Measurements of the astrophysical rates for the ^{192,194,195,196}Pt (n, gamma) reations

P. E. Koehler, J. A. Harvey, S. Raman, K. H. Guber, R. R. Winters, J.A. Becker

Measurements of the Astrophysical Rates for the $^{192,194,195,196}Pt(n,\gamma)$ Reactions

Paul Koehler, Jack Harvey, S. Raman, Klaus Guber, Ron Winters, and John Becker

Physics Division, ORNL

Computational Physics and Engineering Division, ORNL

Denison University

LLNL

Motivation

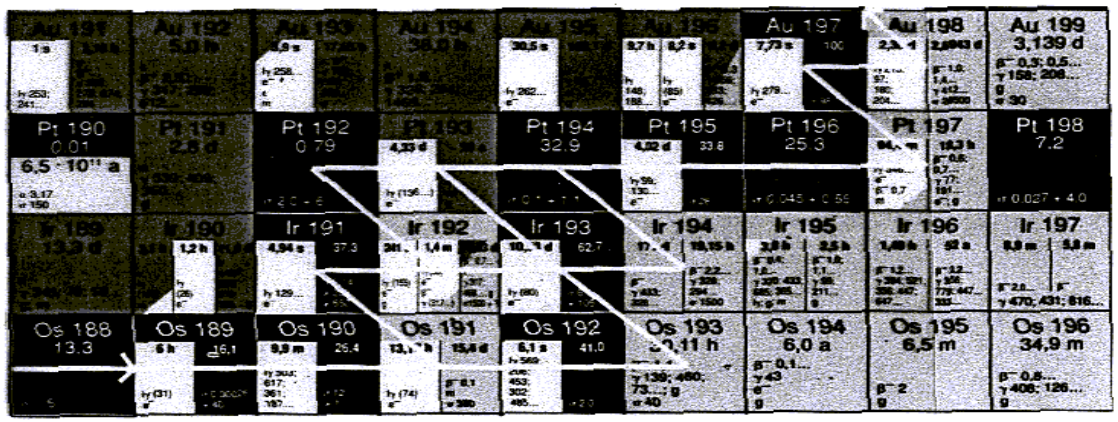
Experimental Details

Results and Astrophysical Implications

Motivation

- ^{192}Pt is the heaviest *s*-only isotope for which no published (n,γ) measurements exist across the range of *s*-process temperatures.
- $\langle\sigma\rangle$ for ^{192}Pt needed to estimate the neutron density during the *s* process. Branching is independent of temperature.
- Long isotopic chain can be used to improve statistical models.
- Corrections to *r*-process residuals near A=190 peak.

The s process in the Pt region

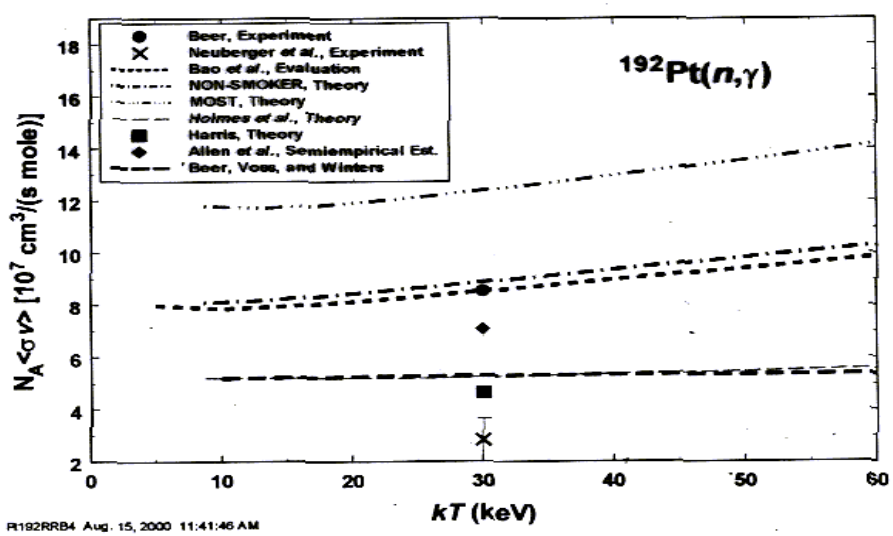


Motivation

- Most recent results for ^{192}Pt (Arlandini *et al.*):

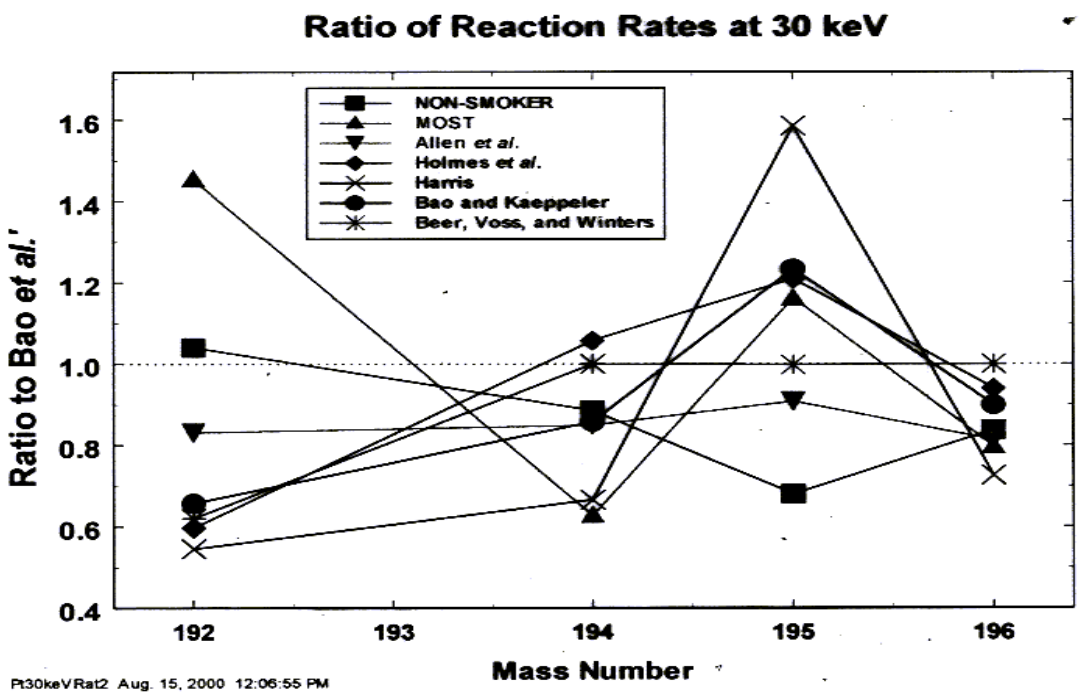
  Classical model overproduces by 50%.
  Stellar model in good agreement with solar abundance.

- Two previous measurements at kT=30 keV differ by almost a factor of 3.
- Statistical model calculations differ by a factor of 3.
- Evaluations have assigned a 50% uncertainty to the rate at kT=30 keV.



Motivation

- Reaction rates for other isotopes of Pt also have large uncertainties.



Experimental Details

- Low natural abundance of ^{192}Pt (0.79%) makes measurement of reaction rate difficult.

  Need ~1 g of separated isotope for a time-of-flight measurement.

  Activation measurements difficult because:

  i) Half life of ^{193}Pt is relatively long.
  ii) Half life of ^{193}Pt is poorly known.
  iii) Decay intensities poorly known.

- Only a 700 mg sample having 56.7% enrichment in ^{192}Pt was available.

  Required longer than usual measurement time.

  Sample had to be refabricated (into a different shape) between (n,γ) and σ_t experiments.

Experimental Details

- Separate (n,γ) and σ_t measurements on $^{194,195,196}Pt$ required.
- Require "simultaneous" resonance analysis of the data for all the measured isotopes.

Sample	Thickness (10^{-3} at/b)		Isotope Percentages			
	(n,γ)	σ_t	192	194	195	196
^{192}Pt	0.463	4.53	56.97	26.16	11.23	4.74
^{194}Pt	1.68	23.6	0.026	96.46	2.44	0.090
^{195}Pt	0.607	23.8	0.01	1.21	97.29	1.4
^{196}Pt	1.71	14.4	0.04	0.67	1.69	97.25

(n,γ) samples were discs.

σ_t samples were cylindrical

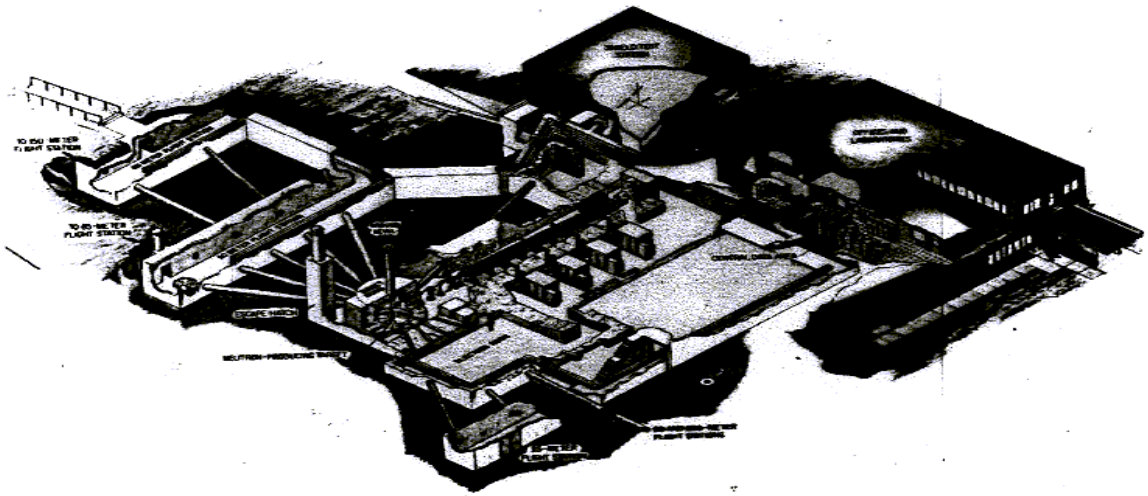
Experimental Details

- Experiments performed at the Oak Ridge Electron Linear Accelerator (ORELA).

  (n,γ) on flight path 7.

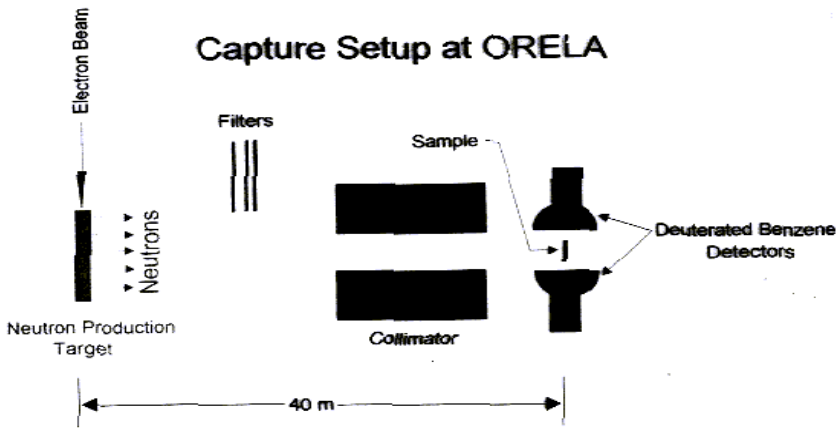
  σ_t on flight path 1.

  ORELA operated at P=7 kW, Δt=8 ns, R=525 Hz.

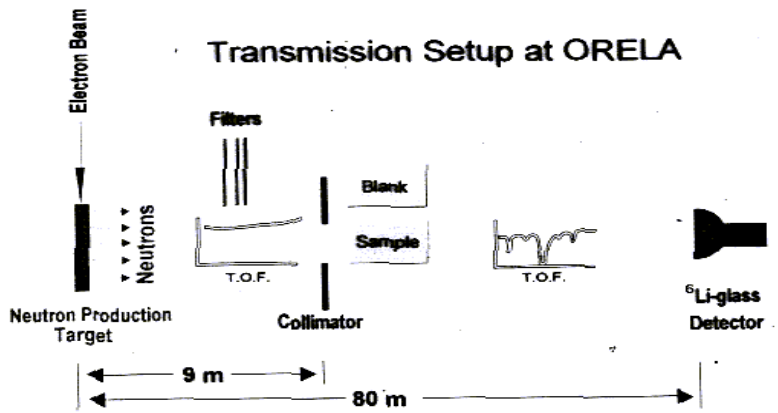


Neutron Capture and Total Cross Section Apparatus at ORELA

Capture Setup at ORELA

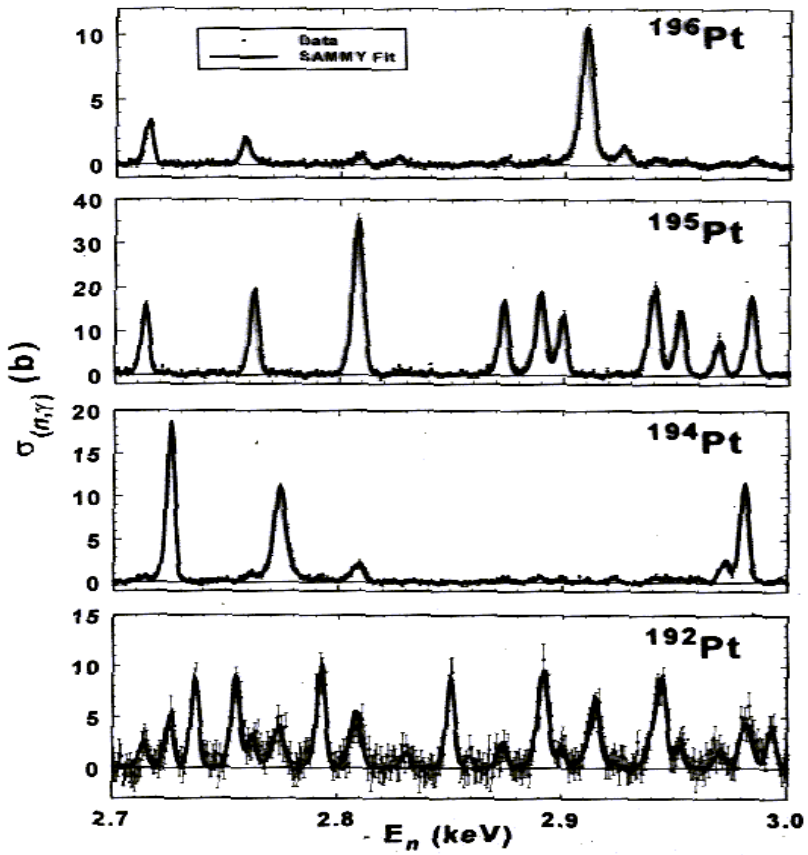


Transmission Setup at ORELA



Results: (n,γ) Cross Sections in the Resolved Resonance Region (E_n< 5 keV)

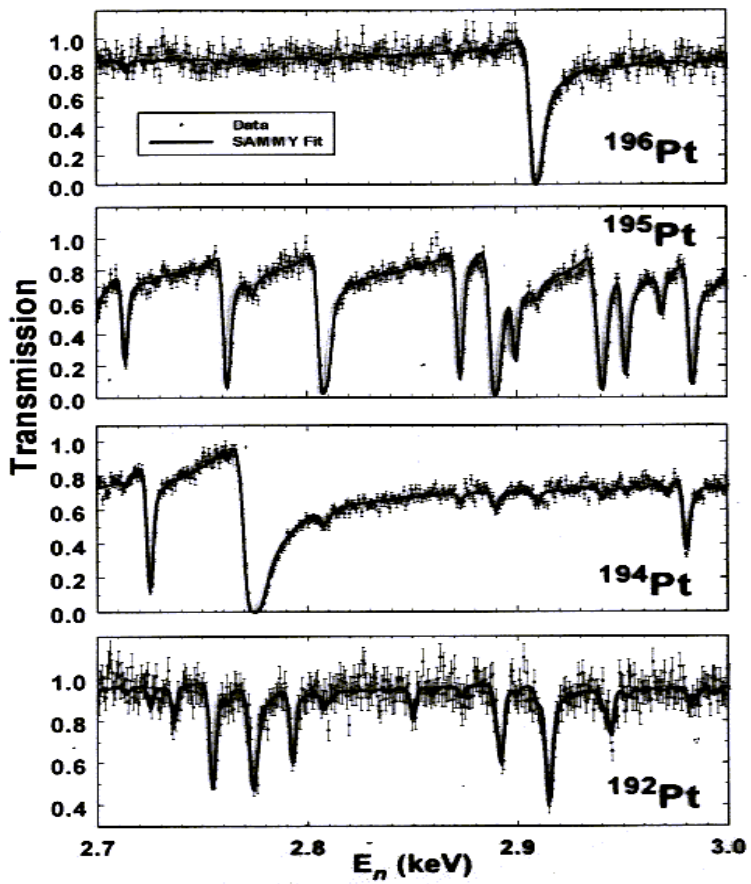
Example Data and *R*-matrix Fits.



Number of Resonances
77 (5)
277 (44)
102 (7)
156 (10)

Results: Total Cross Sections in the Resolved Resonance Region (E_n< 5 keV)

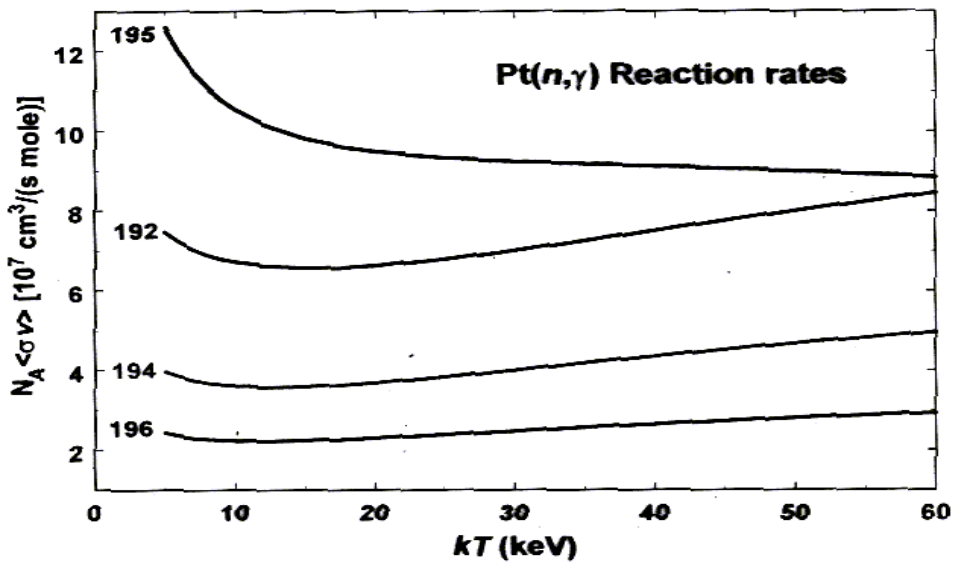
Example Data and *R*-matrix Fits.



	D_0 (eV)
^{196}Pt	167
^{195}Pt	19.2 (18)
^{194}Pt	111 (240)
^{192}Pt	70

Results: Astrophysical Reaction Rates

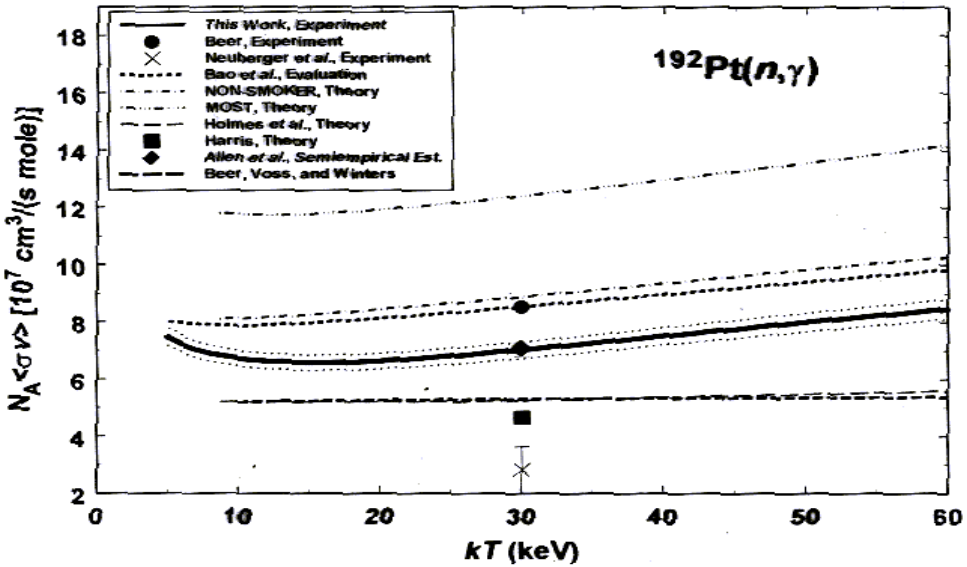
Calculated from resonance parameters plus unresolved data using standard technique.



Isotope	30-keV MACS (mb)
192	485±20
194	277.2±8.4
195	639±19
196	171.5±5.2

Comparison to Previous Work

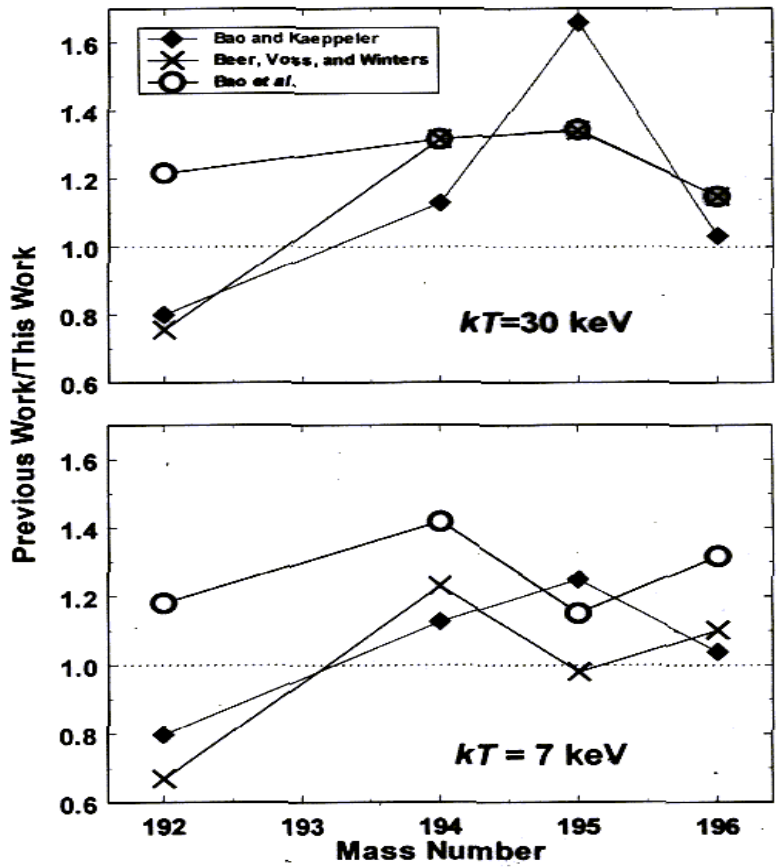
Comparison of $^{192}Pt(n,\gamma)$ Reaction Rates



- Similar results for the other Pt isotopes.
- Previous recommended rates differ by as much as 70%.
- Semi-empirical estimates of Allen *et al.* agree best.
- NON-SMOKER closest to data of statistical models.

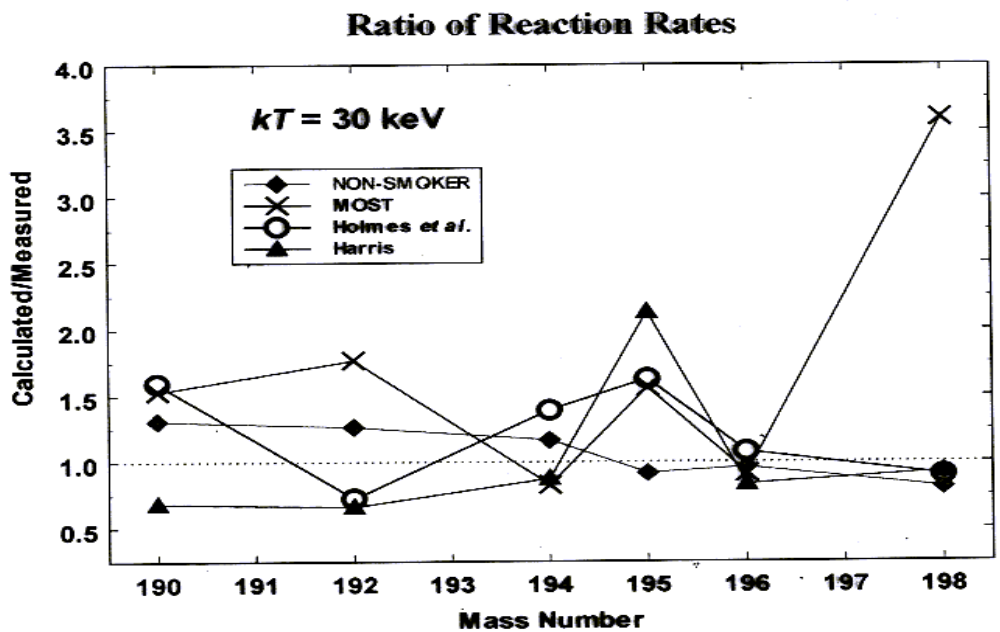
Comparison to Previous Work

Ratios of Reaction Rates at Different Temperatures



Astrophysical Implications

- Significant differences compared to evaluated rates will result in substantial changes in calculated abundances.
- Reduction of uncertainties (from ~50% to 3-5%) will allow meaningful tests of *s*-process models.
- Can be used to test reaction rates calculated with statistical models (including measurements of Beer for ^{190,198}Pt).



Astrophysical Implications:
Neutron density during the *s* process

- Classical analysis of branching at ^{192}Ir.
- Started from recent analysis by Arlandini *et al.*

  $\tau_0 = 0.296\ \mathrm{mb}^{-1}$, $N_s(^{191}\mathrm{Ir}) = 4.57\times10^{-3}$.

  ^{192}Ir half life from Takahashi and Yokoi.
  Reaction rates for other isotopes from Bao *et al.*, 2000.

- Then, $\sigma N_s(^{192}\mathrm{Pt}) = \sigma N_s(^{192}\mathrm{Ir}) * f * \zeta(^{192}\mathrm{Pt})/(1-f)$.

  Where, $\sigma N_s(^{192}\mathrm{Ir}) = \sigma N_s(^{191}\mathrm{Ir})\xi(^{192}\mathrm{Ir})$,

  $$\zeta(^{192}\mathrm{Pt}) = [1+1/(\tau_0\sigma(^{192}\mathrm{Pt}))]^{-1},$$

  $$\xi(^{192}\mathrm{Ir}) = [1/(1-f) + 1/(\tau_0\sigma(^{192}\mathrm{Ir}))]^{-1},$$

  $$f = \lambda_\beta/(\lambda_\beta+\lambda_n),\ \lambda_n = n_n v_T \sigma(^{192}\mathrm{Ir}).$$

- Must add $N_s(^{192}\mathrm{Ir})$ to $N_s(^{192}\mathrm{Pt})$ to account for decay of ^{192}Ir to ^{192}Pt.

Astrophysical Implications:
Neutron density during the *s* process

- Effective neutron densities from classical analyses of *s*-process branching points.

n_n (cm^{-3})	*What*
$(4.1 \pm 0.6) \times 10^8$	A=147 Branching, Toukan *et al.*
$< 5 \times 10^8$	^{192}Ir branching, Käppeler *et al.*
$(7 + 5 - 2) \times 10^7$	^{192}Ir branching, Present Work

- Present result is inconsistent with neutron density from other branchings.
- Comparatively large uncertainty in n_n from ^{192}Ir branching analysis due to factor of 2 uncertainty in reaction rate for ^{192}Ir(n,γ).

Astrophysical Implications:

Comparison of classical and stellar models of the *s* process (following Arlandini *et al.*)

- Stellar model: good agreement at *s*-only ^{192}Pt.

  $N_{s,calc} = 0.0103$

  $N_{s,solar} = 0.0105$

  Used ^{192}Pt(n,γ) rate from Beer, Voss, and Winters and Holmes *et al.* rate for ^{192}Ir (n,γ).

  Gallino (private comm.) calculation with our new reaction rates: $N_{s,calc}/N_{s,solar} = 0.86$.

  If ^{192}Ir(n,γ) rate decreased by 30%, then good agreement.

- Classical model: 51% <u>overproduction</u> of *s*-only ^{192}Pt.

  Result with "standard" $n_n = 4.1 \times 10^8$ cm^{-3} and latest MACS yields 38% <u>underproduction</u> of ^{192}Pt.

  Require $\sigma(^{192}\text{Ir}) \approx 900$ mb (35% of Boa *et al.* value, 26% of Holmes *et al.*) to bring classical model into agreement with solar abundance of ^{192}Pt.

Astrophysical Implications:
Need Better ^{192}Ir(n,γ) Reaction Rate

- Compare calculated to measured MACS for ^{191,193}Ir to derive normalization for ^{192}Ir.

Model	Measured/Theory			
	191	193	Ave.	Norm.*192
MOST	1.39	2.29	1.84	5464
NON-SMOKER	1.39	1.49	1.44	2995
Holmes *et al.*	0.76	0.89	0.84	2906
Harris	0.75	0.88	0.81	2641

- Ignoring MOST, 2850 mb appears to be a reasonable value for the ^{192}Ir(n,γ) reaction rate at 30 keV.

  Very close to value needed by Gallino to get agreement with stellar model (Holmes *et al.*/1.3 = 2560).

Conclusions

- Measured ^{192,194,195,196}Pt(n,γ) and total cross sections from 10 eV to 500 keV.
- Determined reaction rates across entire range of interest to *s* process with 3-5% precision.

  Significant reduction of previous uncertainties (~ 50%).

  Significant (up to 60%) differences with respect to previously recommended reaction rates.

  NON-SMOKER statistical model rates in fairly good agreement with our measurements.

- Effective neutron density derived from classical *s*-process analysis of ^{192}Ir branching is significantly different from value derived from other branchings.
- *s*-process calculations under-produce *s*-only ^{192}Pt.

  Stellar model: 86% of solar.
  Classical model: 62% of solar.

  Stellar model results within uncertainties due to unmeasured ^{192}Ir(n,γ) cross section.