Neutrino Nucleosynthesis

in the outer layers of supernovae

A. Sieverding[1], L. Huther[1], G. Martínez-Pinedo[1],
K. Langanke[1,2],A. Heger[3]
[1]Technische Universität Darmstadt
[2]GSI Helmholtzzentrum, Darmstadt
[3]Monash Centre for Astrophysics, Melbourne

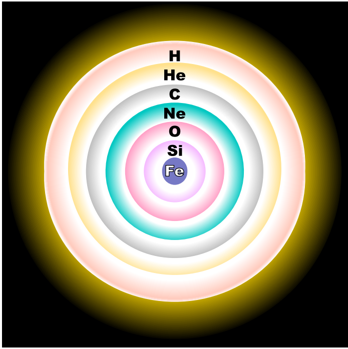
NPCSM long-term workshop
Yukawa institute for Theoretical Physics
15 Nov. 2016

Outline

1. Introduction
    - Neutrino nucleosynthesis
    - Review
    - Constraints on cross-sections
    - Supernova model
2. Results
    - The ν process with updated physics
    - Radioactive nuclei
3. Conclusions and Outlook

Neutrinos and Supernovae

- The core of a massive star collapses after the nuclear burning phases
- Collapse stops when nuclear densities are reached
- Hydrodynamic shock triggers explosive nucleosynthesis
- Cooling core emits neutrinos
- Neutrinos can influence the nucleosynthesis in outer layers of SNe

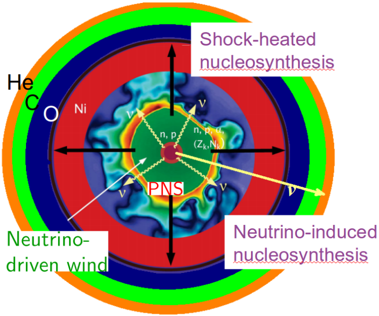


Schematic structure of a massive star

Neutrinos and Supernovae

Neutrinos are crucial for many aspects of Supernovae

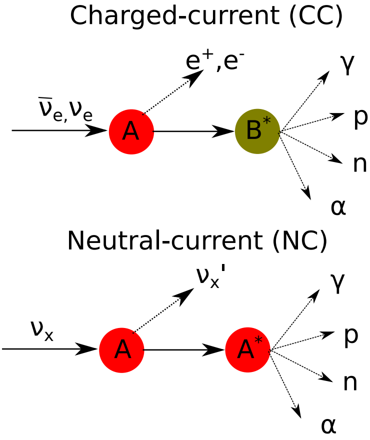
1. Deleptonization and Shock revival
    - Neutrino signal
    - Explosion Dynamics
2. Neutrino driven wind
    - setting initial p/n ratio
3. ν process in the ejecta
    - Ejecta composition
    - Production of radioactive isotopes



Modified, from H.T. Janka

Neutrino nucleosynthesis

- Emission of 10^{58} neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$



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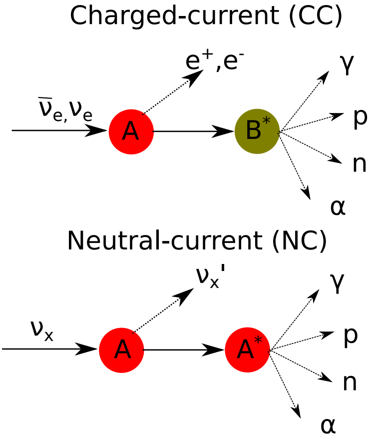

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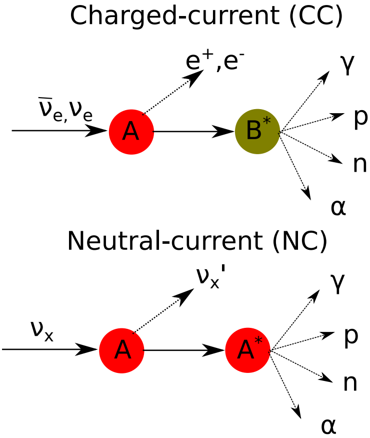

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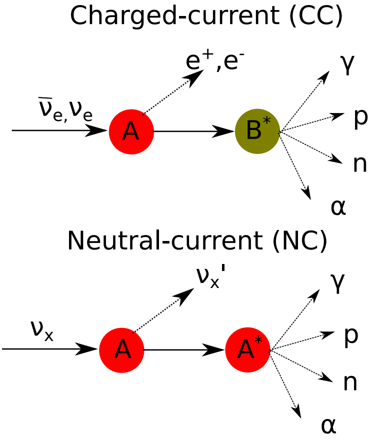
- Particle evaporation
- Capture of spallation products



Neutrino nucleosynthesis

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  ^{19}**F** via ^{20}Ne(ν_x,ν_x' p/n)

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^{19}F via ^{20}Ne(ν_x,ν_x' p/n)

^{138}La and **^{180}Ta** via ^{138}Ba(ν_e,e$^-$) and ^{180}Hf(ν_e,e$^-$)

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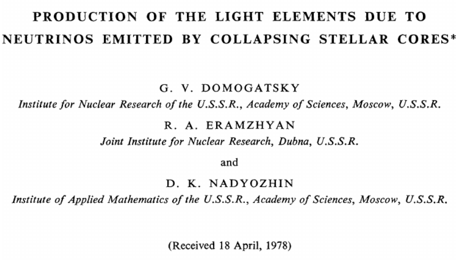
First ideas

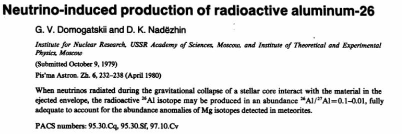


PRODUCTION OF THE LIGHT ELEMENTS DUE TO NEUTRINOS EMITTED BY COLLAPSING STELLAR CORES*

G. V. DOMOGATSKY
Institute for Nuclear Research of the U.S.S.R., Academy of Sciences, Moscow, U.S.S.R.
R. A. ERAMZHYAN
Joint Institute for Nuclear Research, Dubna, U.S.S.R.
and
D. K. NADYOZHIN
Institute of Applied Mathematics of the U.S.S.R., Academy of Sciences, Moscow, U.S.S.R.

(Received 18 April, 1978)

- ν absorption on nucleons and ^{4}He spallation could lead to the production of D,Li,Be,B
- first estimates of the relevant reaction rates



Neutrino-induced production of radioactive aluminum-26

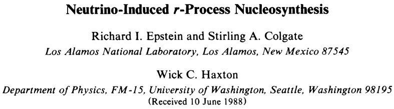
G. V. Domogatskii and D. K. Nadëzhin
Institute for Nuclear Research, USSR Academy of Sciences, Moscow, and Institute of Theoretical and Experimental Physics, Moscow

(Submitted October 9, 1979)
Pis'ma Astron. Zh. 6, 232–238 (April 1980)

When neutrinos radiated during the gravitational collapse of a stellar core interact with the material in the ejected envelope, the radioactive ^{26}Al isotope may be produced in an abundance $^{26}\mathrm{Al}/^{27}\mathrm{Al}=0.1$–$0.01$, fully adequate to account for the abundance anomalies of Mg isotopes detected in meteorites.

PACS numbers: 95.30.Cq, 95.30.Sf, 97.10.Cv

- ^{26}Mg(ν_e,e$^-$) as possible mechanism to produce radioactive ^{26}Al



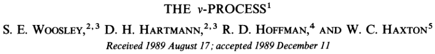
Neutrino-Induced *r*-Process Nucleosynthesis

Richard I. Epstein and Stirling A. Colgate
Los Alamos National Laboratory, Los Alamos, New Mexico 87545
Wick C. Haxton
Department of Physics, FM-15, University of Washington, Seattle, Washington 98195

(Received 10 June 1988)

- ^{4}He spallation as neutron source

Detailed calculations

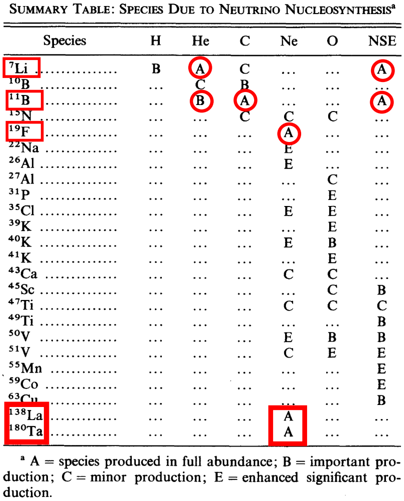


THE ν-PROCESS[1]

S. E. Woosley,[2,3] D. H. Hartmann,[2,3] R. D. Hoffman,[4] and W. C. Haxton[5]

Received 1989 August 17; accepted 1989 December 11

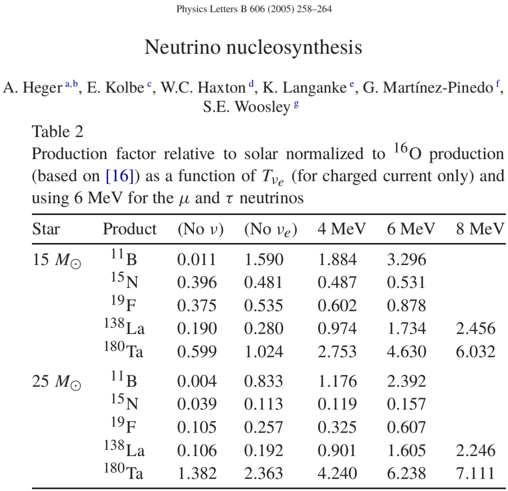
- extended set of neutrino nucleus reactions
- detailed stellar models
- analytic formula for $\rho(t)$, $T(t) \propto T_{\max} e^{-t/\tau}$ for $t \geq t_0$
- $T_{\max} \propto \left(\frac{E_{\mathrm{expl}}}{10^{51}\mathrm{erg}}\right)^{1/4} \times \left(\frac{R}{10^{9}\mathrm{cm}}\right)^{-3/4}$
- constant expansion velocity



Summary Table: Species Due to Neutrino Nucleosynthesis[a]

Species	H	He	C	Ne	O	NSE
^{7}Li	B	A	C	...	...	A
^{10}B	...	C	B	...	...	...
^{11}B	...	B	A	...	...	A
^{15}N	...	...	C	C	C	...
^{19}F	...	...	...	A	...	...
^{22}Na	...	...	...	E	...	...
^{26}Al	...	...	...	E	...	...
^{27}Al	...	...	...	...	C	...
^{31}P	...	...	...	...	E	...
^{35}Cl	...	...	...	E	E	...
^{39}K	...	...	...	...	E	...
^{40}K	...	...	...	E	B	...
^{41}K	...	...	...	...	E	...
^{43}Ca	...	...	...	C	C	...
^{45}Sc	...	...	...	...	C	B
^{47}Ti	...	...	...	C	C	C
^{49}Ti	...	...	...	...	...	B
^{50}V	...	...	...	E	B	B
^{51}V	...	...	...	C	E	E
^{55}Mn	...	...	...	...	...	E
^{59}Co	...	...	...	...	...	E
^{63}Cu	...	...	...	...	...	B
^{138}La	...	...	...	A	...	...
^{180}Ta	...	...	...	A	...	...

[a] A = species produced in full abundance; B = important production; C = minor production; E = enhanced significant production.



Physics Letters B 606 (2005) 258–264

Neutrino nucleosynthesis

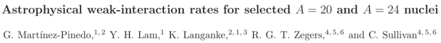
A. Heger [a,b], E. Kolbe [c], W.C. Haxton [d], K. Langanke [e], G. Martínez-Pinedo [f], S.E. Woosley [g]

Table 2

Production factor relative to solar normalized to ^{16}O production (based on [16]) as a function of T_{ν_e} (for charged current only) and using 6 MeV for the μ and τ neutrinos

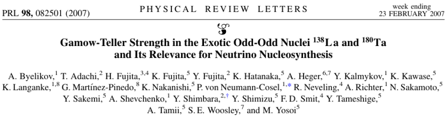
Star	Product	(No ν)	(No ν_e)	4 MeV	6 MeV	8 MeV
15 $M_\odot$	^{11}B	0.011	1.590	1.884	3.296	
	^{15}N	0.396	0.481	0.487	0.531	
	^{19}F	0.375	0.535	0.602	0.878	
	^{138}La	0.190	0.280	0.974	1.734	2.456
	^{180}Ta	0.599	1.024	2.753	4.630	6.032
25 $M_\odot$	^{11}B	0.004	0.833	1.176	2.392	
	^{15}N	0.039	0.113	0.119	0.157	
	^{19}F	0.105	0.257	0.325	0.607	
	^{138}La	0.106	0.192	0.901	1.605	2.246
	^{180}Ta	1.382	2.363	4.240	6.238	7.111

- Neutrino-Nucleus cross sections based on shell model calculations for key nuclei (^{12}C,^{16}O,^{20}Ne,^{24}Mg . . .)
- Hydrodynamic simulation of piston driven explosion



Astrophysical weak-interaction rates for selected $A = 20$ and $A = 24$ nuclei

G. Martínez-Pinedo,[1,2] Y. H. Lam,[1] K. Langanke,[2,1,3] R. G. T. Zegers,[4,5,6] and C. Sullivan[4,5,6]

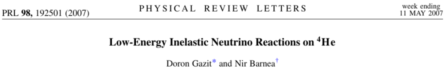


PRL **98,** 082501 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

Gamow-Teller Strength in the Exotic Odd-Odd Nuclei ^{138}La and ^{180}Ta and Its Relevance for Neutrino Nucleosynthesis

A. Byelikov,[1] T. Adachi,[2] H. Fujita,[3,4] K. Fujita,[5] Y. Fujita,[2] K. Hatanaka,[5] A. Heger,[6,7] Y. Kalmykov,[1] K. Kawase,[5] K. Langanke,[1,8] G. Martínez-Pinedo,[8] K. Nakanishi,[5] P. von Neumann-Cosel,[1,*] R. Neveling,[4] A. Richter,[1] N. Sakamoto,[5] Y. Sakemi,[5] A. Shevchenko,[1] Y. Shimbara,[2,†] Y. Shimizu,[5] F. D. Smit,[4] Y. Tameshige,[5] A. Tamii,[5] S. E. Woosley,[7] and M. Yosoi[5]

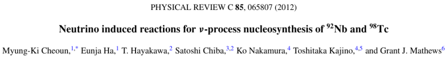
- Dedicated experiments for the determination of cross sections



PRL **98,** 192501 (2007) PHYSICAL REVIEW LETTERS week ending 11 MAY 2007

Low-Energy Inelastic Neutrino Reactions on ^{4}He

Doron Gazit[*] and Nir Barnea[†]

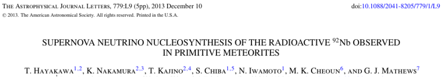


PHYSICAL REVIEW C **85**, 065807 (2012)

Neutrino induced reactions for ν-process nucleosynthesis of ^{92}Nb and ^{98}Tc

Myung-Ki Cheoun,[1,*] Eunja Ha,[1] T. Hayakawa,[2] Satoshi Chiba,[3,2] Ko Nakamura,[4] Toshitaka Kajino,[4,5] and Grant J. Mathews[6]

- Detailed calculations of cross sections



THE ASTROPHYSICAL JOURNAL LETTERS, 779:L9 (5pp), 2013 December 10 doi:10.1088/2041-8205/779/1/L9

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SUPERNOVA NEUTRINO NUCLEOSYNTHESIS OF THE RADIOACTIVE ^{92}Nb OBSERVED IN PRIMITIVE METEORITES

T. HAYAKAWA[1,2], K. NAKAMURA[2,3], T. KAJINO[2,4], S. CHIBA[1,5], N. IWAMOTO[1], M. K. CHEOUN[6], AND G. J. MATHEWS[7]

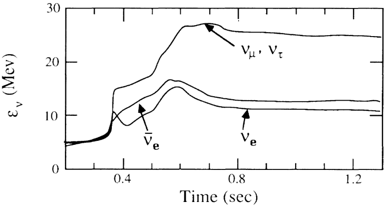
PRL **106,** 152501 (2011) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2011

^{11}B and Constraints on Neutrino Oscillations and Spectra from Neutrino Nucleosynthesis

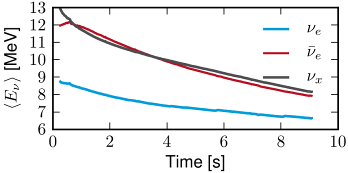
Sam M. Austin,[1,2,*] Alexander Heger,[3,†] and Clarisse Tur[1]

- observational constraints and uncertainties

Neutrino Spectra from state-of-the art SN simulations



Bruenn et al. (1983)



Fischer et al. (2014)

current standard

- $f_\nu(E_\nu) \propto \frac{1}{1+\exp(E_\nu/T_\nu)}$
  - $\langle E_{\nu_e} \rangle = 12$ MeV
  - $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV
  - $\langle E_{\nu,\bar{\nu}_{\mu,\tau}} \rangle = 19$MeV
  - “high ν energies”

- Detailed descriptions of neutrino transport are included
- More channels for neutrino-matter interactions
- Inelastic channels reduce the average energies

Description of ν emission

- Decreasing Luminosity $L_\nu \propto \exp\left(-\frac{t}{\tau_\nu}\right)$
- Emission of 3×10^{53} ergs
- Fermi-Dirac distributed energies, $\langle E_\nu \rangle = 3.15 \times T_\nu$

Low ν energies

- $\langle E_{\nu_e} \rangle = 9\ \mathrm{MeV} (T_\nu = 2.8\ \mathrm{MeV})$
- $\langle E_{\bar{\nu}_e} \rangle = 13\ \mathrm{MeV} (T_\nu = 4\ \mathrm{MeV})$
- $\langle E_{\nu_{\mu,\tau}} \rangle = 13\ \mathrm{MeV} (T_\nu = 4\ \mathrm{MeV})$

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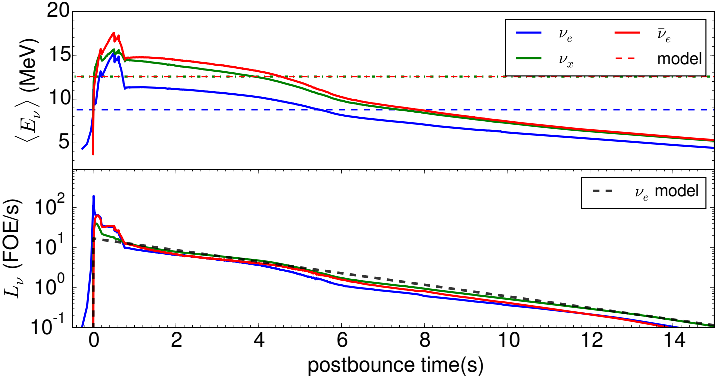
High ν energies

- $T_{\nu_e} = 4$ MeV
- $T_{\bar{\nu}_e} = 5$MeV
- $T_{\nu,\bar{\nu}_{\mu,\tau}} = 6$MeV

Realistic ν signal



- ν signal from a multi-D simulation for a 27 $M_\odot$ progenitor of solar metalicity provided by T. Janka

- Points for improvement:
  - time-dependence of ν energies
  - burst luminosities
  - non- Fermi-Dirac spectra

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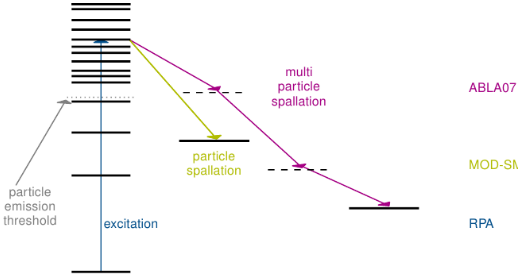
Neutrino cross sections

- Two step process: Excitation and decay
- $\sigma^k_{X\to Y}(E_\nu) = \sum_i \sigma_i^{RPA}(X) \times P_i(Y)$

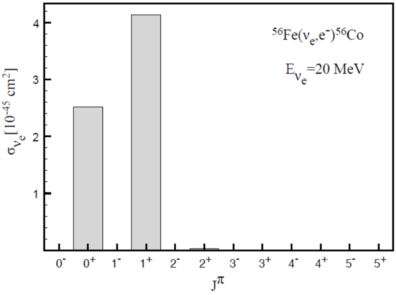
- Excitation cross-section based on RPA
- Decay rates from Hauser-Feshbach statistical models
- Including emission of up to 4 particles

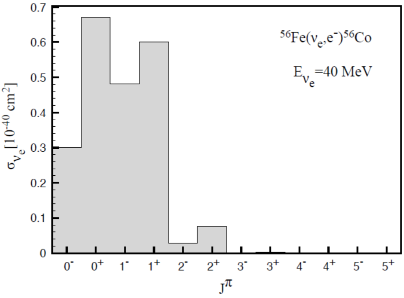


L. Huther, PhD ThesisTU Darmstadt, 2014

Neutrino-Nucleus reaction cross sections

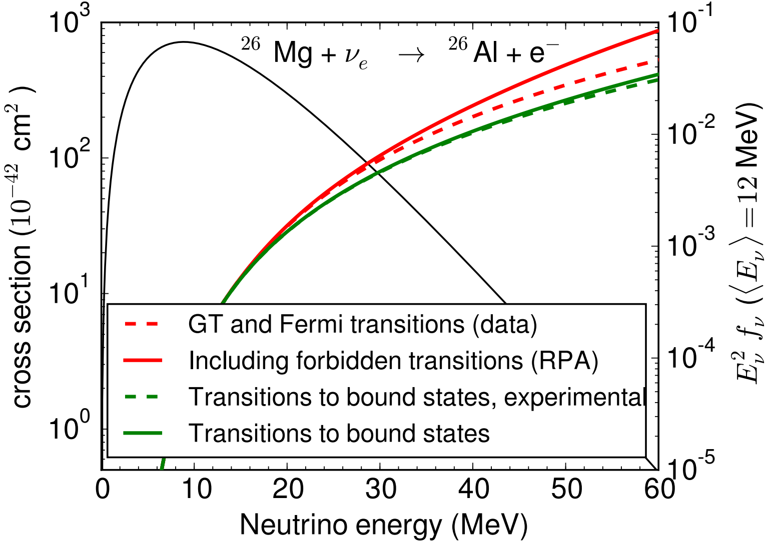
- **Charged-current neutrino absorption**
  - Transitions to bound states are most important
  - Dominated by $J = 0^+$ and $J = 1^+$ transitions
- **Neutral-current scattering**
  - Only particle emission is relevant for nucleosynthesis
  - Mainly collective excitations at higher energies

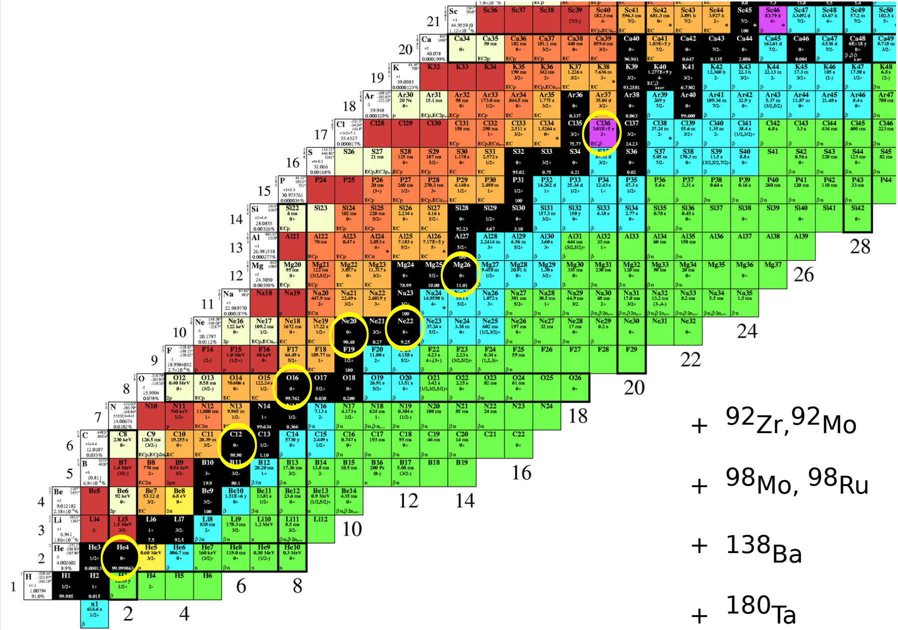




From: Paar,Vretenar,Marketin,Ring Phys.Rev.C 77(2008) 024608

Cross-sections supplemented by experimental data





+ ^{92}Zr, ^{92}Mo

+ ^{98}Mo, ^{98}Ru

+ ^{138}Ba

+ ^{180}Ta

Important reactions constrained by experiment

- ^{20}Ne(ν,ν'),^{20}Ne(ν_e,e$^-$),^{20}Ne($\bar{\nu}_e$,e$^+$) (*Anderson et al. 1991*

- ^{22}Ne(ν_e,e$^-$) (from ^{22}Mg decay, *Hardy et al. 2003*)

- ^{24}Mg(ν,ν'),^{24}Mg(ν_e,e$^-$) (*Zegers et al. 2008*)

- ^{26}Mg(ν_e,e$^-$) (*Zegers et al. 2005*)

- ^{138}Ba(ν_e,e$^-$) (*Byelikov et al. 2007*)

- ^{180}Ta(ν_e,e$^-$) (*Byelikov et al. 2007*)

- ^{36}Ar($\bar{\nu}_e$,e$^+$), ^{36}S(ν_e,e$^-$) (Shell model calculations)
- ^{4}He(ν , *) (*Gazit et al., (2007), Suzuki et al. (2006)*)
- ^{12}C(ν , *) (*Woosley et al. (1990)*)

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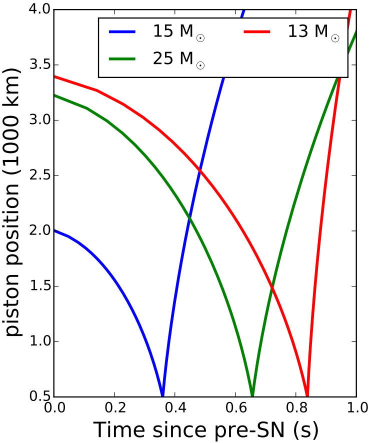
Supernova model

- 1D piston driven explosions (Heger et al. 2007)
- kinetic explosion energy $E_{\mathrm{expl}} = 1.2 \times 10^{51}\mathrm{erg}$



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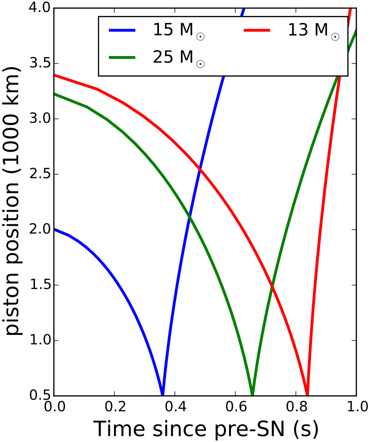
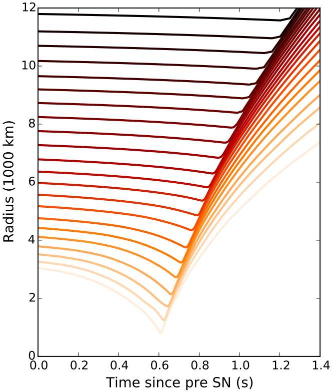
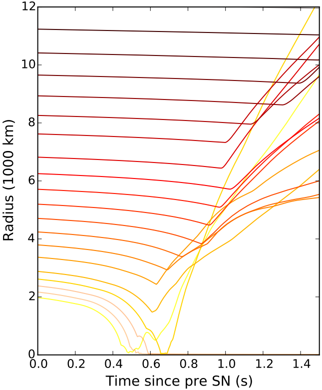


Neutrino flux

- Exponentially decreasing neutrino luminosity
- Thermal Fermi-Dirac spectrum

1D vs. multi-D





- Typical 1D trajectory
- 2D simulation (Harris et al.)

For outer layers little qualitative differences in the individual trajectories

Updated physics in the current project

- Simulations including detailed neutrino transport give new estimates for typical neutrino energies:
  $\langle E_\nu \rangle$=8-13 MeV compared to 13-25 MeV
- Nuclear reaction data from *JINA Reaclib V2.0 (2013)*
- Lower neutrino energies put make charged-current reactions more important
- Neutrino-nucleus cross-sections have been calculated for almost the whole nuclear chart (L. Huther 2014, PhD. Thesis)
- Where available, cross-sections have been supplemented by experimental data and/or results of shell-model calculations

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Preliminary studies

Full reaction network calculations based on the analytic explosion trajectories (arXiv:1505.01082)

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Evaluation of CCSNe nucleosynthesis calculations

- The solar abundances provide observational information for nucleosynthesis results to compare with

Production factor

- $P_{A,\text{normalized}} = \left(\frac{X_A}{X_A^{\odot}}\right) / \left(\frac{X_{^{16}\text{O}}}{X_{^{16}\text{O}}^{\odot}}\right)$

Assuming that CCSNe are the main source of solar ^{16}O

- $P_{A,\text{normalized}} \sim 1$ indicates CCSNe as possible production site
- $P_{A,\text{normalized}} \ll 1$ hints another production site or mechanism

Production factors normalized to ^{16}O

- IMF averaged production factor for 13-30 $M_\odot$ stars (solar metallicity)

Nucleus	no ν	Low energies[1]	High energies[2]
^{7}Li	0.001	0.07	0.91
^{11}B	0.005	0.45	1.81
^{15}N	0.06	0.09	0.15
^{19}F	0.12	0.25	0.40
^{138}La	0.12	0.86	1.70
^{180}Ta*	0.6	1.49	2.67

- 1) $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e,\nu_x} \rangle = 13$ MeV
- 2) $\langle E_{\nu_e} = 13$MeV ,$\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = 19$ MeV
- *) Only about 40% of ^{180}Ta survive in the long-lived isomeric state

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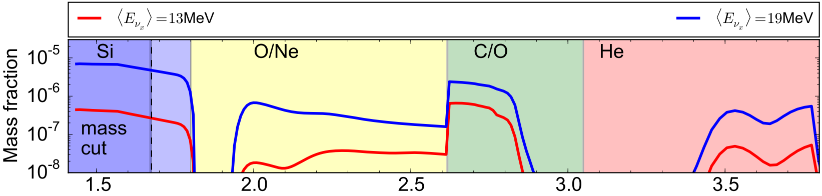
(Over)Production of ^{11}B

1. Si shell

2. O/Ne shell

3. C/O shell

4. He shell



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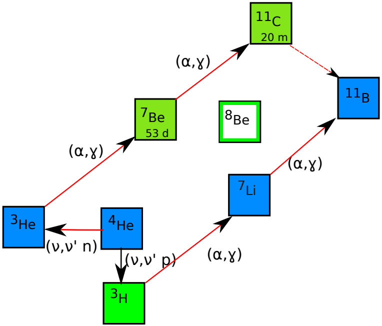

1. Si shell
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   - Spallation of ^{4}He
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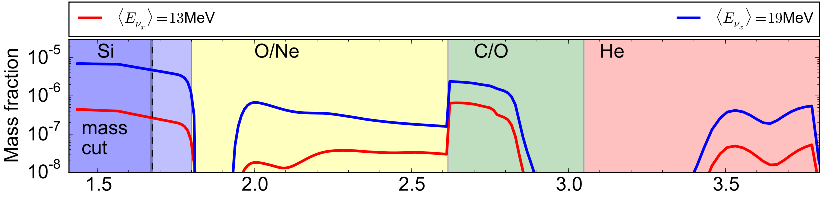

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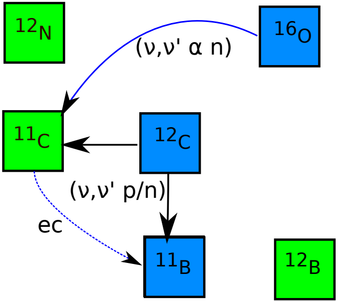

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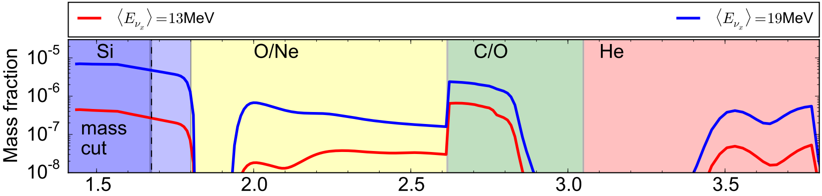

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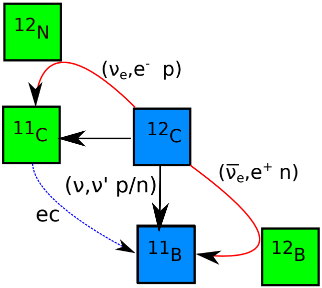

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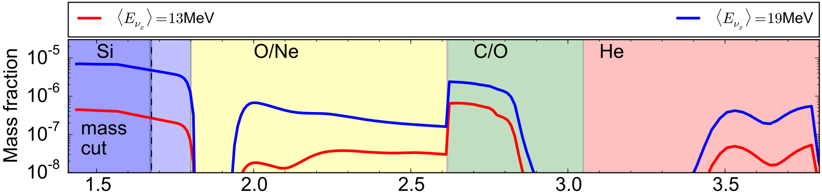

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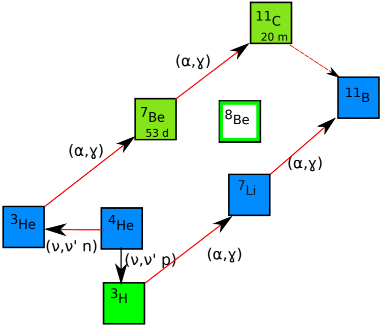

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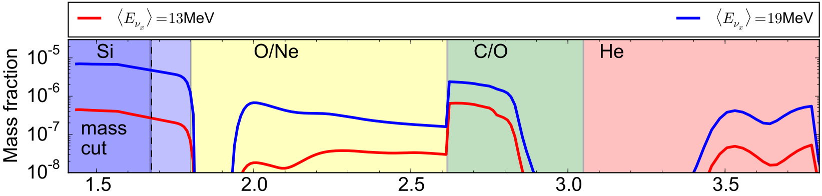
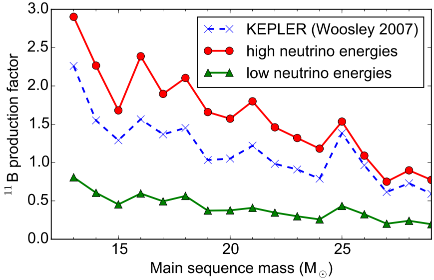
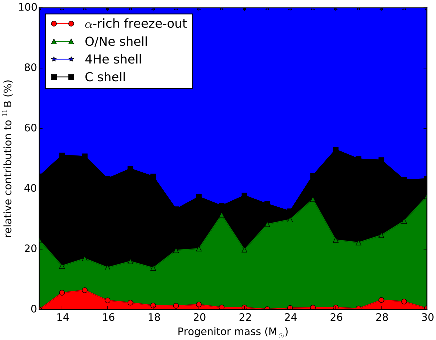


Contributions to ^{11}B production





- ^{11}B production factors

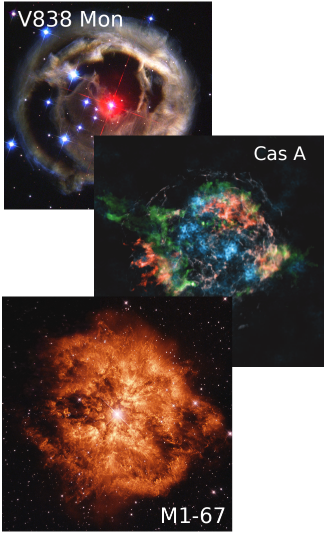
ν induced production of light elements is particularly effective in low-mass low-metallicity stars (cf. Banerjee+ Phys. Rev. Lett. 110, 141101)

- relative contributions from different regions
- reflects stellar structure

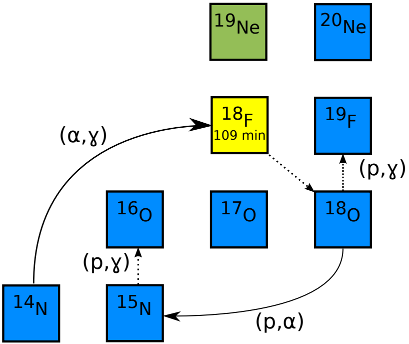
Production of ^{19}F

Contributions from different sites

- AGB stars
  - He-burning thermal pulses
    Lugaro et al. (2004)
  - Observationally confirmed
- Core-Collapse Supernovae
  - Neutrino spallation
  - shock-heated nucleosynthesis
  - Dominating at low metallicity *Kobayashi et al. (2011)*
- Wolf-Rayet stars
  - Ejection of He-burning material
    Renda et al. (2004)

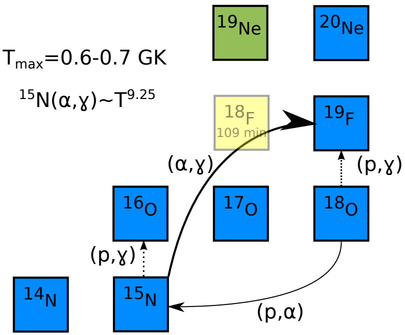


Production of ^{19}F



- Without neutrinos:
  - H- and He-shell burning create regions enriched in ^{18}O and ^{15}N

Production of ^{19}F



- Without neutrinos:
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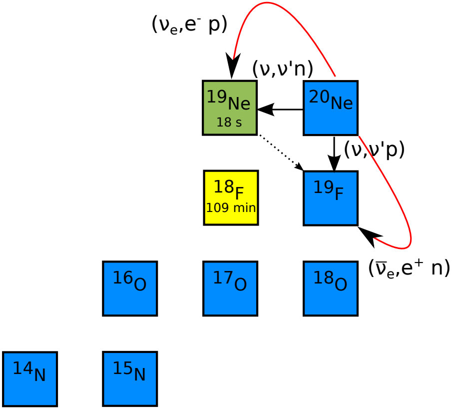
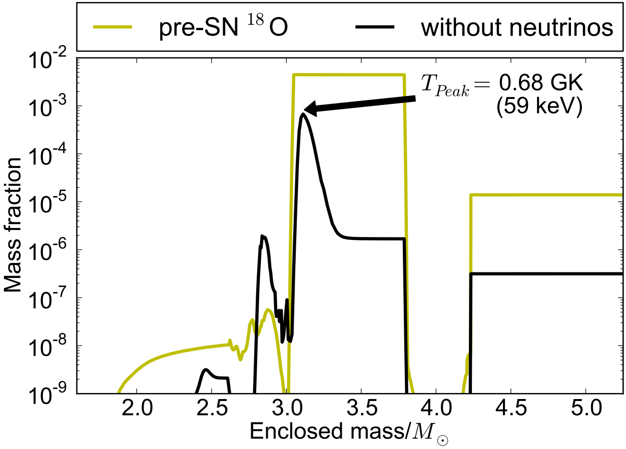


- Without neutrinos:
  - H- and He-shell burning create regions enriched in ^{18}O and ^{15}N
  - High shock temperatures enhance ^{15}N(α,γ) and ^{18}O(p,γ)
- Neutral-current and charged-current neutrino reactions on ^{20}Ne

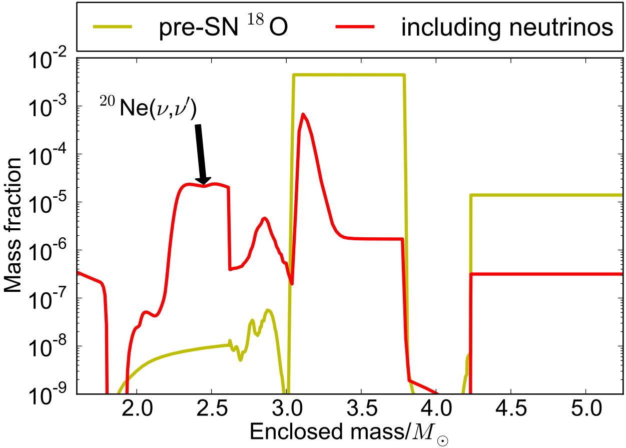
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Explosive nucleosynthesis without neutrinos

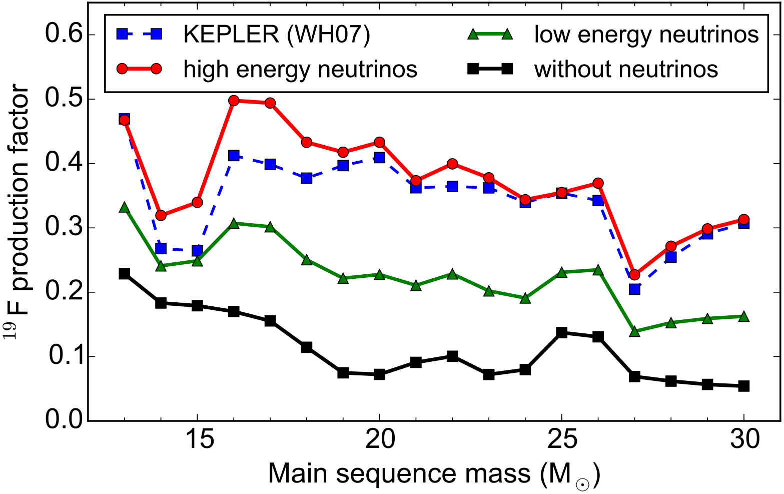


Production of ^{19}F for a 15 $M_\odot$ progenitor

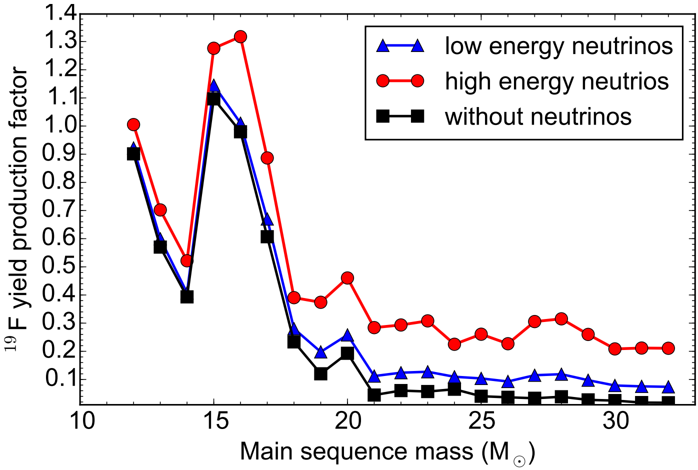
- Including neutrino interactions



Importance of neutrinos for the production of ^{19}F

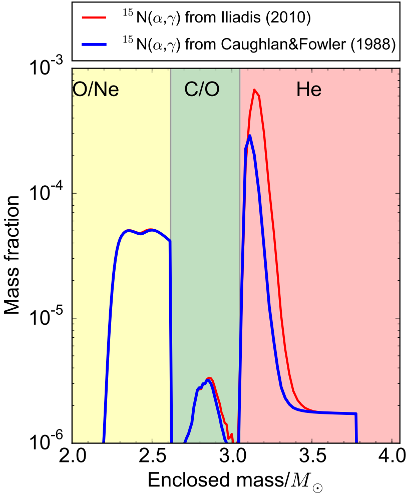


- Using the description of the explosion as in Woosley+(1988) corresponding to an explosion energy of 1.0×10^{51} erg



- ^{19}F yields up to solar even without neutrinos

Sensitivity to ^{15}N(α,γ) reaction rate



- Without neutrinos
  - Yield: $7.3 \times 10^{-5} M_\odot$
- Low energy spectrum
  - Yield: $8.0 \times 10^{-5} M_\odot$
- High energy spectrum
  - Yield: $9.2 \times 10^{-5} M_\odot$
- High energy spectrum, ^{15}N(α,γ) from Caughlan&Fowler
  - Yield: $4.8 \times 10^{-5} M_\odot$

low energy spectra: $\langle E_{\nu_x,\bar{\nu}_e} \rangle = 13$MeV , $\langle E_{\nu_e} \rangle = 9$MeV
high energy spectra: $\langle E_{\nu_x} \rangle = 19$MeV , $\langle E_{\nu_e,\bar{\nu}_e} = 13$MeV

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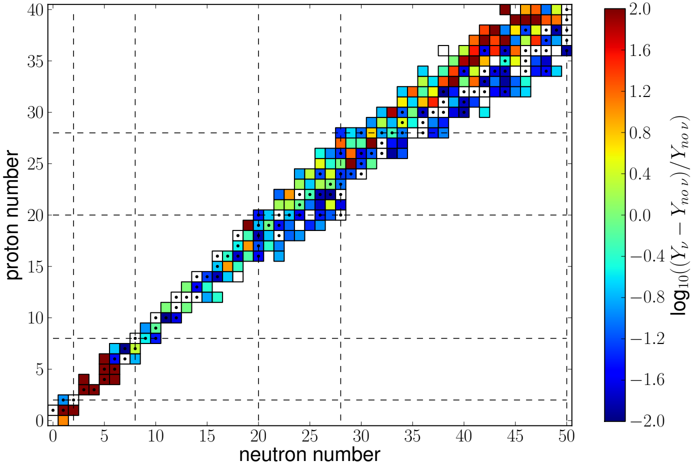
Impact of neutrinos on the nucleosynthesis



- Large range of radioactive nuclei are affected

γ-ray astronomy

Isotope	Decaytime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li}^*$	478
^{56}Ni	111 d	$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}^* \rightarrow {}^{56}\mathrm{Fe}^* + e^+$	847, 1238
^{57}Ni	390 d	$^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}^*$	122
^{22}Na	3.8 y	$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}^* + e^+$	1275
^{44}Ti	89 y	$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc}^* \rightarrow {}^{44}\mathrm{Ca}^* + e^+$	1157, 78, 68
^{26}Al	$1.04\ 10^{6}$y	$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}^* + e^+$	1809
^{60}Fe	$2.0\ 10^{6}$y	$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co}^*$	1173, 1332

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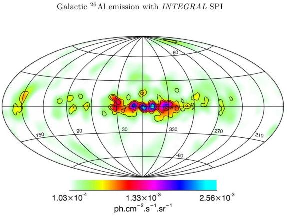
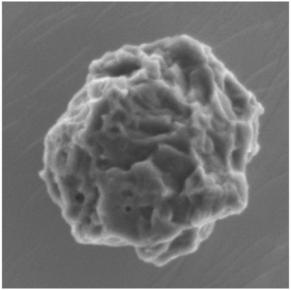
Production of ^{26} Al

- Well studied radioisotope
  - By γ-ray telescopes
  - $2.8 \pm 0.8 M_\odot$ in the Galaxy *Diehl et al. 2006*
  - in pre-solar grains
  - $^{26}\mathrm{Al}/^{27}\mathrm{Al} \approx \quad 10^{-5}$
- Mainly from Supernovae and WR-stars *Limongi&Chieffi (2006)*
- Up to 10% contribution from AGB stars *Siess&Arnould (2008)*

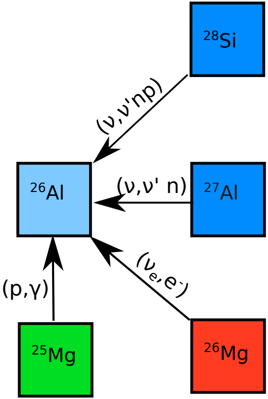


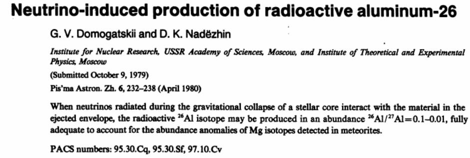
Bouchet et al. (2015)



Hynes &Gyngard (2009)

Production channels for ^{26} Al





Neutrino-induced production of radioactive aluminum-26

G. V. Domogatskii and D. K. Nadĕzhin

Institute for Nuclear Research, USSR Academy of Sciences, Moscow, and Institute of Theoretical and Experimental Physics, Moscow

(Submitted October 9, 1979)

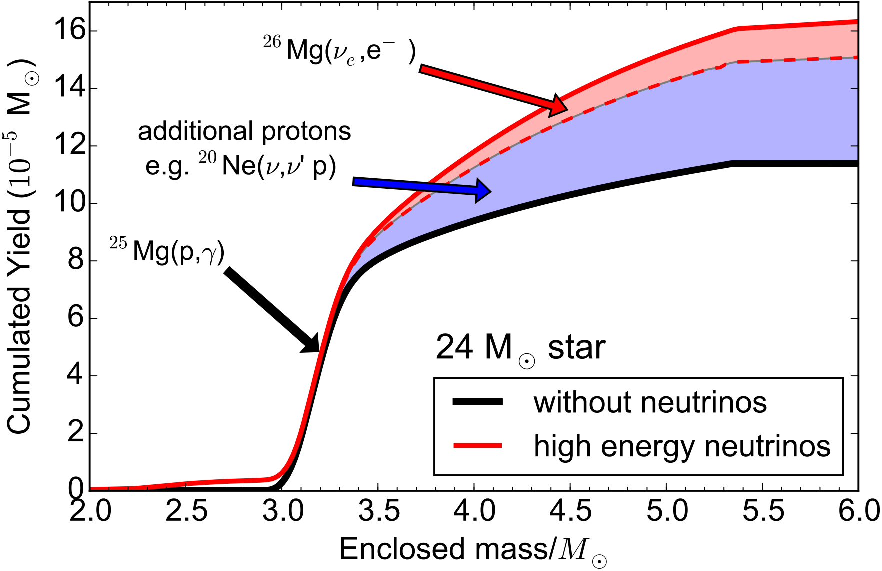
Pis'ma Astron. Zh. 6, 232–238 (April 1980)

When neutrinos radiated during the gravitational collapse of a stellar core interact with the material in the ejected envelope, the radioactive ^{26}Al isotope may be produced in an abundance ${}^{26}\mathrm{Al}/{}^{27}\mathrm{Al}=0.1$–$0.01$, fully adequate to account for the abundance anomalies of Mg isotopes detected in meteorites.

PACS numbers: 95.30.Cq, 95.30.Sf, 97.10.Cv

- Different mechanisms:
  - enhancement of p-captures
  - charged-current channel
  - neutral-current channels

IMF averaged Yield



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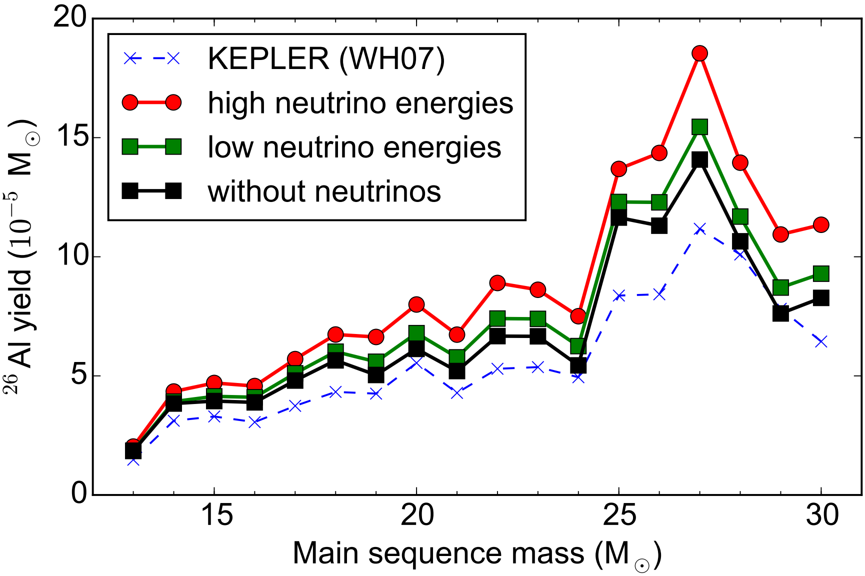
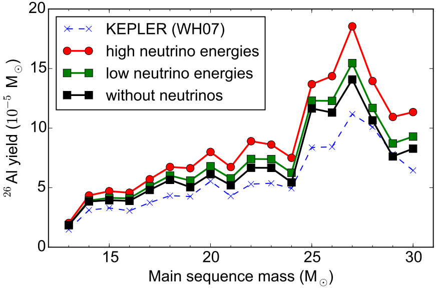


IMF averaged Yield



- ^{60}Fe/^{26}Al ≈ 1.25 (Observations give ≈ 0.35)
- Further contributions from less massive stars, Wolf-Rayet stars, rotating stars

Isotope	without ν	low energy ν	high energy ν
^{26}Al	5.19	5.64	6.56
^{22}Na	0.20	0.27	0.39

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- Conclusions
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  - Calculations with updated neutrino energies
  - Important neutrino-nucleus cross-sections constrained by data
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- Outlook
  - Cross sections based on QRPA
  - Tracer particles from multi-D SN simulations
  - Take into account time-dependent,non-Fermi-Dirac neutrino spectra