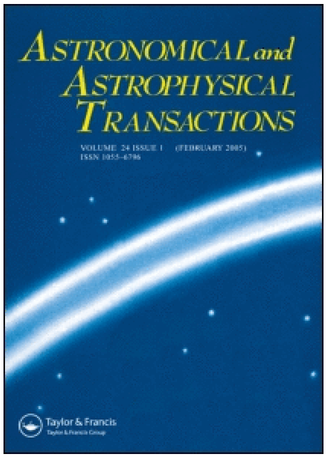

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DECAY DATA FOR RADIONUCLIDES AS A TEST OF ASTROPHYSICAL CONDITIONS OF NATURAL SYNTHESIS OF HEAVY ELEMENTS (NUCLEOSYNTHESIS AFTER GAMOW)

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In view of the present nucleosynthesis picture, an impotant role of radioactive nuclides is emphasized. Some recent works concerning a study of radionuclide decay data as a test of nucleosynthesis physical conditions are reviewed.

1 INTRODUCTION

Gamow's idea of the hot Universe and the $\alpha\beta\gamma$ – theory stimulated the development of extensive nucleosynthesis investigations and now we have a great branched "tree" of the nucleosynthesis theory (Figure 1). Its root is primary nucleosynthesis. This tree also includes the synthesis of "fragile" light nuclides, the thermonuclear synthesis in stars, the cosmogenic synthesis, and the synthesis of heavy elements in astrophysical processes of neutron capture.

It is difficult to review varying significance of radionuclides in every branch of the nucleosynthesis tree. So this paper concerns only some specific interesting questions discussed in the latest years mainly connected with decay data for radionuclides as sensible indicators of s- and r-process environments.

2 BIG BANG NUCLEOSYNTHESIS

For some conditions the synthesis of heavy elements can occur in an inhomogeneous Big Bang (Applegate *et al.* 1987). In addition to nuclides in the $7 \leq A \leq 16$ region, it is considered that the "neutron-source" nuclide, ^{22}Ne, can be produced in significant amounts in inhomogeneous cosmological nucleosynthesis. This raises

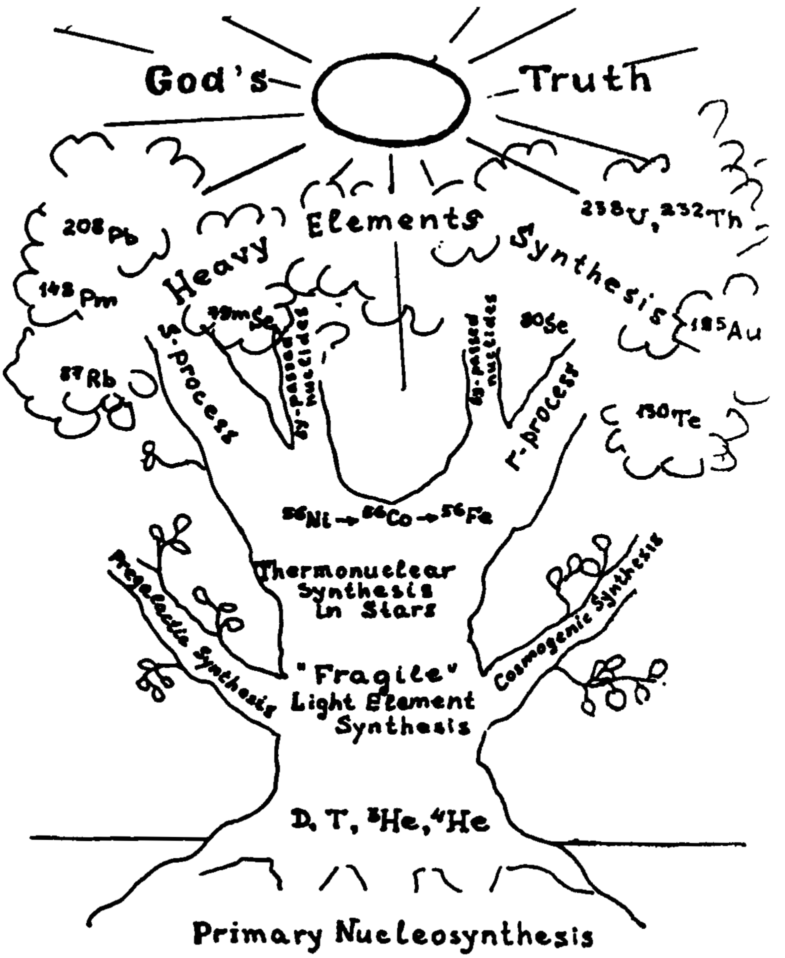

Figure 1 Nucleosynthesis tree.

the possibility that a "mini-r-process" might produce trace amounts of even the heaviest nuclides, favourable for explaining traces of heavy elements in the oldest observed stars (Barnes, 1990).

The most likely reaction sequence in neutron-rich zones leading to the production of $A \geq 12$ nuclides, is believed to be: $^1H(n,\gamma)\,^2H(n,\gamma)\,^3H(d,n)\,^4He(^3H,\gamma)\,^7Li(n,\gamma)\,^8Li(\alpha,n)\,^{11}B(n,\gamma)\,^{12}B(\beta\gamma)\,^{12}C$.

Till recently, no experimental information relative to the cross section has been available for the key reaction of this chain, $^8Li(\alpha,n)\,^{11}B$, due to the short half-life, 838 ms, of ^8Li radionuclide. However recent experimental studies (Kossionides *et al.*, 1990) of the inverse $^{11}B(n,\alpha)\,^8Li$ reaction rate has shown that the astrophysical S(E) factor for the $^8Li(\alpha,n)\,^{11}B$ reaction is dominated at $T_9 = 1$ by a resonance and it is higher than the "standard" value from statistical model calculations. This result strengthens the importance of considerations of inhomogeneous Big Bang nucleosynthesis. Of course there are also contrary evidences concerning, for example, the insufficient production of ^{9}Be and heavier nuclides in more realistic multi-zone scheme of inhomogeneous universe (Sato and Terasawa, 1990). Nevertheless the inhomogeneous Big Bang nucleosynthesis models are worthy of careful investigations. Here it is wonderful that we deal with original reversion to Gamow's idea of creation of all elements in one act of primary nucleosynthesis.

At the same time the inhomogeneous models are speculative to some extent because the standard theory of the formation of the chemical elements successfully explains a natural synthesis of heavy elements by means of nuclear processes occurring in a stellar (galactic) stage of the universe evolution.

It is known that natural abundances of stable and long-lived nuclides are probes in description of these processes in stars. Like this, decay data for radionuclides can be sensible tests of astrophysical conditions of nucleosynthesis. In this respect, some recently published results are reviewed below.

3 RADIONUCLIDE OF ^{56}Ni

The reinvestigation of ^{56}Ni decay and the consideration of this radionuclide as a probe of cosmic ray nature has been presented by Sur *et al.* (1990). ^{56}Ni is a final nuclide in chains of thermonuclear reactions with charged particles proceeding in the stellar interiors. This is the most abundantly produced isotope in the silicon burning. The light output from the supernova remnant is believed to be due to the energy from the radioactive decay of ^{56}Ni(EC) ^{56}Co(EC, β^+) ^{56}Fe. This prediction has been confirmed by the observation of the 77.1 day exponential decay of the light output from supernova 1987A (the half-life of ^{56}Co is 77.31 ± 0.19 days (IAEA 1991). In assumption of supernovae as sites for acceleration of relativistic nuclei found in cosmic rays, ^{56}Ni can be one of the nuclei that will be accelerated and stripped of its atomic electrons. The bare ^{56}Ni nucleus in cosmic rays cannot decay via electron capture, and the problem consists in the investigation of energetically possible rare β^+ decay of ^{56}Ni.

The decay scheme for ^{56}Ni deduced by Sur *et al.* (1990) is shown in Figure 2. Theoretically, the most intense β^+ transition is expected to be that to the 158-keV level since the decay to the ground state takes place through a fourth forbidden transition, and the decay to the 970-keV level has only 144 keV of available energy. Sur *et al.* established an upper limit of 5.8×10^{-7} for the branching ratio of the second forbidden unique β^+ decay to the 158-keV level in ^{56}Co. This corresponds to an upper limit of 2.9×10^4 yr for the half-life of fully ionized ^{56}Ni nuclei in cosmic rays. Since the solar system is about 30000 light years from the center of Galaxy, this result means that bare relativistic ^{56}Ni nuclei would be able to survive in the cosmic rays and reach the earth. The authors of the paper under discussion conclude that the detection of ^{56}Ni in cosmic rays would thus put constraints on

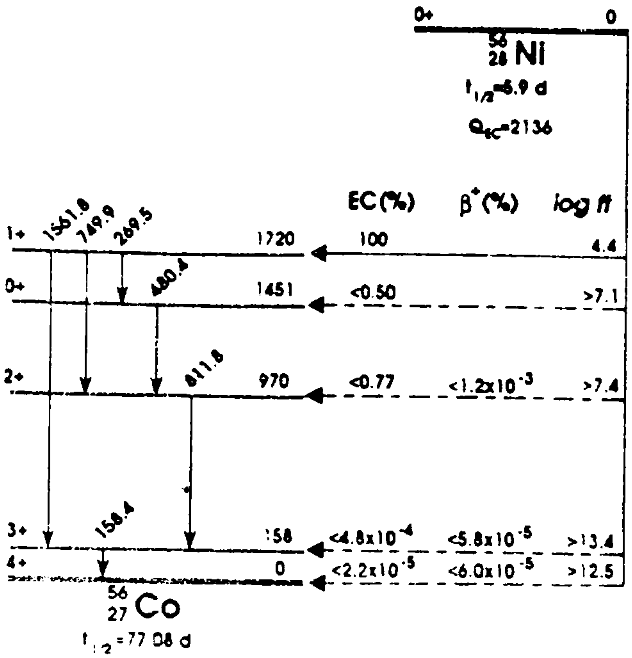

Figure 2 Decay scheme for ^{56}Ni showing EC and β^+ branching ratios measured by Sur *et al.* (1990) (Figure 1 in their paper).

the acceleration mechanism for relativistic nuclei in cosmic rays or/and the rate of supernova explosions in Galaxy.

4 RADIONUCLIDES AS INDICATORS OF PHYSICAL CONDITIONS OF THE S-PROCESS ENVIROMENT

During the recent years, the greatest progress has been attained on a study of the *s*-process details, its astrophysical site, physical conditions of its development (neutron density and temperature) not by means of an improvement of mathematical description but rather on the way back to the classic (phenomenological) approach to the *s*-process. This has been favoured by an analysis of behaviour of radionuclides in points of the *s*-process branching (for reviews see, e.g., Chechev and Kramarovskii, 1981).

Branching of the *s*-process will appear if the competition arises between neutron capture and β^--decay because of relatively long β-decay lifetimes (λ_β) for some radionuclides along the path of the *s*-process. About 20 such branching points are known for the *s*-process nuclei region up to ^{209}Bi.

The ratio of *s*-abundances of nuclei in different branches after a branching point is determined by the ratio $\lambda_\beta/(\lambda_\beta+\lambda_n)$ where $\lambda_n = n_n\langle\sigma_{n\gamma}V\rangle$ is the rate of neutron capture, n_n is the neutron number density (cm^{-3}) and $\langle\sigma_{n\gamma}V\rangle$ is the thermally

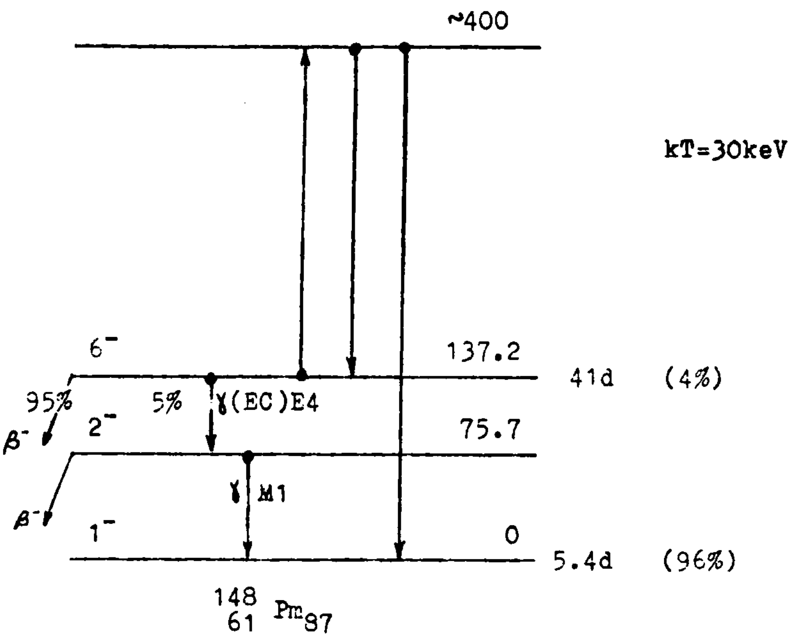

Figure 3 Level scheme of ^{148}Pm with conventional level at 400 keV which permits the equilibration of the ground and isomeric ^{148}Pm states. Lesko *et al.* (1989) have identified three such levels at ≈400 keV.

averaged (n, γ) reaction rate. For known λ_β, $\langle\sigma_{n\gamma}V\rangle$ values in the branching point field the neutron capture rate λ_n and correspondingly the neutron density n_n can be calculated from the observed abundances of nuclides in the Solar system. For several branching points such estimations give $n_n = (0.8 \div 3.5) \times 10^8$ cm^{-3} (Beer *et al.*, 1984).

A special interest is arisen by the cases when in the branching point a nucleus is found having low-lying exited states which can be populated thermally in the interior of a star. An analysis is complicated in this case, but in addition it allows to use possible low-lying isomer states as *thermometers* of the *s*-process. Here, for increase of analysis exactness, it often becomes important to carry out new precize measurements of decay data for radionuclides in order to reduce uncertainties. Recent investigations of ^{148}Pm and ^{79}Se decay data can be examples of such approach.

4.1 Radionuclide of ^{148}Pm

Lesko *et al.* (1989) deduced a level scheme of ^{148}Pm up to 800 keV from gamma-ray coincidence data and particle transfer data. They have identified three levels (among 36 ones) below 500 keV in excitation which decay to both the ground state and to the isomeric level at 137 keV (Figure 3). The energies of these levels are 363.0, 385.5, and 409.6 keV. They have short electromagnetic decay half-lifes and

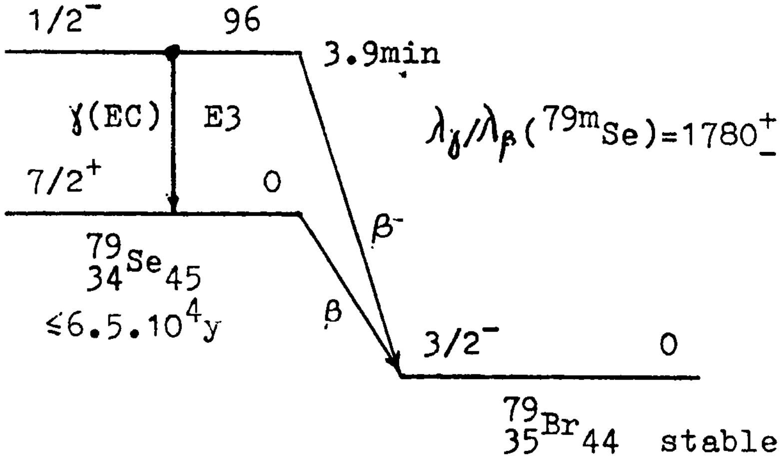

Figure 4 Decay scheme of $^{79}Se^{g,m}$ with the allowed β-transition for ^{79m}Se ($1/2^- \rightarrow 3/2^-$) the probability of which has measured by Klay and Käppeler (1988).

thus will be in thermal equilibrium with the isomeric and ground states during the *s*-process for temperatures $T > 10^8$ K. This results in thermal equilibrium between the ^{148}Pm ground and isomeric states at the *s*-process temperature of 30 keV due to photoexcitation, inelastic scattering and Coulomb excitation. The calculations show that in this case only 4% of the ^{148}Pm nuclei will exist in the isomeric state (41 d) and thus the effective half-life of the $^{148}Pm^{g,m}$ radionuclide in a star will be 5.5 days (for $T = 3 \times 10^8$ K). It follows that the *s*-process neutron density is $n_n = 3 \times 10^8$ cm^{-3} being deduced from the measured $\sigma_{n\gamma}$ cross sections and observed nuclide abundances in the region of the ^{148}Pm branching point (Winters *et al.*, 1986).

^{148}Pm radionuclide is synthesized via the $^{147}Pm(n,\gamma)$ reaction by the "main" component of the *s*-process which is resposible for the production of the *s*-nuclides with mass number $90 \leq A \leq 204$. Therefore, the investigation of the decay data and the level scheme for ^{148}Pm gives a test of this component's parameters.

4.2 Radionuclide of ^{79}Se

A still more striking example of the significance of radionuclide decay data for probing the stellar *s*-process enviroment is connected with the experimental study of ^{79m}Se β-decay rate (Klay and Kaeppeler, 1988). The decay scheme of $^{79}Se^{g,m}$ is presented in Figure 4. The first low-lying excited state of ^{79}Se is a 3.9 min isomer at 96 keV which decays by the gamma transition into the ground state but can also undergo the allowed β^--decay. In the interior of a star, thermal excitation of the isomer will lead to an enhanced β^--decay rate for ^{79}Se. Therefore, like for ^{148}Pm, in the case of thermal excitation of the isomer, the half-life of ^{79}Se will be a function of temperature, and the real effective stellar half-life of ^{79}Se can be used for an es-

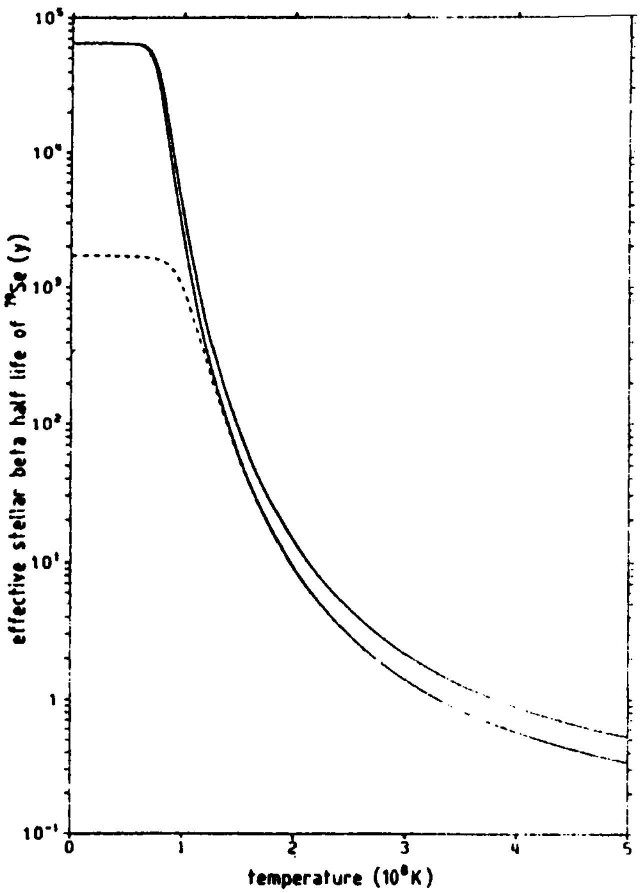

Figure 5 Stellar half-life of ^{79}Se as a function of temperature. The error band reflects the uncertainty of Klay and Käppeler's (1988) measurement. The dashed line refers to log $ft = 8.5$ for the ground state decay.

timation of the *s*-process temperature if this half-life can be derived in an independent way from the observed nuclide abundances and the neutron capture cross sections in the mass region $78 \leq A \leq 82$. The better we know the branching ratio between the internal gamma transition and β^--decay of the ^{79m}Se isomer $(\lambda_\gamma/\lambda_\beta)$, the higher will be sensitivity of such a method of "measurement" of the *s*-process temperature.

Klay and Kaepeler (1988) determined $\lambda_\gamma/\lambda_\beta$ experimentally with high precision by a mini-orange-Si(Li) detection system and used their result for calculation of the temperature dependence of the effective β^- half-life of ^{79}Se in the stellar interior (Figure 5). Their next step was in deducing the real effective stellar half-life of ^{79}Se from a quantitative analysis of element synthesis by the *s*-process for the ^{79}Se branching using the empirical $\sigma_{n\gamma}$ N values of the two *s*-only isotopes ^{80}Kr and ^{82}Kr forming after branching point. The neutron density was estimated independently for the "weak component" of the *s*-process from the experimental $\sigma_n\gamma$ N values of the *s*-only or *s*-dominated nuclides from ^{58}Fe to ^{88}Sr: $0.8 \leq n_n/10^8\ \mathrm{cm}^{-3} \leq 1.9$. The resulting limits for the stellar beta half-life of ^{79}Se, taking into account all uncertainties, were found by klay and Käppeler as $2.3\ y \leq T_{1/2}(\beta) \leq 16$ y. It is of interest to note that for ^{79}Se the stellar beta half-life proved to be known better that the terrestrial one for which only an upper limit of 65000 y estimated obtained.

In Figure 5, the evaluated limits on the real stellar half-life of ^{79}Se are transformed into the narrow temperature range between 182 and 295 million degrees for the temperature of the weak component of the *s*-process.

5 DECAY DATA OF NEUTRON-RICH RADIONUCLIDES AS INDICATOR OF THE ASTROPHYSICAL SITE OF THE R-PROCESS

Kratz *et al.* (1993) showed in their detailed discussion and calculations that the classic approach can be also fruitful for deriving constraints on the physical conditions of another astrophysical process of neutron capture – *r*-process. It turned out that here also a test based only on observed abundances and nuclear physics parameters was a useful tool for a choice of the *r*-process astrophysical site.

During the recent years, the discussion of the *r*-process astrophysical site concentrates on two main suggestions.

The first of them, classical, is connected with the neutron-rich cores of Type II supernovae. In this case ($n_n \gg 10^{20}\ \mathrm{cm}^{-3}$) the statistical equilibrium of the nuclei, neutrons, and photons ($\mathrm{n}\gamma \leftrightarrow \gamma\mathrm{n}$) is attained and the waiting-point approximation becomes valid. The duration of the classical *r*-process is several seconds.

The second, alternative, suggestion is connected with the He-burning layers of a supernova where the *r*-process proceeds from previously *s*-processed material and neutrons are released from (α, n) reactions at rapid heating of helium layers, when the supernova shock wave is passing through them. This mode of the *r*-process is characterized by absence of the $\mathrm{n}\gamma \leftrightarrow \gamma\mathrm{n}$ equilibrium, by necessity of a calculation of the nuclear reaction network and by the duration of the *r*-process of 0.5 s.

Recent experimental data and calculated values (Table 1 from Kratz *et al.*, 1993) for beta decay half-lives of neutron-rich nuclides ($N = 50$ and $N = 82$ isotopes) allow to make choice between the two above-mentioned possibilities arguing in favour of the classical *r*-process.

The duration of the *r*-process is formed as the sum of beta-decay lifetimes of radionuclides in the waiting points and, as one can see from Table 1, these lifetimes do not confirm the possibility of a short time scale for reproducing the $A \simeq 80$ and $A \simeq 130$ *r*-process peaks.

Kratz *et al.* (1993) performed an additional test having shown validity of the classical waiting-point approximation for the $A \simeq 80$ and $A \simeq 130$ abundance peaks and also fruitfulness of a steady-flow equilibrium $Y(Z)\ \lambda_\beta(Z) = \mathrm{const}$. Here $Y(Z) = \sum_A Y(Z,A)$ is a total abundance in a given isotopic chain. The *r*-process correlation

Table 1. Experimental, calculated, and steady-flow model-predicted beta decay half-lives ($T_{1/2}$, ms)

Radionuclide	Experiment	QRPA shell model	Steady-flow model
^{77}Co	–	10	$\leq$11.5
^{78}Ni	–	210	185
^{79}Cu	188 $\pm$ 25	195	200
^{80}Zn	537 $\pm$ 29	420	750
^{81}Ga	1221 $\pm$ 5	1365	–
^{83}Ga	308 $\pm$ 1	235	–
^{127}Rh	–	70	100
^{128}Pd	–	115	140
^{129}Ag	–	140	160
^{130}Cd	195 $\pm$ 35	170	180
^{131}In	278 $\pm$ 3	285	–
^{135}In	195 $\pm$ 3	170	–

$\lambda_\beta(Z) \propto 1/Y(Z)$ is analogous to the relation $\lambda_{n\gamma} \propto 1/N$ for the steady *s*-process and, like that, it can be used for prediction of nuclear parameters in the waiting point region. From the empirical abundances of stable nuclides and known beta delayed neutron emission probabilities, one can predict the abundances of the progenitor radionuclides in the *r*-process path, and hence also "predict" the beta decay half-lifes for these radionuclides. Such predictions in steady-flow approximation (Table 1) agree very well with experimental values and theoretical calculations fulfilled using the quasi-particle random-phase approximation (QRPA) (Moeller and Randrup, 1990). This leads to the conclusion that the *r*-process abundances in the region of the $A \simeq 80$ and $A \simeq 130$ peaks are due to a high-density and high-temperature enviroment which supports the $n\gamma \leftrightarrow \gamma n$ equilibrium excluding the alternative mechanism of the *r*-process.

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