NOTAS DE FÍSICA
VOLUME XIX
Nº 6

ON THE DELAYED NEUTRONS IN THE FINAL STAGE OF THE R-PROCESS

by
Takeshi Kodama and Kohji Takahashi

CENTRO BRASILEIRO DE PESQUISAS FÍSICAS
Av. Wenceslau Braz, 71 - Botafogo - ZC-82
RIO DE JANEIRO, BRASIL
1972

Notas de Física - Volume XIX - Nº 6

ON THE DELAYED NEUTRONS IN THE FINAL STAGE OF THE R-PROCESS

Takeshi Kodama*
Centro Brasileiro de Pesquisas Físicas
Rio de Janeiro, Brasil

and
Kohji Takahashi
Institute of Physics, University of Aarhus,
Aarhus, Denmark

(Received November 30th, 1972)

The gross theory of beta decay is applied to the r-process calculation. In particular, it is explicitly shown that the delayed neutron emissions in the final stage of the r-process smooth out the abundance curve significantly.

* Supported by CAPES and CNPq of Brasil.

The calculation of the rapid neutron capture process (r-process) requires our knowledge of at least two gross properties of nuclei lying far from the beta stability line, i.e. masses and beta-decay half-lives. In contrast to the elaborate efforts in examining the mass formulae[1], rather primitive methods have been adopted with regards to the beta-decay half-life calculation. Recently, however, the "gross theory" of beta decay has enabled us to predict the beta-decay properties of unkown nuclei more or less convincingly[2,3].

In this letter, we apply the gross theory of beta decay to the r-process calculation. In particular, we pay our chief attention to the roles played by the delayed neutron emissions after an abrupt removal of the astrophysical conditions sustaining the r-process synthesis. As for the synthesis equation, we simply follow the time-dependent method given by Seeger, Fowler and Clayton (SFC)[4] but not the "dynamics" proposed by Cameron, Delano and Truran[5].

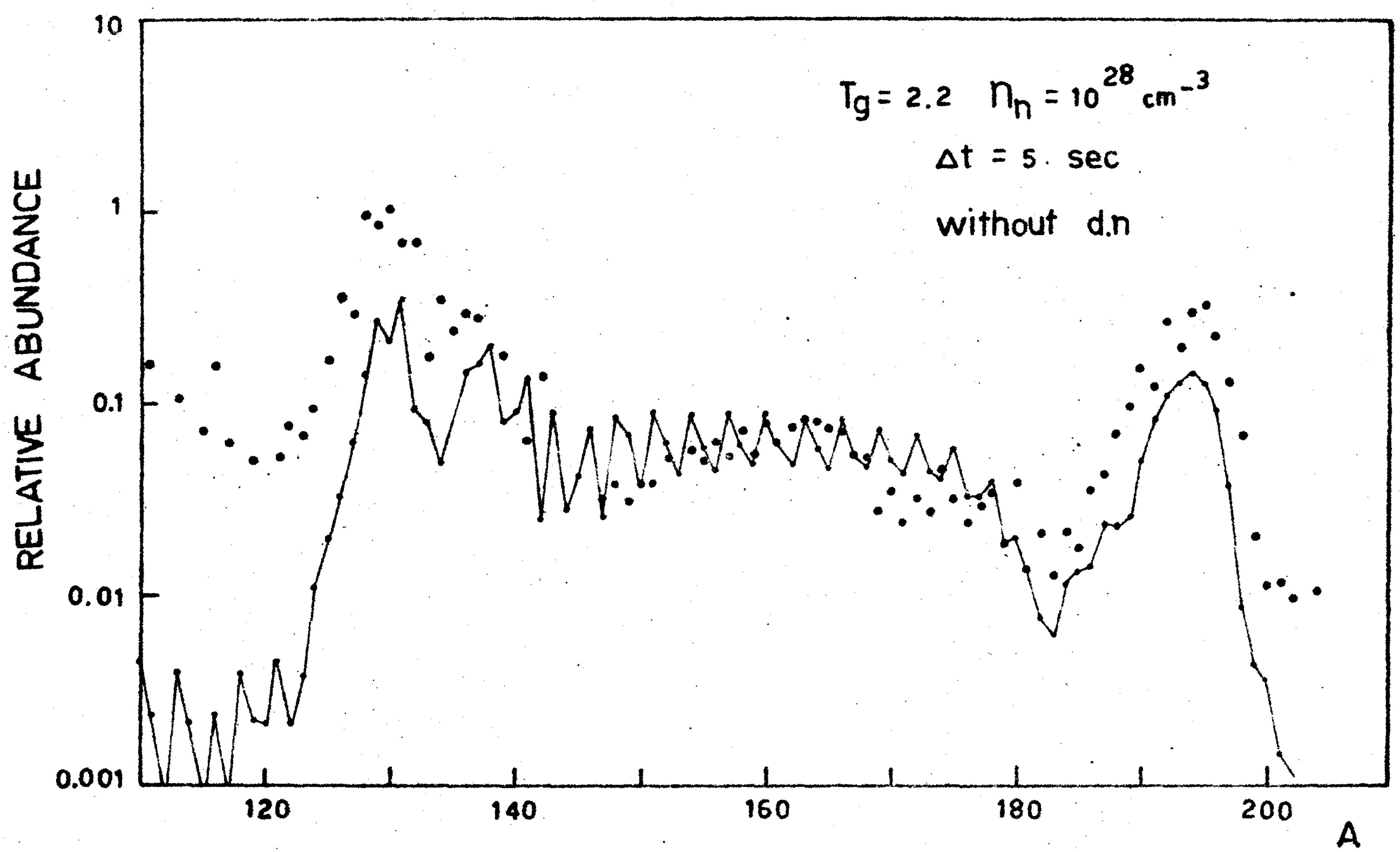
Of the two sorts of solutions of SFC synthesis equation i.e. the short-time solution and the long-time solution, we take the former as an example. Before moving on to the effects of delayed netrons, we show in fig. 1 the short-time solution for a certain combination of the values of the three parameters: temperature (in 10^9 K) T_9 (with consideration for possible fluctuation up to 10%), neutron flux n_n and duration time Δt. Here and in the following, the beta-decay half-lives are calculated by the gross theory[3] with modified-Lorentz single-particle strength function (σ_N = 12 MeV) and the nuclear masses are calculated from the mass formula of Myers and Swiatecki[6].

If the astrophysical conditions for the synthesis are removed abruptly, the synthesized very-neutron-rich nuclei undergo beta-decays towards the beta-stability region. As forecasted early by B^2FH [7], the mass "abundance" curve in this stage will be varied gradually by the intervening delayed-neutron emissions i.e. by the neutron emissions from the excited states fed by beta-decays above the neutron separation energy in the daughter. To take account of this effect, we use a simple approximate formula for the delayed-neutron emission rates[8], $\lambda_n = 10^{-4}(Q-S_n)^{4.5}$ sec^{-1}, which is based on the gross theory, where Q is the beta decay Q-value between ground states and S_n is the neutron separation energy(all in MeV). In addition, we restrict ourselves to the discussion of one-neutron evaporation. In fig. 2, we can see how do the successive cascades of beta decays and delayed neutron emissions from a synthesized nucleid influence over the final abundances of several nucleides. In fig.3, an example is shown of the final abundance curve in consideration of the delayed neutrons,which has revealed itself considerably different from the corresponding "frozen" abundance curve in fig. 1. (If no fluctuation in temperature were taken into account, somewhat larger even-odd effects could be seen in the "frozen" curve.) In fig.4, our results for the"hump" region around the mass number A=160 are shown in the normal scale together with the "experimental" and with other theoretical values.

In conclusion, we can say that the delayed neutron emissions play an essential role to smooth out the zigzags seen in the "frozen" abundance curve. In the case of the long-time solution, where the even-odd fluctuation in the frozen curve seems to be much larger, another delayed process will occur i.e. the delayed fissions[9]. Further results and discussions including this effect will appear elsewhere.

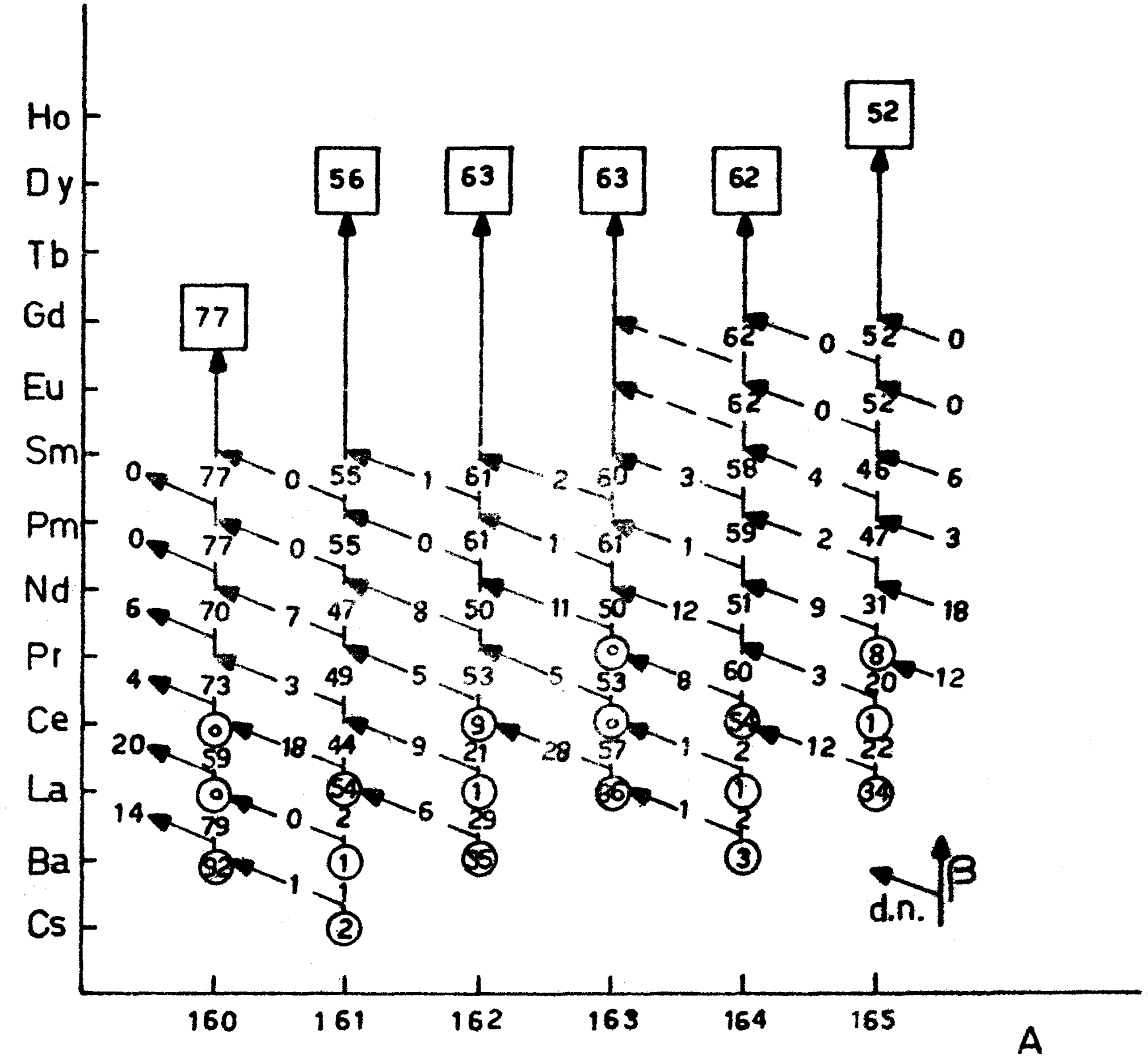
One of us (T.K.) owes much thanks to Professor A. Marques for the hospitality extended to him and the other (K.T.) to Professor P. Gregers Hansen and Dr. N. Onishi. We are also indebted to Professor Y. Fujimoto, Professor M. Yamada and Mr. K. Sato for conversations. The numerical calculation has been done with TOSBAC 3400 at INS, University of Tokyo and IBM370 at C.B.P.F. We want to thank the staffs of these two computation centres for their help.

* * *



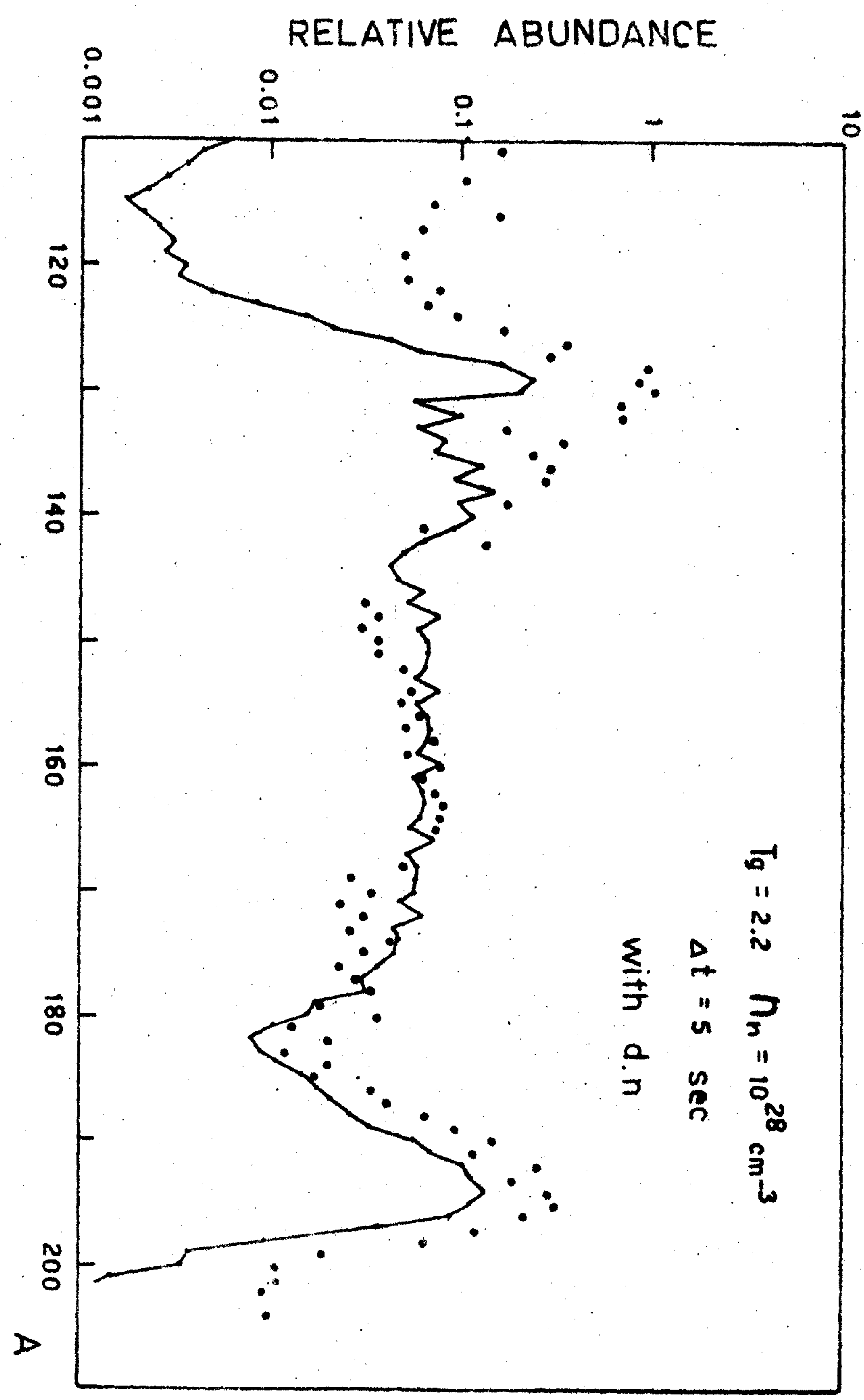
Example of short-time solution without consideration for delayed neutrons. Dots represent the "experimental" data taken from ref. 4, where the s-process contributions have been subtracted from the observed solar-system abundances.

FIG. 1



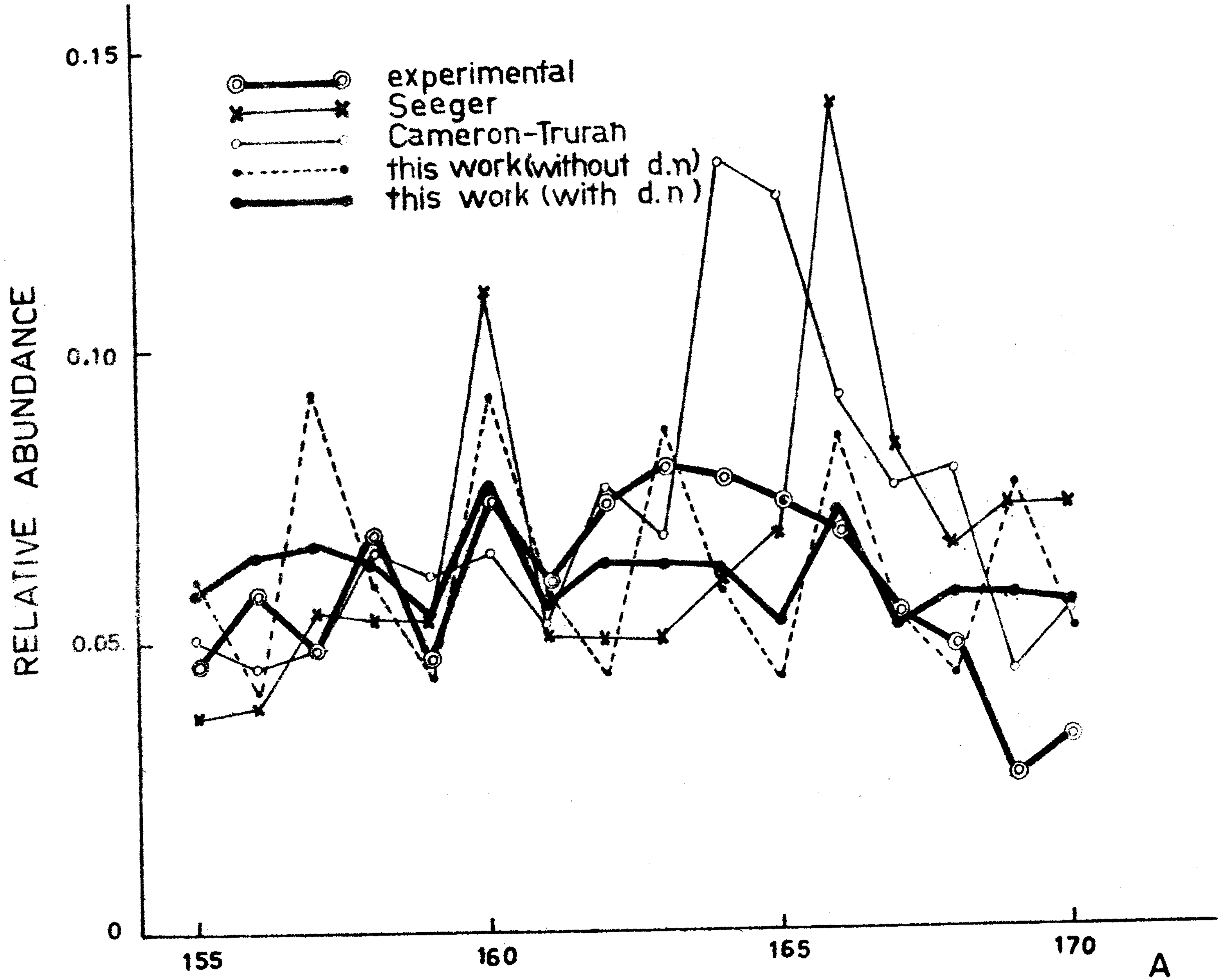
Ilustrative diagram of beta-decay and delayed-netron-emission cascade in the final stage. The relative "frozen" abundances are circled and the figures in the squares represent the relative abundances, which are to be compared with figs. 1, 3 and 4 by multiplying the factor 10^{-3}.

FIG. 2



Example of short-time solution in consideration of delayed neutrons in the final stage (cf. fig. 1).

FIG. 3



Comparison of the present results in the "hump" region with the "experimental" date and with other theoretical values taken form Seeger[1].

FIG. 4

REFERENCES

1. P.A. Seeger, CERN report, CERN 70-30 (Genève, 1970) p.217;
A.G.W. Cameron and E.Hilf, ibid. p.275; see also, E. Comay, S. Lirian, J. Wagman and N. Zeldes, ibid. p.165.

2. M. Yamada, K. Takahashi and S.I. Koyama, CERN report, op.cit. p.397.
M. Morita et al. Progr.Theor.Phys.Suppl.No.48(1971) 41.

3. K. Takahashi, Progr.Theor.Phys.45(1971)1466.

4. P.A. Seeger, W.A. Fowler and D.D. Clayton, Astrophys.J.Suppl.No. 97 XI(1965) 121.

5. A.G.W. Cameron, M.D. Delano and J.W. Truran, CERN report, op.cit. p.735.

6. W.D. Myers and W.J. Swiatecki, Nucl.Phys.81(1966) 1.

7. E.M. Burbidge, G.R. Burbidge, W.A. Fowler and F.Hoyle, Rev.Mod.Phys. 29(1957) 547; see also, ref. |5|.

8. K. Takahashi, Prog.Theor.Phys.47(1972) 1500.

9. E.Ye. Berlovich and Yu.N.Novikov, Docl.AN SSSR 185(1969) 1025.

* * *