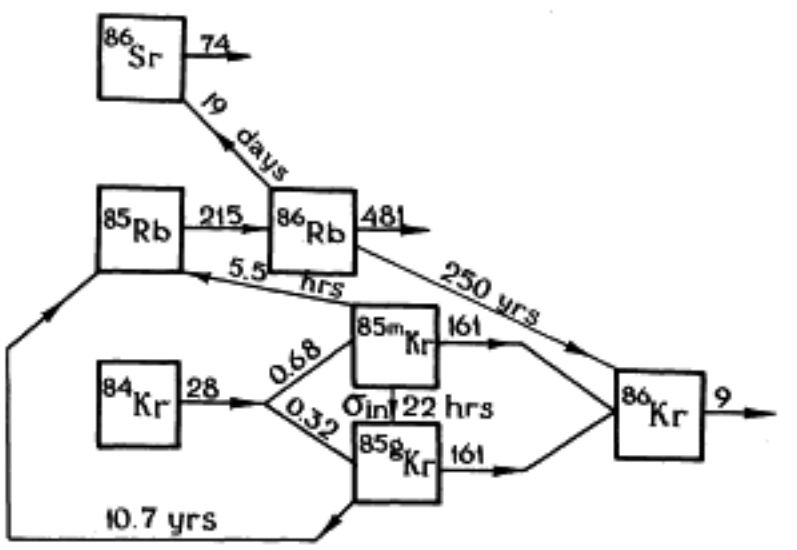

FIG. 1.—Branching in the ^{85}Kr region. Gamma-decay and INNA reaction are indicated by the vertical arrows; Beta-decays and electron capture, by the diagonal arrows, and neutron captures by the horizontal arrows. Capture cross sections (in millibarns) and β-decay half-lives are those used by Cosner, Iben, and Truran (1980).

TABLE 1

TIME-DEPENDENT NUCLIDE ABUNDANCES IN THE ^{85}Kr REGION (Si ≡ 10^6)

t (s)	ϕ (neutrons cm^{-2} s^{-1})	σ_{in} = 0 mb					δ_{in} = 25 mb					σ_{in} = 100 mb				
		^{85g}Kr	^{86}Kr	^{85}Rb	^{86}Rb	^{86}Sr	^{85g}Kr	^{86}Kr	^{85}Rb	^{86}Rb	^{86}Sr	^{85g}Kr	^{86}Kr	^{85}Rb	^{86}Rb	^{86}Sr
0	5.9×10^{19}	0	8.1	4.2	0	2.7	0	8.1	4.2	0	2.7	0	8.1	4.2	0	2.7
2.5×10^5	5.5×10^{19}	1.8	11	1.7	0.77	1.0	2.0	10	1.9	0.76	1.0	3.0	12	1.6	0.72	0.99
1.1×10^6	4.6×10^{19}	2.1	22	1.6	0.72	0.12	2.4	20	1.9	0.70	0.12	5.1	37	1.5	0.66	0.12
4.6×10^6	2.2×10^{19}	2.1	35	1.8	0.76	0.18	2.5	35	1.9	0.75	0.17	5.4	78	1.7	0.73	0.17
1.7×10^7	3.2×10^{18}	2.1	38	1.9	0.67	0.88	2.5	41	1.9	0.67	0.88	5.6	92	1.9	0.67	0.87
6.5×10^7	6.9×10^{16}	2.0	38	2.0	0.074	3.2	2.4	42	2.0	0.075	3.2	5.3	94	2.2	0.079	3.3
∞	0	0	38	4.0	0	3.3	0	42	4.4	0	3.3	0	94	7.4	0	3.4

NOTE.—Like Cosner, Iben, and Truran (1980), we kept the ^{84}Kr abundance constant (=27). Note that severe depletion of ^{85}Rb shown in their Table 3 must be wrong. Due to its large capture cross section, this nuclide rapidly reaches equilibrium concentration. Hence, its abundance is proportional to that of ^{84}Kr multiplied by the ratio $\sigma_{^{84}Kr}/\sigma_{^{85g}Rb}$ and the product of branching ratios 0.68 × 0.8 = 0.54. This estimate gives a nearly constant value of approximately 1.9 for the ^{85}Rb concentration.

in several papers (Beer *et al.* 1981; Ward and Beer 1981; Käppeler *et al.* 1982).

Cosner, Iben, and Truran (1980) performed detailed numerical calculations of the production of the elements with $A = 84$–88 through the pulsed *s*-process. These authors have abandoned the assumption that ^{85m}Kr is thermalized and thus managed to improve the agreement of the predicted abundances with the observed ones. In order to illustrate the effect of the INNA reaction, we repeat here their calculation for the $A = 84$–86 region.

Our network and the adopted values of nuclear constants are shown in Figure 1. The INNA cross section for ^{85m}Kr is calculated using the HFM formulae. The parameters of the OM potential are chosen in the spirit of the SPRT method of Lagrange (Lagrange 1975; Petrov and Shlyakhter 1977). The value of σ_{in} is proportional to the neutron strength function S_0, which is unknown for ^{85m}Kr. If the OM potential for ^{85m}Kr fits the value $S_0 = (0.26 \pm 0.03) \times 10^{-4}$ for ^{87}Sr (Mughabhab and Garber 1973), σ_{in} is about 25 millibarns in the 30–40 keV region. The latest value $S_0 = (0.39 \pm 0.05) \times 10^{-4}$ for ^{87}Sr (Mughabhab, Divadeenam, and Holden 1981) increases σ_{in}. Finally, if the value $S_0 = (1.0 \pm 0.2) \times 10^{-4}$ for ^{85}Rb (Mughabhab *et al.* 1981) is fitted, σ_{in} will increase even more. Because of this uncertainty, we have performed the calculation for two values of σ_{in}: 25 and 100 millibarns.

III. RESULTS AND DISCUSSION

The results for a single pulse are presented in Table 1. As one would expect, the main effect of the INNA reaction is the increase of ^{85g}Kr (the ground state) abundance as well as the abundances of its immediate products ^{86}Kr and ^{85}Rb. Because of the delay of about 15 years in the ^{85}Rb production, the INNA reaction increases its concentration only at the end of the pulse. Neutron flux is already small by that time, so that ^{86}Rb and ^{86}Sr concentrations are nearly the same as without the INNA reaction. However, in the subsequent pulses, the INNA reaction will increase their abundances too.

The cross sections used above are not precise enough for a reliable calculation of nuclide abundances. For example, the values of ^{85}Kr capture cross section calculated by several authors vary from 25 to 155 millibarns (see Käppeler *et al.* 1982). Furthermore, a population probability for the isomeric level of ^{85m}Kr of $P = 0.68$ was adopted here to be the same as for thermal neutrons ($kT = 0.025$ eV), while the special measurements at $kT = 30$ keV (Beer and Käppeler 1981) gave the value $P = 0.54 \pm 0.07$. The calculated INNA cross section is not quite reliable as well. Let us note, by the way, that one can estimate the sensitivities of the calculated nuclide densities to the adopted values of cross sections using the "depletion functions" approach (Shlyakhter 1983).

Thus, our results should be considered only as an illustration of the importance of the INNA reaction and not as a consistent calculation of the actual abundances.

IV. CONCLUSIONS

The inelastic acceleration of neutrons by ^{85m}Kr should be taken into account in the calculations of nucleosynthesis through the pulsed *s*-process if the neutron flux reaches values of about 10^{19} neutrons cm^{-2} s^{-1} (the free-neutron density being about 5×10^{10} neutrons cm^{-3}). Despite the lack of reliable nuclear data, our calculations demonstrate that the abundances of nuclides following ^{85m}Kr may change by several times when the INNA reaction is taken into account. The effect of this reaction can be even more pronounced for isomers with higher values of the acceleration cross section (e.g., ^{180m}Hf).

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