KfK 3451
Januar 1983

s-Process Chronometers

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+) This article was presented as an invited talk at the "Workshop über Fragen der nuklearen Astrophysik" Mainz, 13.- 15. Oktober 1982

Kernforschungszentrum Karlsruhe GmbH
ISSN 0303-4003

Abstract

The radionuclei ^{40}K, ^{81}Kr, ^{87}Rb, ^{93}Zr, ^{107}Pd, ^{147}Sm, ^{176}Lu and ^{205}Pb are built up totally or partially by the s-process. Due to their long half life they are potential chronometers for the age and the development of the s-process. The usefulness of the various nuclei is discussed. For the determination of the mean age of the s-process synthesis and with it the age of the galaxy, ^{176}Lu is best suited. It is demonstrated that this age can be calculated solely from measured cross section and abundance ratios. Various effects which can limit the usefulness of ^{176}Lu as a clock are discussed.

s-Prozeß Chronometer

Zusammenfassung

Die Radionuklide ^{40}K, ^{81}Kr, ^{87}Rb, ^{93}Zr, ^{107}Pd, ^{147}Sm, ^{176}Lu und ^{205}Pb werden ganz oder teilweise im s-Prozeß aufgebaut. Auf Grund der langen Halbwertszeit stellen sie mögliche Chronometer für das Alter und den Verlauf des s-Prozesses dar. Die Brauchbarkeit der verschiedenen Nuklide wird diskutiert. Zur Bestimmung des mittleren Alters der s-Prozeßsynthese und damit des Alters der Galaxie ist ^{176}Lu am besten geeignet. Es wird dargelegt, daß dieses Alter allein aus gemessenen Querschnitts- und Häufigkeitsverhältnissen berechnet werden kann. Verschiedene Effekte, die die Brauchbarkeit von ^{176}Lu als Uhr begrenzen, werden diskutiert.

INTRODUCTION

Among the synthesized heavy elements there exist long-lived isotopes which can be used for dating the nucleosynthesis. As the nucleosynthesis most probably takes place in stars in the galaxy we obtain in this way a measure of the age of the galaxy which is a lower limit of the age of the univers [1], [2].

Certainly not every long-lived isotope is suited for this kind of age determination. A cosmic clock or cosmochrometer has to fullfill at least the following two conditions:

1) In order to be sensitive for the period of time to be measured the half-life of the radioactive nucleus must be between $10^5 yr < T_{1/2} < 10^{11} yr$

2) There must exist a prescription to calculate the original abundance in addition to the present day abundance. This way of calculation must be, of course, accurate enough and has to make use of the models of nucleosynthesis (s-process, r-process). For extinct isotopes one needs an isotopic anomaly which can give evidence for the life incorporation of the radioactive isotope into the meteorite [3].

POTENTIAL s-PROCESS CHRONOMETERS

According to the subject of this study a search for possible s-process chronometers leads to the candidates summarized in Table I. The only cosmic clocks of this list which can be really used if we apply our condition 2 are the long- lived isotpes ^{87}Rb [2] and ^{176}Lu. ^{87}Rb has the disadvantage that its abundance is a mixture of s and r-process which cannot be separated accurately. The s-contribution is, however, dominant (∿80 % s-process, ∿20 % r-process). It is possible that s- and r-process have different time histories.

Concerning half life, ^{40}K would be a very interesting cosmic clock, but the kind of its synthesis is unclear presently, although the s-process is a possible way to produce its abundance using ^{39}K, $^{36,38}Ar$ as seed materials.

^{205}Pb with a half life of 1.5×10^7 yr would be a very convenient cosmic clock among the extinct isotopes, but until now no ^{205}Tl anomaly correlated with lead has been found in meteorites (Huey and Kohman [4]).

THE GENERAL FEATURES OF NUCLEOSYNTHESIS

Using the nomenclature of Schramm [5] (Fig. 1) we can specify a time dependent rate of s-process synthesis $\psi(\tau)$, a time T for the duration of synthesis from the formation of the galaxy to the time where no more s-process material is added to the cloud of dust and gas which after a span of time Δ will solidify to the solar system. An average synthesis age $\bar{t}$ is defined by

$$\bar{t} = \frac{\int_0^T \tau\psi(\tau)d\tau}{\int_0^T \psi(\tau)d\tau} \qquad (1)$$

The ^{205}Pb chronometer would be sensitive to the end of the s-process synthesis rate. It would provide information about $\psi(\tau = T)$ and the time interval Δ.

^{176}Lu (^{87}Rb) yield the model independent average age of the s-process:

$$\bar{T} = T - \bar{t} + \Delta \qquad (2)$$

According to Schramm and Wasserburg [6] $\bar{T}$ is given by the simple relation

$$\bar{T} = \frac{1}{\lambda_i} \ln \frac{P_i/P_j}{N_i/N_j} \qquad (3)$$

where i stands for ^{176}Lu and j for a stable s-process nucleus. $P_{i,j}$ are the formation rates of the nuclei i and j and the relation holds that

$$P_i/P_j = \sigma_j/\sigma_i \qquad (4)$$

with $\sigma_{i,j}$ the respective Maxwellian averaged capture cross sections. $N_{i,j}$ are the abundances of i and j at the time of the solidification of the solar system.

Using $\sigma N \sim$ constant we can reformulate eq. (3)

$$\bar{T} = \frac{1}{\lambda_i} \ln \frac{\frac{\sigma_j}{\sigma_i} N_j}{N_i} = \frac{1}{\lambda_i} \ln \frac{N_i^*}{N_i} \qquad (3a)$$

where N_i^* is the average original ^{176}Lu (^{87}Rb) abundance.

Eq. (3) (3a) can be interpreted in terms of a sudden nucleosynthesis at the time $t = \bar{t}$.

THE ^{87}Rb COSMIC CLOCK

The ^{87}Rb chronometer is in principle a similar case as the ^{187}Re r-process chronometer [2] (Fig. 2).

$$\bar{T} = \frac{1}{\lambda(^{87}Rb)} \ln \frac{N^*(^{87}Rb)}{N_\odot(^{87}Rb)} = \frac{1}{\lambda(^{87}Rb)} \ln \left[1 + \frac{N_{rad}(^{87}Rb)}{N_\odot(^{87}Rb)} \right] \qquad (5)$$

The decayed ^{87}Rb can be determined via the σN correlation applied to $^{86,87}Sr$

$$N_{rad.}(^{87}Rb) = N_\odot(^{87}Sr) - \frac{\left[1 + \frac{1}{\tau_o \sigma(^{87}Sr)}\right]^{-1} \sigma N_\odot(^{86}Sr)}{\sigma(^{87}Sr)} \qquad (6)$$

where $\tau_o = 0.24\ mb^{-1}$ [7] and

$\sigma(^{86}Sr) = 74 \pm 7$ mb [8] $N_\odot(^{86}Sr) = 2.34/10^6 Si$ [9]

$\sigma(^{87}Sr) = 109 \pm 9$ mb [8] $N_\odot(^{87}Sr) = 1.63/10^6 Si$ [9]

$N_\odot(^{87}Rb) = 2.1/10^6 Si$ [9]

$N_\odot(^{88}Sr) = 19.57/10^6 Si$ [9]

A calculation leads to

$$\bar{T} = \frac{4.8 \cdot 10^{10}}{\ln 2} \ln [1.0869 \pm 0.097]$$

$$= 5.8 \times 10^9 yr \text{ with } 100\ \% \text{ uncertainty}$$

In the calculation only the uncertainty of the cross sections was taken into account. The uncertainty of the Sr and Rb solar abundance additionally amounts to 7 to 8 %.

s- and r-process contribution $N_s(^{87}Rb)$, $N_r(^{87}Rb)$ can be separated in principle, if we make full use of the properties of s-process theory:

We can write down 3 eqs.

$$\sigma N_s(^{88}Sr) = \zeta(^{88}Sr)\,[\sigma N_s(^{87}Sr) + \sigma N_s(^{87}Rb)] \qquad (7)$$

$$N_s(^{87}Sr) + N_s(^{87}Rb) + N_r(^{87}Rb) = N_\odot(^{87}Sr) + N_\odot(^{87}Rb) \qquad (8)$$

and reformulating eq. (6) we obtain

$$N_s(^{87}Rb) + N_r(^{87}Rb) - N_\odot(^{87}Rb) = N_\odot(^{87}Sr) - \zeta(^{87}Sr)\,\frac{\sigma N_\odot(^{86}Sr)}{\sigma(^{87}Sr)} \qquad (9)$$

The propagator $\zeta(i)$ is defined as

$$\zeta(i) = \left[1 + \frac{1}{\tau_o\sigma(i)}\right]^{-1}$$

Eq (7) + (8) + (9) yield

$$N_s(^{87}Rb) = \frac{\sigma N_s(^{88}Sr)}{\sigma(^{87}Rb)}\,\zeta^{-1}(^{88}Sr) - \zeta(^{87}Sr)\,\frac{\sigma N_\odot(^{86}Sr)}{\sigma(^{87}Rb)} \qquad (10)$$

$$N_r(^{87}Rb) = N_\odot(^{87}Rb) + N_\odot(^{87}Sr) + \left[1 - \frac{\sigma(^{87}Rb)}{\sigma(^{87}Sr)}\right]\frac{\sigma N_\odot(^{86}Sr)}{\sigma(^{87}Rb)}\cdot \zeta(^{87}Sr) - \frac{\sigma N_s(^{88}Sr)}{\sigma(^{87}Rb)}\,\zeta^{-1}(^{88}Sr) \qquad (11)$$

The still unknown s-process abundance of ^{88}Sr can be obtained via a relation to s-only ^{96}Mo

$$\sigma N_s(^{88}Sr) = \left[\prod_{i=^{89}Y}^{^{96}Mo} \zeta(i)\right]^{-1} \sigma N_\odot(^{96}Mo) \qquad (12)$$

THE ^{176}Lu COSMIC CLOCK

The isotope ^{176}Lu and stable isotopes in its vicinity are shown in Fig. 3. We can classify the nuclei in s-, r- and p-process isotopes according to the different production mechanisms of the heavy elements. For pure r-, s- and p-process isotopes the solar abundance is designated. The s-process synthesis path is located in the stability valley whereas the r-process occurs at the neutron rich side. The decay back of the synthesis products to the valley of stability is indicated by inclined arrows. In the mass range where ^{176}Lu is situated a classification of s-, r- and p-process nuclei is obvious from the size of the abundances. Therefore ^{176}Hf should belong to the s-process isotopes. This suggests that at ^{176}Lu in spite of its long half life a branching of the s-process path occurs. This branching can be mediated by an isomeric state at 127 keV with a 3.68 h beta decay half-life [10,11,12,13]. Important stable s-only nuclei which can act as normalization points (see eq. 3) are ^{170}Yb, ^{160}Dy and ^{176}Hf. For ^{160}Dy and ^{170}Yb it is required that the radioactive progenitor does not give rise to a branching. The half lives of ^{160}Tb and ^{170}Tm under stellar s-process conditions are 3h and 11d, respectively. This means that at ^{170}Tm we might have a branching as indicated in Fig. 3. But ^{160}Dy represents a suitable stable nucleus for the ^{176}Lu chronology. The mean age $\bar{T}$ of the s-process is given by

$$\bar{T} = \frac{1}{\lambda} \ln \frac{N(^{176}\mathrm{Lu})}{N_\odot(^{176}\mathrm{Lu})} = \frac{1}{\lambda} \ln \left[\frac{\frac{\sigma(^{160}\mathrm{Dy})}{\sigma(^{176}\mathrm{Lu})} N_\odot(^{160}\mathrm{Dy})}{N_\odot(^{176}\mathrm{Lu})} f_n \right] \quad (13)$$

Applying the σN correlation the original ^{176}Lu abundance $N(^{176}\mathrm{Lu})$ can be related to ^{160}Dy by

$$\sigma N(^{176}\mathrm{Lu}) = \sigma N_\odot(^{160}\mathrm{Dy}) \cdot f_n \quad (14)$$

For simplification $\sigma N(A)$ = constant will be assumed in eq. (14) and the following relations. Eq. (14) represents the defination for f_n the fraction of synthesized ^{176}Lu. For the calculation of the mean age $\bar{T}$, therefore, an additional relation to obtain f_n is needed.

It can be assumed that f_n is determined by the population of the 3.68 h isomeric state via neutron capture on ^{175}Lu [12]. This leads to

$$f_n = \frac{\sigma^g(^{175}Lu)}{\sigma(^{175}Lu)} = 1 - \frac{\sigma^m(^{175}Lu)}{\sigma(^{175}Lu)} \qquad (15)$$

$\sigma^{m,g}$ are the capture cross sections to the ^{176}Lu isomer and ground state, σ is the total capture cross section. But f_n from eq. (14) and (15) must not be equal necessarily, as thermal effects at the site of the s-process can change the population of $^{176}Lu^m$ [13].

Before discussing this subject further let us calculate $\bar{T}$ via ^{176}Hf:

$$\bar{T} = \frac{1}{\lambda} \ln \frac{1 + N_\odot(^{176}Hf) \,/\, N_\odot(^{176}Lu)}{1 + \frac{1-f_n}{f_n} \frac{\sigma(^{176}Lu)}{\sigma(^{176}Hf)}} \qquad (16)$$

This equation was first derived by Arnould [11] and it is interesting to discuss it in detail. The difference between (13) and (16) originates from the fact that in (16) one must account for the ^{176}Lu decay during the synthesis. We can formulate two relations:

$$\sigma N(^{176}Lu) + \sigma N\,(^{176}Hf) = \sigma N_\odot(^{160}Dy) \qquad (17)$$

With the definition of f_n [eq.(14)] we obtain

$$\sigma N(^{176}Hf) = \sigma N(^{176}Lu) \; \frac{1-f_n}{f_n} \qquad (18)$$

The second relation uses the constancy of the sum of abundances

$$N(^{176}Lu) + N(^{176}Hf) = N_\odot(^{176}Lu) + N_\odot(^{176}Hf) \qquad (19)$$

eq. (18) and (19) allow the formulation of eq.(16) by some simple algebra.

But it is not necessary to relate eq. (18) and (19), eq. (17) and (19) also leads to a formula for $\bar{T}$ which is independent of the branching factor f_n [14]:

$$\bar{T} = \frac{1}{\lambda} \ln \frac{\dfrac{\sigma N_\odot(^{160}Dy)}{\sigma(^{176}Hf) N_\odot(^{176}Lu)} - \dfrac{N_\odot(^{176}Hf)}{N_\odot(^{176}Lu)} - 1}{\dfrac{\sigma(^{176}Lu)}{\sigma(^{176}Hf)} - 1} \tag{20}$$

f_n can be determined additionally

$$f_n = \frac{\sigma N(^{176}Lu)}{\sigma N_\odot(^{160}Dy)} = \frac{\sigma N_\odot(^{176}Lu)}{\sigma N_\odot(^{160}Dy)} \; \frac{N(^{176}Lu)}{N_\odot(^{176}Lu)} > \frac{\sigma N_\odot(^{176}Lu)}{\sigma N_\odot(^{160}Dy)} \tag{21}$$

where $\frac{N(^{176}Lu)}{N_\odot(^{176}Lu)}$ is given by the argument under the logarithm in eq. (20).

Eq. (20) requires that $\sigma(^{176}Hf) \neq \sigma(^{176}Lu)$. This condition is fullfilled, as the capture cross sections of odd-odd isotopes (^{176}Lu) are always about a factor of two larger than their even-even isobars (^{176}Hf).

From eq. (20) and (21) important conclusions can be drawn by the comparison of (21) with (15):

- If f_n from (14) and (21) are equal then no thermal effects were present during ^{176}Lu synthesis, ^{176}Lu is an excellent cosmic clock and the age can be measured via (13) or (16) in conjunction with (15) or via eq. (20)
- If (14) and (21) disagree then thermal effects were important in the population of the ^{176}Lu ground and isomeric state. ^{176}Lu might still be a cosmic clock determined through eq. (20) if the freeze out of ^{176}Lu after termination of the s-process neutron flux does not change the ^{176}Lu abundance.

- If f_n from eq. (21) is identical with

$$f_n = \frac{(2J_m+1)\exp(-E_m/kT)}{(2J_{o+1}) + (2J_m+1)\exp(-E_m/kT)} \tag{22}$$

which assumes thermal equilibrium between ground state o and isomeric state m then ^{176}Lu represents also a stellar thermometer.

From the experimental point of view eq. (20) is an important result, too. Only ratios of total cross sections and abundances have to be measured. This is always easier than the measurement of absolute quantities. For the capture measurements it should be noted that by avoiding the use of eq. (15) also means only one experimental technique because f_n determined via (15) requires an activation measurement <u>and</u> a time-of-flight measurement.

In order to obtain a reliable age for ^{176}Lu the cross section and abundance ratios must be determined to $\leq$ 1.5 % accuracy. This is due to the fact that the s-process age is of the order of 8×10^9yr.

The calculation with $\sigma(^{176}Lu)$ = 1718 mb, $N_\odot(^{176}Lu)$ = 0.000989/10^6Si (Cameron's [15] calculation of the isotopic ^{176}Lu abundance is in error by 6 %), f_n = 0.36 and $\sigma N(A = 1.76)$ = 5.47 (mb $\cdot$ Si $\equiv 10^6$) yields $\bar{T} = (8 \pm 8) \times 10^9$yr.

The high accuracy required for the data of the ^{176}Lu cosmic clock is the general weakness of this chronometer. We have to ask ourselves for instance: Is the applied σN correlation correct to better than 1.5 %? The evidence has not yet been furnished (only $\leq$ 6 % has been verified according to ref. [16]). How do we determine elemental solar abundances with 1.5 % accuracy from meteorites? Is there a class of meteorites with unfractionated and well-mixed solar system matter at all? The stellar atmosphere of the sun contains these well-defined abundances but the spectrum measurements are much more unreliable than meteoritic results.

Besides these general objections there are yet more special problems which shall be discussed now.

In our treatment of ^{176}Lu we always have relied on the s-only nature of ^{160}Dy, ^{176}Lu and ^{176}Hf. It is certainly true that these nuclei are shielded from the r-process but they are <u>not</u> shielded from the p-process. This is a small contribution but nevertheless important. From the nearby p-only nuclei ^{174}Hf and ^{158}Dy we can assume that the correction is $\leq$ 3 to 4 % for ^{160}Dy and ^{176}Hf. For ^{176}Lu as an odd odd isotope the p-process can reproduce only negligible amounts [17]. A correction of the solar ^{160}Dy and ^{176}Hf abundance is therefore highly effective with respect to eqs. (13), (16) or (20).

^{160}Dy and ^{176}Hf have 2^+ excited states at $\sim$ 88 keV which are in the s-process environment occupied by $\sim$ 20 %. ^{176}Lu on the other hand has no such state. For instance a 5 % higher capture cross section at these 2^+ states compared to the ground state would change the effective capture cross sections of ^{160}Dy and ^{176}Hf by 1 % but the ^{176}Lu capture cross section would be the same. Again a significant effect in age calculations according to our specified equations.

^{175}Yb, the radioactive progenitor of ^{175}Lu, has a laboratory half life of 4d which remains unchanged under stellar s-process conditions. Therefore, it is possible that at ^{175}Yb, ^{176}Lu and ^{176}Hf are bypassed in the s-process partially by a small branching to ^{176}Yb. This branching would affect the age determination according to eq. (13) and (20) but not eq. (16). For a neutron density of $10^7/cm^3$ the fraction of the s-process flow bypassing ^{176}Hf is only 0.14 %, for $10^8/cm^3$ this fraction is already 1.2 % and for $10^9/cm^3$ as big as 11.1 %. The ^{175}Yb cross section was assumed to be 1b.

^{176}Lu has a sizeable thermal cross section of 2107 b whereas ^{160}Dy has only 61 b and ^{176}Hf 36 b. Therefore, ^{176}Lu could be selectively depleted in meteorites by spallation neutrons from cosmic ray particles. For ^{149}Sm this effect was estimated to be $\leq$ 4 % by Macklin et al. [16].

^{176}Yb has an isomeric state with 11.7 sec at 1.051 MeV which due to its spin and parity 8^- can make an allowed ß transition to the 7^- ^{176}Lu ground state. This situation allows the production of r-process ^{176}Lu via the population of the ^{176}Yb isomer from the ^{176}Tm decay followed by the fractional $^{176}Yb^m$ beta decay to ^{176}Lu. The r-process contribution can be estimated:

$$\frac{N_r(^{176}Lu)}{N_\odot(^{176}Lu)} = \frac{N_\odot(^{176}Yb)\cdot P\cdot f_\beta}{N_\odot(^{176}Lu)}$$

P according to the table of isotopes [18] is 0.86 % and f_β was estimated to 0.14 %. We obtain

$$\frac{N_r(^{176}Lu)}{N_\odot(^{176}Lu)} \sim 3\cdot 10^{-4} \quad \text{a negligible effect.}$$

CONCLUSIONS

We have found only two suitable s-process chronometers ^{87}Rb and ^{176}Lu which due to their long half lives can provide a mean age. ^{87}Rb is complicated because of a mixture of s- and r-process. A way to separate these contributions is indicated in this work. So far ^{87}Rb was not used as a cosmic clock. This is due to the high accuracy required for the data.

The application of ^{176}Lu as a cosmic clock is much more advanced than in the case of ^{87}Rb. The ^{176}Lu clock requires capture and abundance data to accuracies better than 1.5 %. The final accuracy of this clock is, however, probably limited by a series of necessary corrections which both concern the abundances and the cross sections.

For the p-process correction of ^{176}Hf and ^{160}Dy it is perhaps reasonable to use the abundances of ^{174}Hf and ^{158}Dy multiplied by a factor of 0.9 derived in analogy to the ratios ^{126}Xe/^{124}Xe and ^{132}Ba/^{130}Ba. The ratios ^{A}Z/$^{A-2}$Z of other isotopic p-only nuclei with different size are considered not relevant as they either exhibit properties of closed neutron or proton shells (^{94}Mo/^{92}Mo; ^{114}Sn/^{112}Sn; ^{138}Ce/^{136}Ce) or contributions from the s-process (^{164}Er/^{162}Er). A small s-process contribution to ^{158}Dy via a branching at ^{157}Gd is also possible.

To estimate the s-process neutron density for the ^{175}Yb branching an investigation of the ^{170}Tm branching might be helpful. The same is true for the ^{185}W branching.

The importance of fractionation effects in C1 carbonaceous chondrites can be checked by comparing $\sigma N_o(^{110}Cd)$ with $\sigma N_o(^{104}Pd)$ as Pd and Cd show a quite different volatility [19]. The Lu/Hf ratios for different types of meteorites are also important in this context.

The validity of the σN correlation is hard to be tested to very high accuracy as for all cases with more than one s-only isotope in the chain (^{122,123,124}Te, ^{128,130}Xe, ^{134,136}Ba and ^{148,150}Sm) one has to subtract p-process contributions and to correct for small s-process branchings. A careful study of the ^{122,123,124}Te case, however, seems to be most suited.

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Table I Potential s-process chronometers (10^5 yr< $T_{1/2}$<10^{11} yr) One can distinguish nuclei still alive in the solar system (underlined) and extinct radioactivities

^AZ	Decay	$T_{1/2}$(yr)	Process	Condition 2
<u>^{40}K</u>	ß	1.3×10^9	weak s-process?	no
^{81}Kr	EC	2.1×10^5	s-only	no
<u>^{87}Rb</u>	ß	4.7×10^{10}	s+r process	yes
^{93}Zr	ß	9.5×10^5	"	no
^{107}Pd	ß	6.5×10^6	"	no
<u>^{147}Sm</u>	α	1.5×10^{11}	"	no
<u>^{176}Lu</u>	ß	3.6×10^{10}	s-only	yes
^{205}Pb	EC	1.5×10^7	"	no

FIGURE CAPTIONS

Fig. 1 A schematic drawing to illustrate s-process nucleosynthesis. ψ is the synthesis rate, T the duration of the s-process and Δ represents the time interval between end of nucleosynthesis and solidification of solar system matter.

Fig. 2 s-process nucleosynthesis at ^{87}Rb ($T_{1/2}$ = 4.8 x 10^{10}yr) represented by the solid line connecting the various isotopes. The r-process contributions is indicated by inclined arrows. The s-process synthesis of ^{87}Sr is possible due to a branching at ^{85}Kr.

Fig. 3 The various processes of nucleosynthesis that contribute in the neighbourhood of ^{176}Lu. The s-process path is shown by the solid line. Possible r-process contributions are indicated by dashed arrows. For s- r- and p-only nuclei the solar abundance is given.

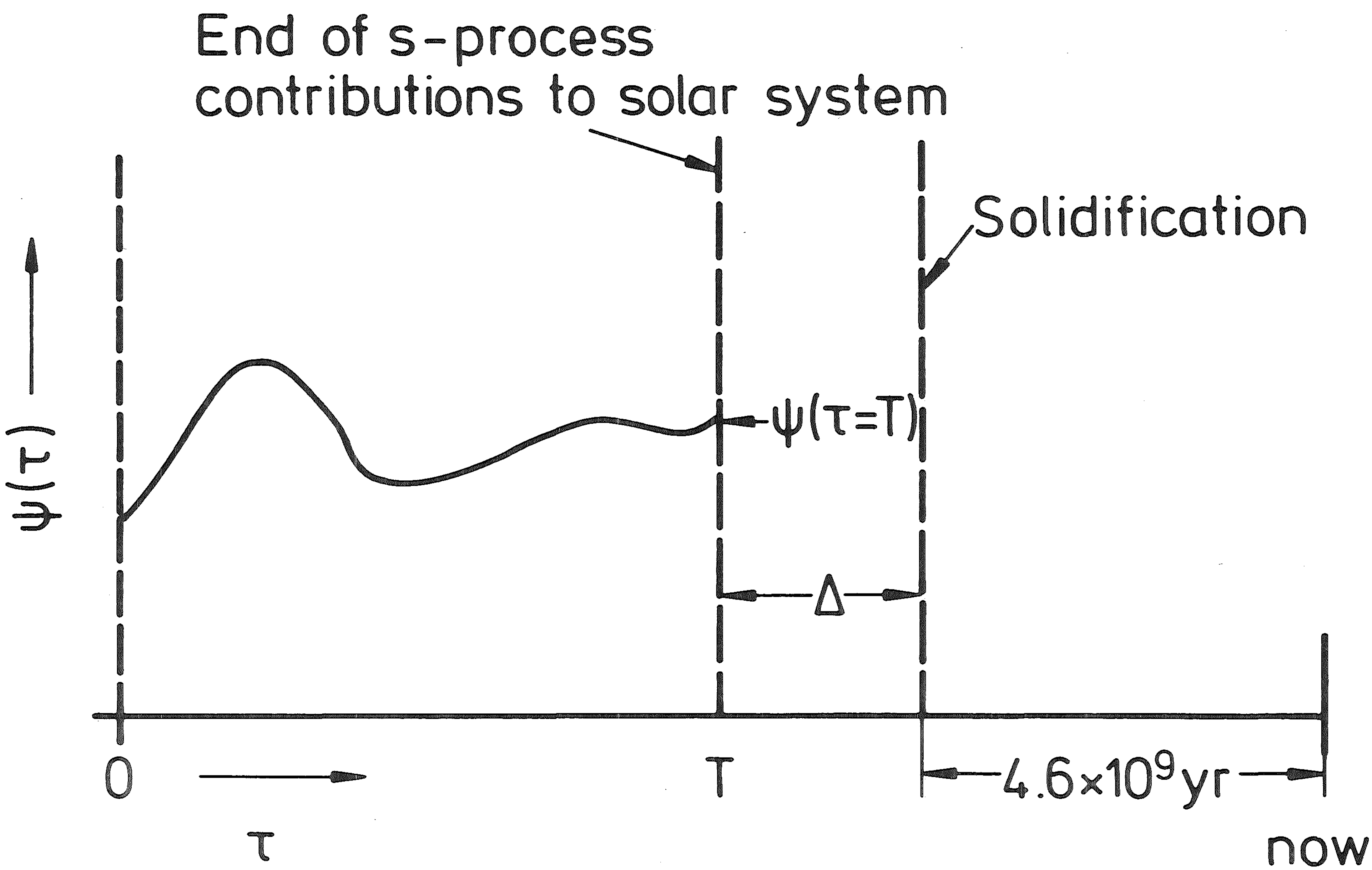
End of s-process
contributions to solar system
Solidification
ψ(τ)
ψ(τ=T)
Δ
0
T
τ
4.6×10⁹yr
now

Fig.1

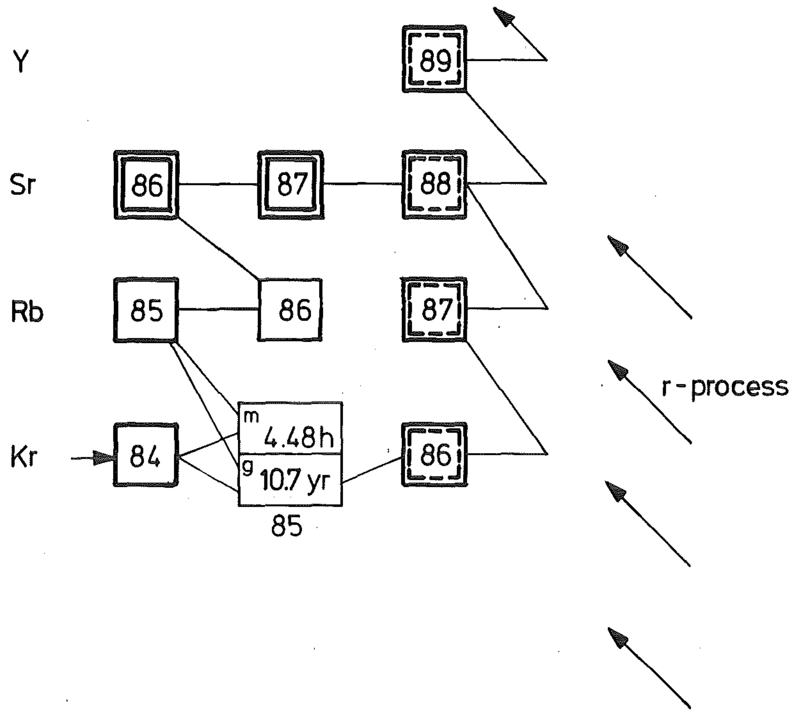

Fig.2

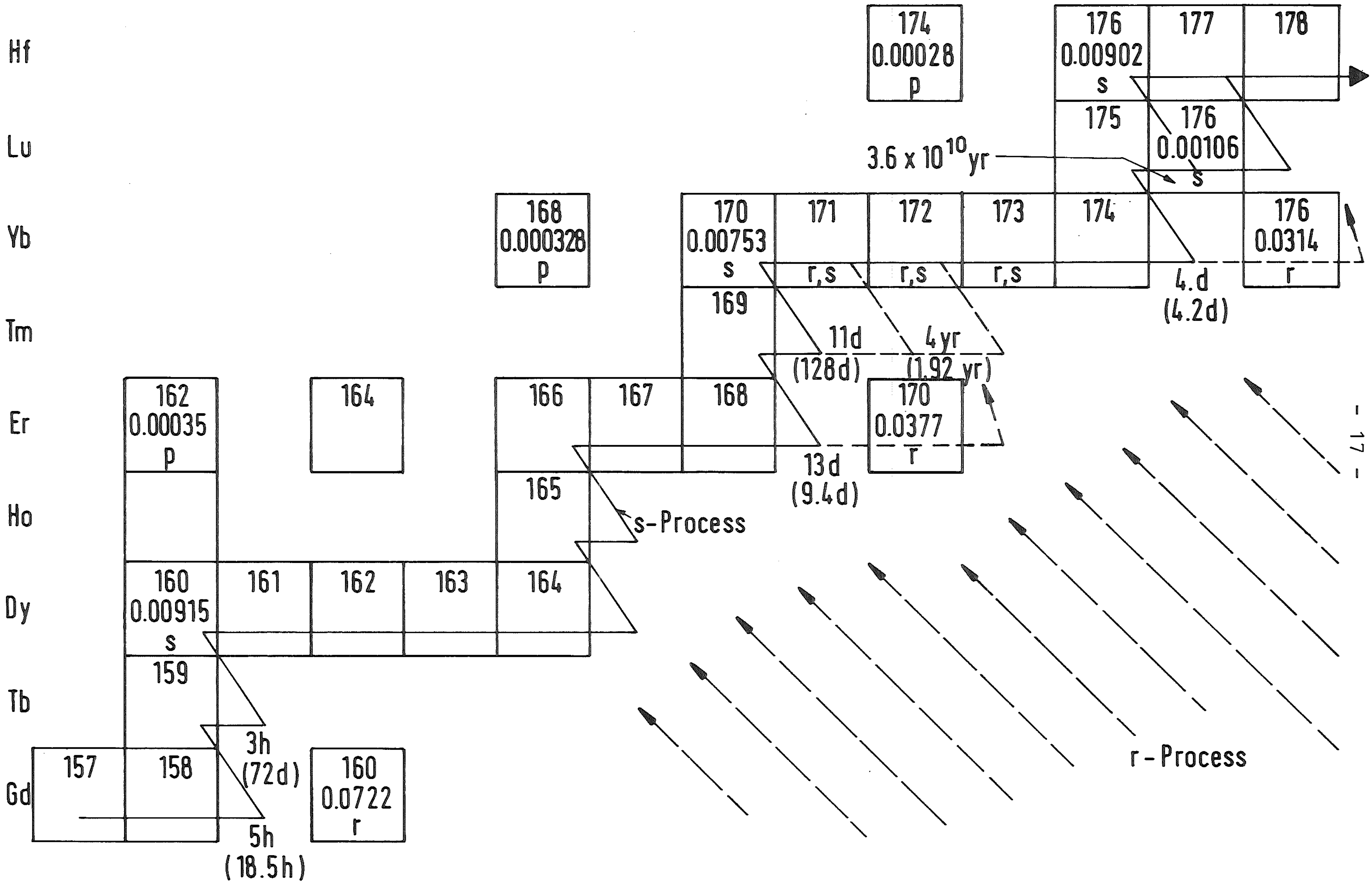
Hf
Lu
Yb
Tm
Er
Ho
Dy
Tb
Gd
174
0.00028
p
176
0.00902
s
177
178
175
176
0.00106
s
3.6 x 10^10 yr
168
0.000328
p
170
0.00753
s
171
172
173
174
176
0.0314
r
r,s
r,s
r,s
4.d
(4.2d)
169
11d
(128d)
4yr
(1.92 yr)
162
0.00035
p
164
166
167
168
170
0.0377
r
13d
(9.4d)
165
s-Process
160
0.00915
s
161
162
163
164
159
3h
(72d)
157
158
160
0.0722
r
5h
(18.5h)
r - Process

Fig.3