

# Reaction Rates for $^{44}\text{Ti}$

A “lightning” summary of a few important reactions

# Outline

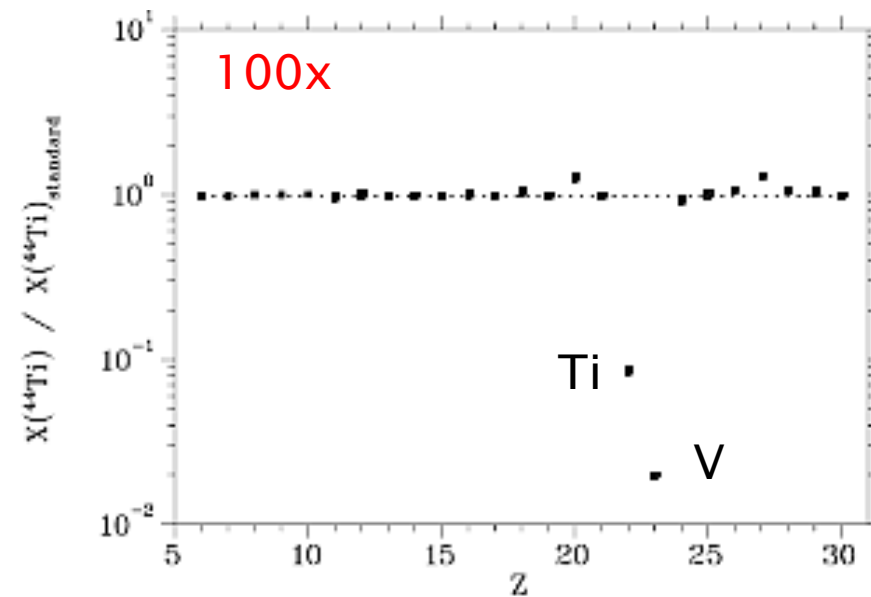
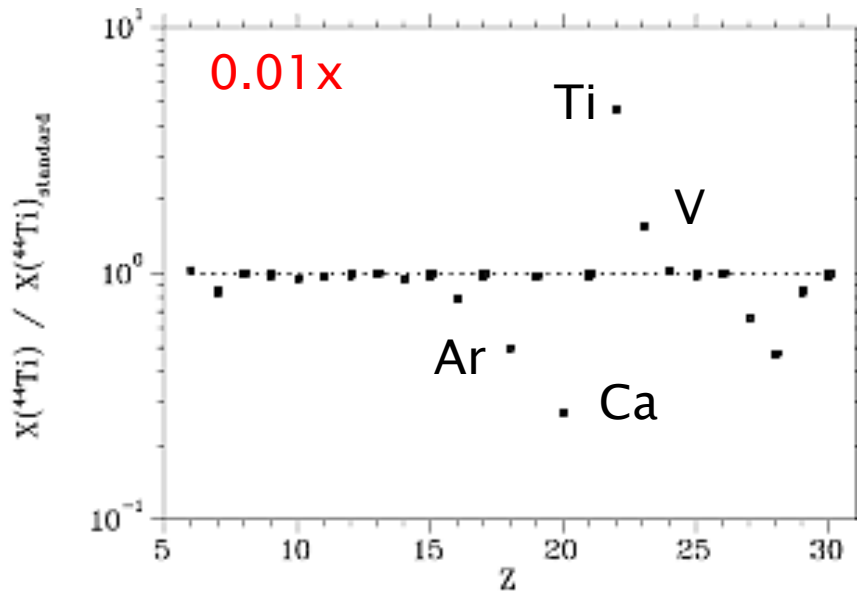
- ▶ **Reminder of the SN model features**
  - Quick intro to the The et al. model essentials
  - Results of rate sensitivity study
- ▶ **Reactions of interest *unique* to  $^{44}\text{Ti}$  issue**
  - $^{44}\text{Ti}(\alpha, \text{p})^{47}\text{V}$
  - $^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$
  - $^{45}\text{V}(\text{p}, \gamma)^{46}\text{Cr}$
  - $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$

# SN Model Essentials

[L. S. The et al., ApJ 504 (1998)]

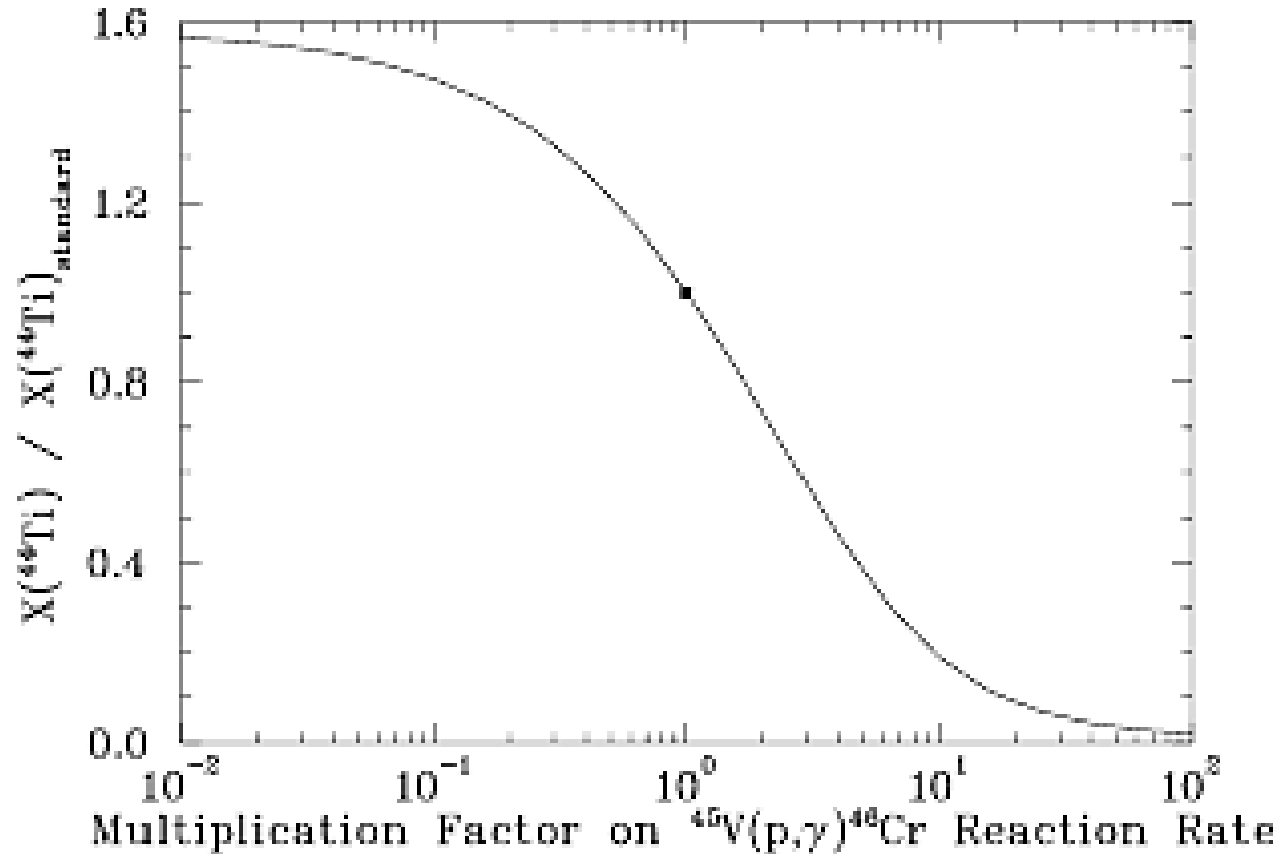
## ► Search for rate sensitivities

- Variation of rates:  $\alpha, \gamma$ ;  $\alpha, p$ ;  $\alpha, n$ ;  $p, \gamma$ ;  $p, n$ ;  $n, \gamma$
- Rates in SMOKER library varied 100-fold up & down
- Done for isotopes of carbon up to bromine ( $Z=6,35$ )
- Rerun  $\alpha$ -rich freeze-out to see  $^{44}\text{Ti}$  change



# SN Model Essentials

[L. S. The et al., ApJ 504 (1998)]



# $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ : Experiment

## ▶ $^{44}\text{Ti}$ RIB: ~133 MeV

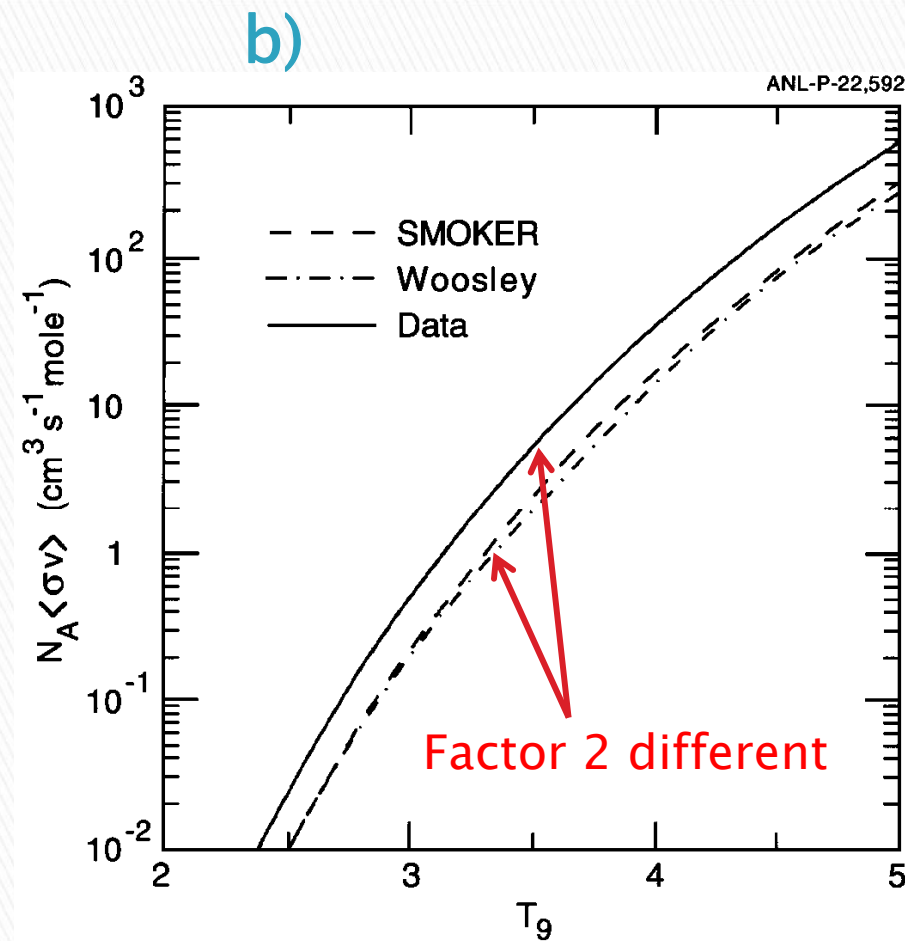
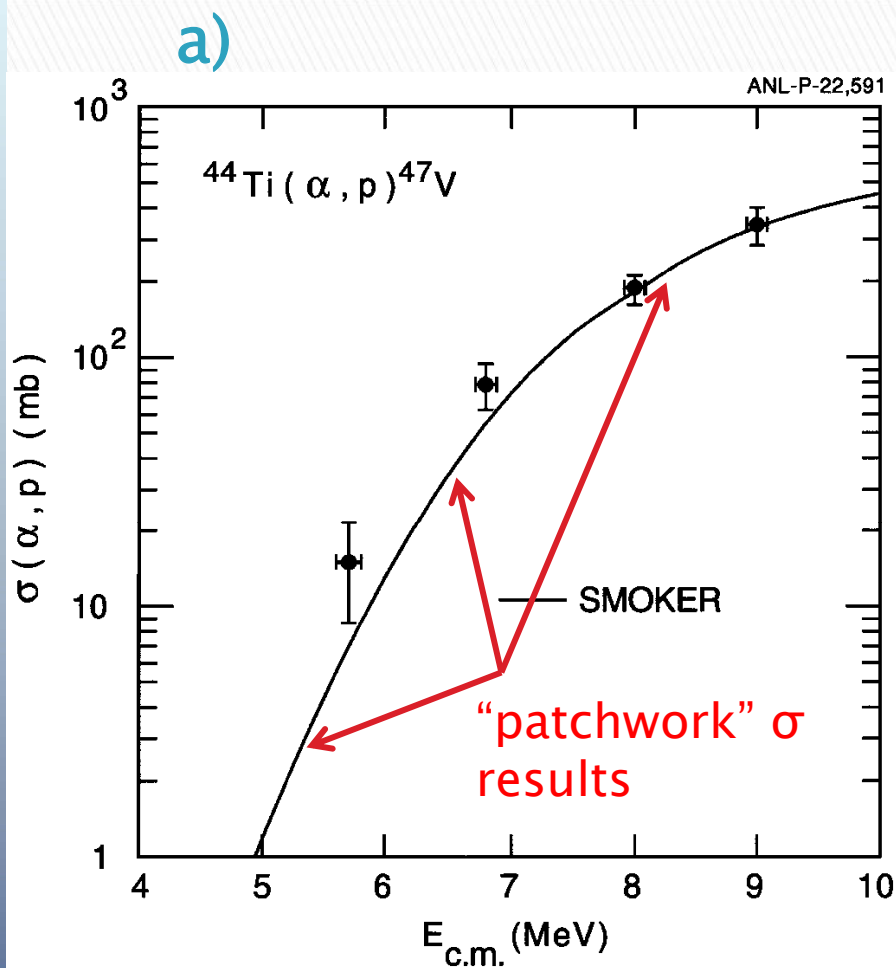
- Production:  $\text{Sc}(p, X)$  at 50 MeV proton energy
  - Chemical extraction of  $^{44}\text{Ti}$
  - Beam of  $\sim 5 \times 10^5$   $^{44}\text{Ti}$  on  $^4\text{He}$  gas target cell
- Inverse kinematics

## ▶ $^{47}\text{V}$ Detection

- Unreacted  $^{44}\text{Ti}$  beam and  $^{47}\text{V}$  recoils mass separated
- Particle ID
  - TOF + Si-detector energy measurement

## ▶ Cross section

- recoil counts and elastic beam normalization

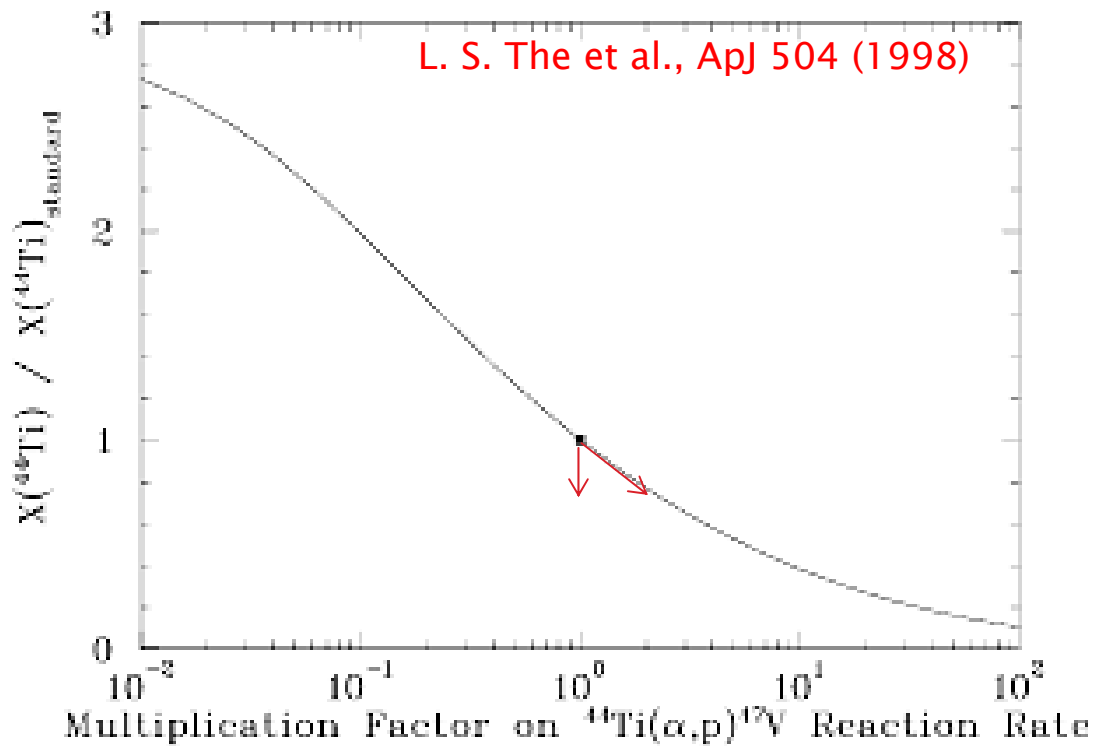


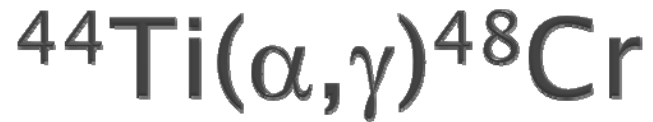
## $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ Experimental Results

- a) Measured  $\sigma(E)$  and theory
- b) Measured rate compared to theory

# $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ : Upshot

- ▶ New rate increases by factor  $\sim 2$ 
  - Result is that  $^{44}\text{Ti}$  yield decreases by 25%





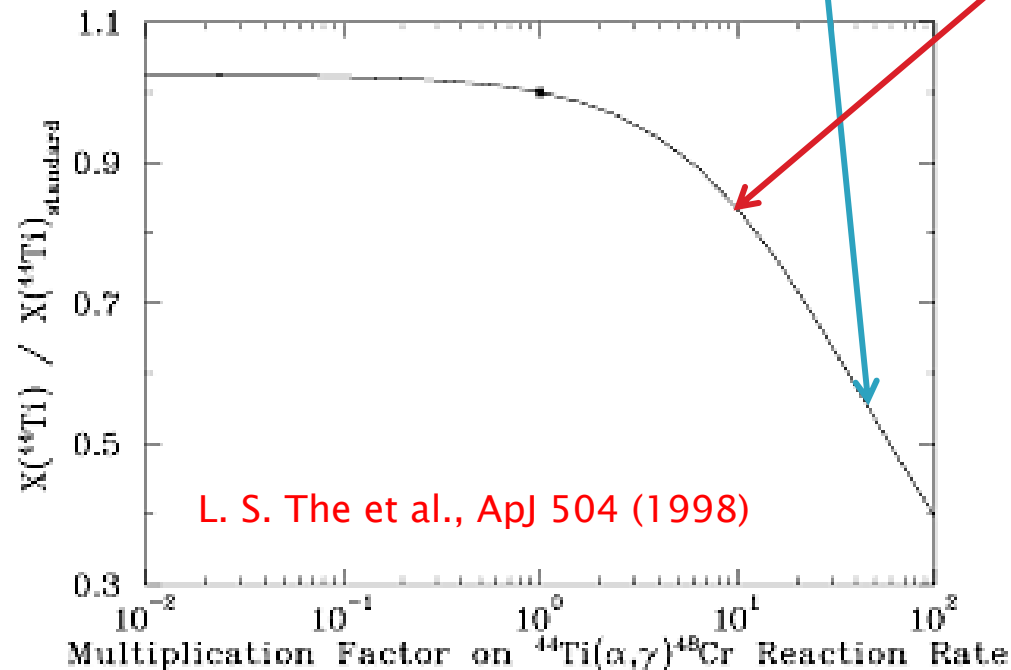
- ▶ No rate measurements exist
- ▶ Purely Hauser–Feschbach treatment in SN models
- ▶ Several HF reaction libraries exist
  - Hoffman, Woosley et al. looked at comparisons of SN model output with chosen library [R. D. Hoffman et al., ApJ 521 (1999)]
  - Uncertainties in this rate could be between 10 and 50
    - This is a big problem

# $^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$

R. D. Hoffman et al., ApJ 521 (1999)

COMPARISON OF STELLAR  $(\alpha, \gamma)$  REACTION RATES ON SELF-CONJUGATE NUCLEI DERIVED FROM THE CRSEC, SMOKER, AND NON-SMOKER STATISTICAL MODEL CODES

Reaction	$T_9$	CRSEC ( $\text{cm}^3 \text{s}^{-1} \text{mole}^{-1}$ )	SMOKER ( $\text{cm}^3 \text{s}^{-1} \text{mole}^{-1}$ )	SM/CR	NONSMOKER ( $\text{cm}^3 \text{s}^{-1} \text{mole}^{-1}$ )
$^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$ .....	2.5	1.1(1)	3.7(1)	3.36	2.8(0)
$^{28}\text{Si}(\alpha, \gamma)^{32}\text{S}$ .....	2.5	3.8(-1)	4.5(0)	11.71	4.6(-1)
$^{32}\text{S}(\alpha, \gamma)^{36}\text{Ar}$ .....	2.5	2.3(-1)	8.9(-1)	3.87	9.4(-2)
$^{36}\text{Ar}(\alpha, \gamma)^{40}\text{Ca}$ .....	2.5	3.4(-3)	2.4(-2)	7.06	1.6(-3)
$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$ .....	2.5	1.5(-2)	7.8(-2)	5.70	3.3(-3)
$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$ .....	2.5	3.3(-6)	1.6(-4)	48.48	1.8(-5)



# $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$

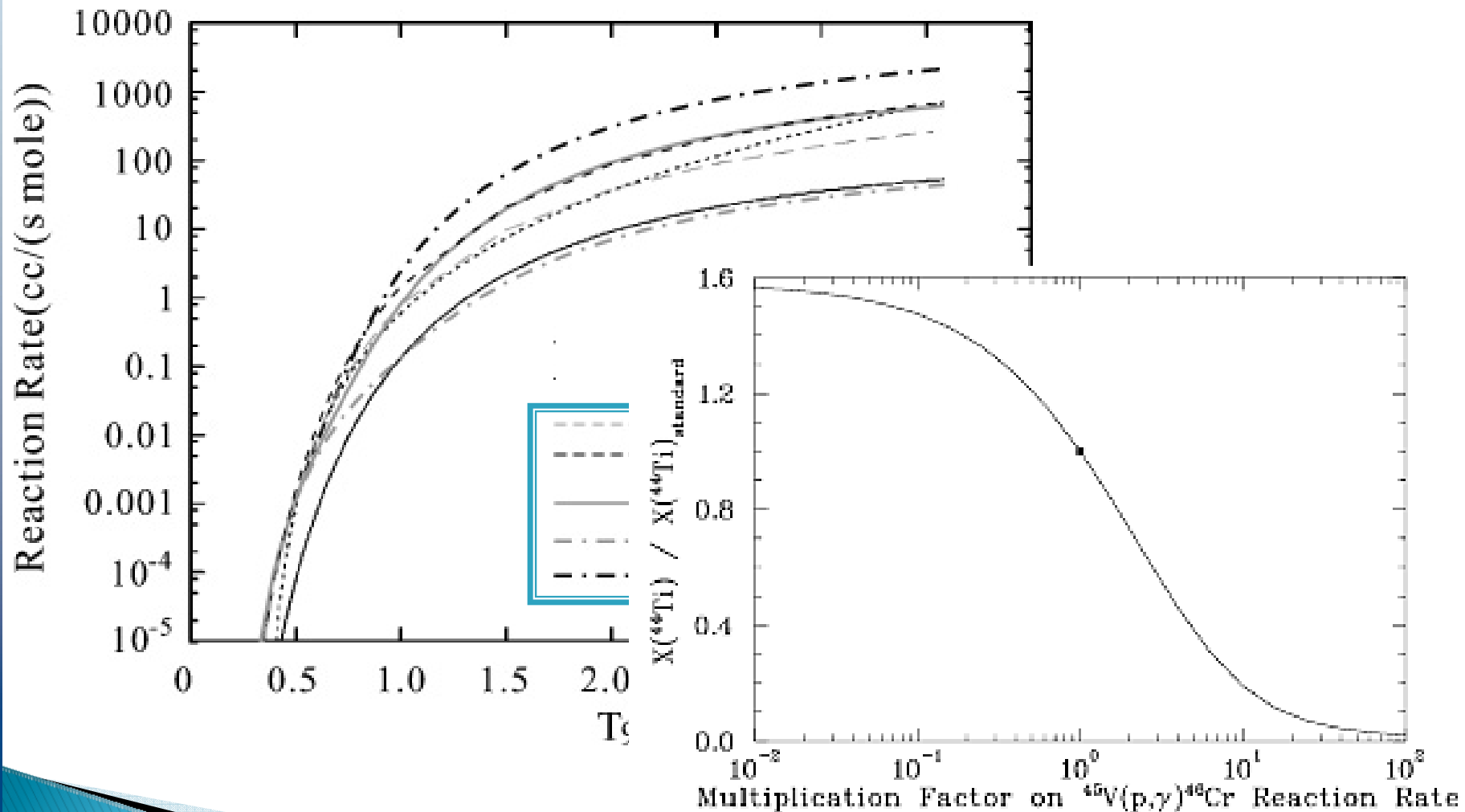
## ▶ Mirror nucleus $^{46}\text{Ti}$ well studied

- Thomas–Ehrman level displacement + mirror symmetry = resonance energies in  $^{46}\text{Cr}$
- Single particle model to calculate  $\Gamma_p$
- Simple Weisskopf estimates to estimate  $\Gamma_\gamma$  for ( $E1$ ,  $E2$ ) capture
- Recent calculation of this has been done [J. J. He et al., PRC 75 (2007)]

## ▶ Recent experimental info on low level scheme

- $^{12}\text{C}(^{36}\text{Ar},2n)^{46}\text{Cr}$  with Gammasphere [P. Garret et al, PRC (2007)]
- Above proton threshold (4.88 MeV), 4 states seen

# $^{45}\text{V}(p,\gamma)^{46}\text{Cr}$ : Upshot



# Summary

## ▶ There is work to be done

- Remeasure  $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ : confirm shape of x-section and get more data points
- $^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$
- Elucidate more states in  $^{46}\text{Cr}$  for  $^{45}\text{V}(p, \gamma)^{46}\text{Cr}$ ; only 4 states known above threshold

## ▶ Work now being done....

- $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$

TABLE 7

ORDER OF IMPORTANCE OF REACTIONS PRODUCING  $^{44}\text{Ti}$  AT  $\eta = 0.002$ 

REACTION RATE MULTIPLIED BY 1/100			REACTION RATE MULTIPLIED BY 100	
RANK	Reaction	$^{44}\text{Ti}$ Change (percent)	Reaction	$^{44}\text{Ti}$ Change (percent)
1	$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$	+208	$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$	-93
2	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	-72	$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$	-66
3	$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$	-66	$^{27}\text{Al}(\alpha, n)^{30}\text{P}$	-60
4	$^{20}\text{Ne}(\alpha, \gamma)^{24}\text{Mg}$	-16	$^{30}\text{Si}(\alpha, n)^{33}\text{S}$	-33
5	$^{30}\text{Si}(p, \gamma)^{31}\text{P}$	-9.2	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	+18
6	$^{36}\text{Ar}(\alpha, p)^{39}\text{K}$	-7.9	$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$	+15
7	$^{59}\text{Ni}(p, n)^{59}\text{Cu}$	-4.7	$^{23}\text{Na}(\alpha, p)^{26}\text{Mg}$	-4.7
8	$^{59}\text{Ni}(p, \gamma)^{60}\text{Cu}$	-4.7	$^{39}\text{K}(\alpha, p)^{42}\text{Ca}$	+4.7
9	$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$	+2.8	$^{27}\text{Al}(p, \gamma)^{28}\text{Si}$	+4.3
10	$^{27}\text{Al}(\alpha, n)^{30}\text{P}$	+2.7	$^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$	+4.2

TABLE 8

ORDER OF IMPORTANCE OF REACTIONS PRODUCING  $^{44}\text{Ti}$  AT  $\eta = 0.006$ 

REACTION RATE MULTIPLIED BY 1/100			REACTION RATE MULTIPLIED BY 100	
RANK	Reaction	$^{44}\text{Ti}$ Change (percent)	Reaction	$^{44}\text{Ti}$ Change (percent)
1	$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$	+211	$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$	-93
2	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	-79	$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$	-65
3	$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$	-65	$^{27}\text{Al}(\alpha, n)^{30}\text{P}$	-56
4	$^{20}\text{Ne}(\alpha, \gamma)^{24}\text{Mg}$	-11	$^{30}\text{Si}(\alpha, n)^{33}\text{S}$	-39
5	$^{30}\text{Si}(p, \gamma)^{31}\text{P}$	-9.6	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$	+19
6	$^{36}\text{Ar}(\alpha, p)^{39}\text{K}$	-7.5	$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$	+15
7	$^{27}\text{Al}(\alpha, p)^{30}\text{Si}$	-4.0	$^{58}\text{Ni}(\alpha, \gamma)^{62}\text{Zn}$	-8.7
8	$^{33}\text{S}(p, \gamma)^{34}\text{Cl}$	+3.8	$^{27}\text{Al}(p, \gamma)^{28}\text{Si}$	+6.0
9	$^{16}\text{O}(\alpha, \gamma)^{20}\text{Ne}$	-3.8	$^{24}\text{Mg}(\alpha, \gamma)^{28}\text{Si}$	+6.0
10	$^{30}\text{Si}(\alpha, n)^{33}\text{S}$	+3.5	$^{39}\text{K}(\alpha, p)^{42}\text{Ca}$	+5.3