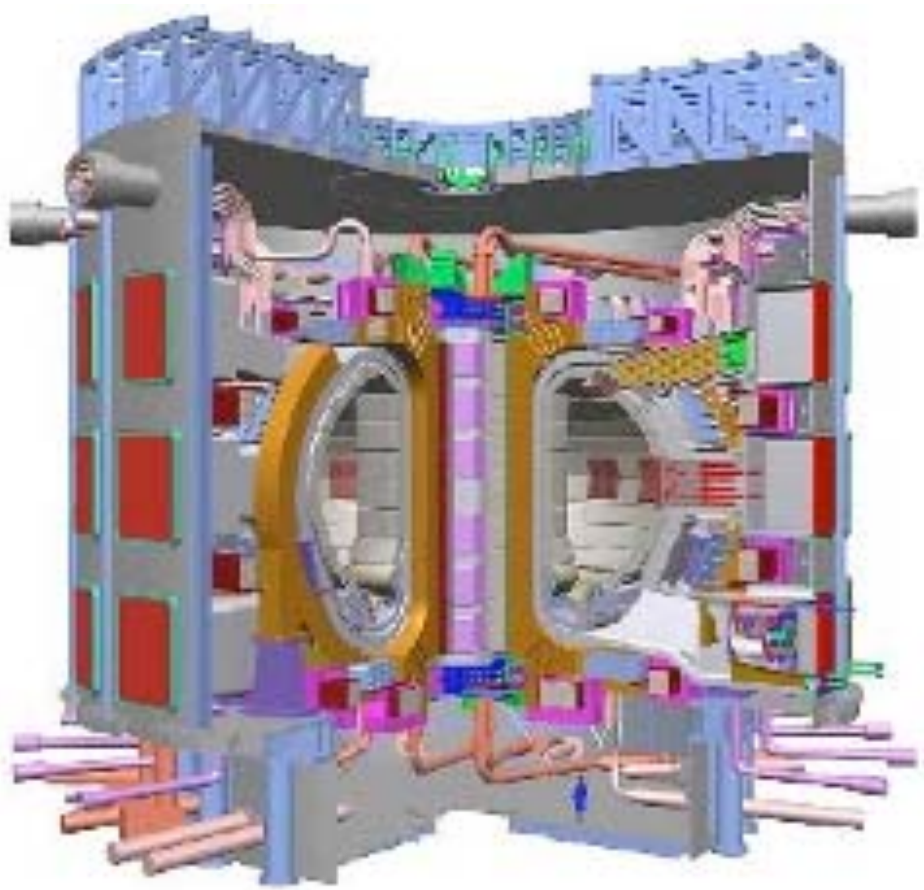
# “Alpha Knock-On Measurements on ITER Using Neutron Activation”



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***General Atomics***

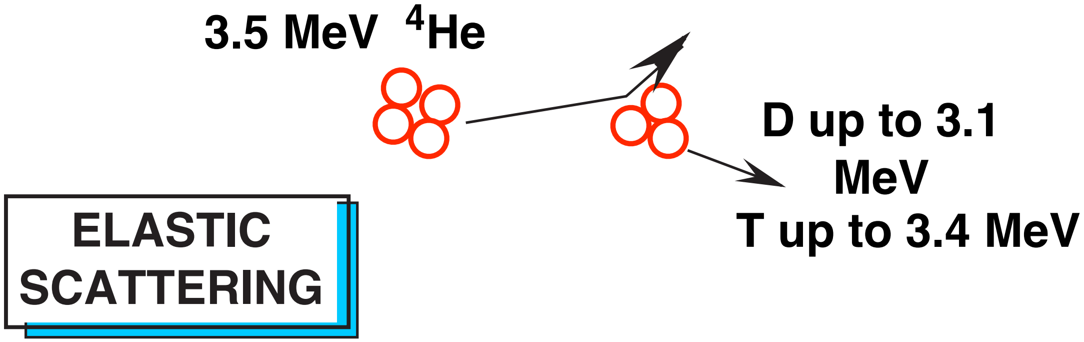
***12th ITPA Topical Group Meeting on Diagnostics***

***March 26 to April 1, 2007***

GENERAL ATOMICS

# Alpha Collisions With Fuel Ions Creates Knock-On Tail

- <u>Presence of alphas creates high energy D, T ion tails</u>



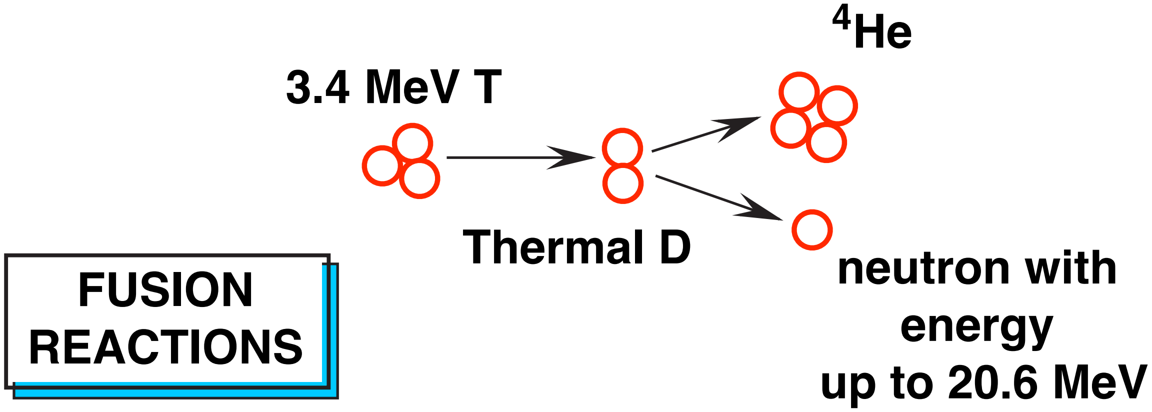
3.5 MeV $^4$He

D up to 3.1 MeV

T up to 3.4 MeV

**ELASTIC SCATTERING**

- <u>Energetic ion tails produce tail on DT neutron distribution</u>



$^4$He

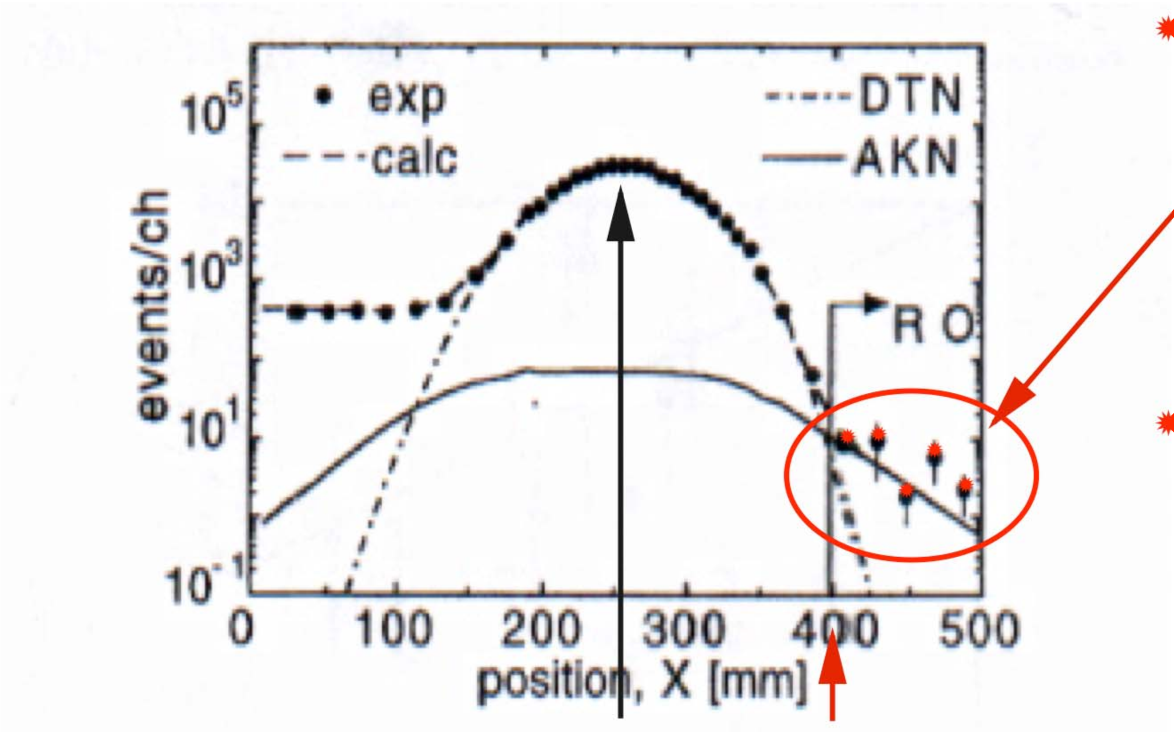
3.4 MeV T

Thermal D

neutron with energy up to 20.6 MeV

**FUSION REACTIONS**

# Knock-On Neutron Tail Has Been Experimentally Observed on JET Using MPR and agrees with predictions



14.2 MeV

15.5 MeV

neutron energy (MeV)

- J. Kallne, et.al., have observed the knock-on neutron tail at En > 15.5 MeV on JET using the Magnetic Proton Recoil Spectrometer (MPR)

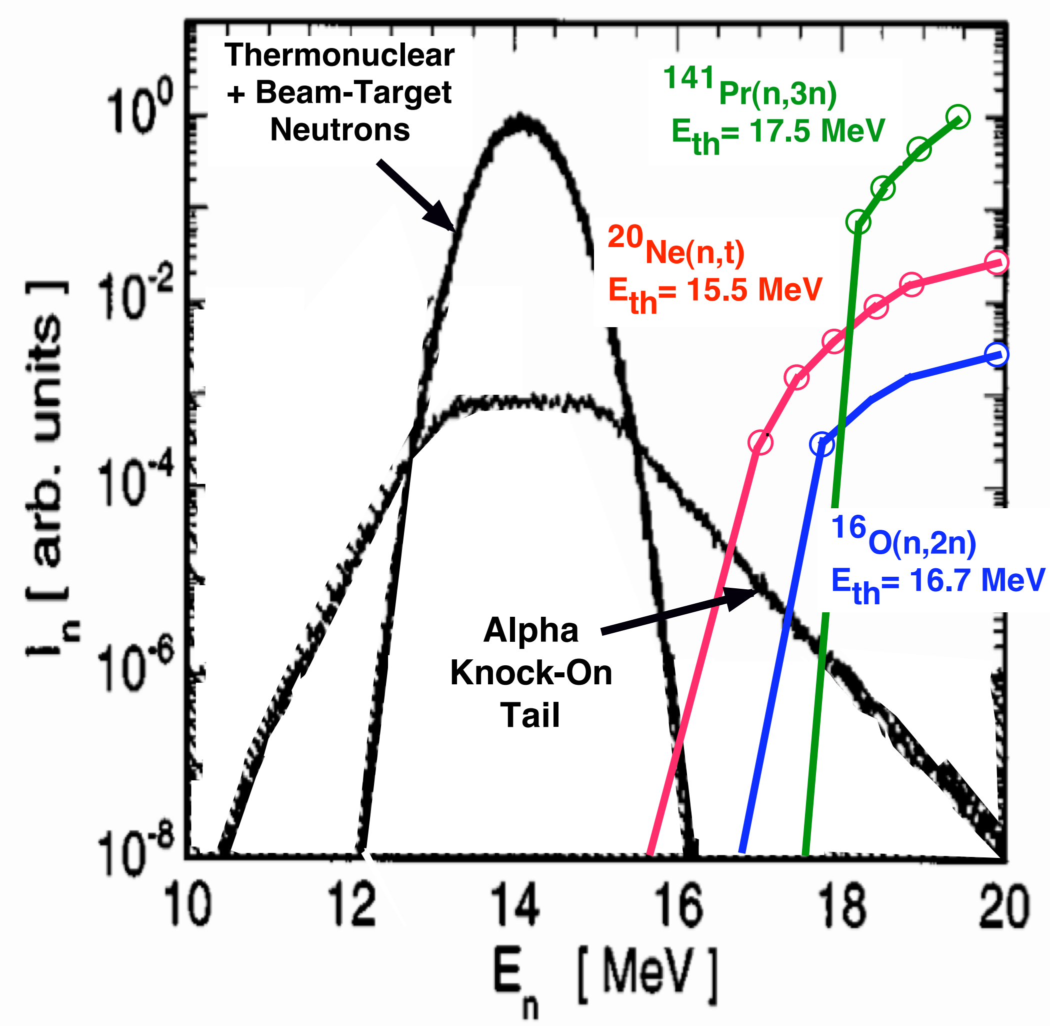
- Knock-on tail was ~ 10-4 of total DT neutrons; consistent with predictions under JET plasma conditions and good alpha confinement

- MPR requires large aperture on ITER for adequate statistics to study alpha particle physics

Fig. 2 from J. Kallne, et.al., Phys. Rev. Lett. 85, 1246 (2000)

# Knock-On Measurements Using Neutron Activation

- Activation targets with different threshold energies between ~15 and 20 MeV would measure the knock-on neutron tail spectrum, and yield information on the energy spectrum of the confined alphas in ITER



- yields information on the confined alphas in the hot plasma core, where most of the neutrons are emitted

- the targets can be exposed to the very high neutron flux ( $>10^{13}$ n/cm$^2$/sec) near the first wall of ITER, allowing signal levels large enough to allow alpha particle physics studies

# Neutron Activation vs. Bubble Detectors, Proton Tracks

*Why am I now advocating neutron activation rather than earlier suggestions of bubble neutron detectors and proton tracks in nuclear emulsions?*

- ***neutron activation looks far more straightforward** than the other two approaches*

  *- bubble neutron detectors require temperature control to ~ 0.1 deg C; for single gas detectors, need ~ 5 detectors at 5 different temperatures*

  *- avoids need to measure the lengths of thousands of recoil proton tracks in emulsion approach*

- *our initial early tests on TFTR were unsuccessful, and problem of background decays due to even parts per billion of impurities in activation target appeared insurmountable; but now realize that*

  *- careful selection of activation targets and the use of radiochemistry techniques to reduce the background decays should allow knock-on measurements using neutron activation*

# Advantages and Limitations of Activation Approach

## Pros

- *Large signal levels* - The targets can be exposed to the very high neutron flux ( $>10^{13}$n/cm$^2$/sec) near the first wall of ITER, allowing signal levels large enough to allow alpha particle physics studies

- *Relatively easy to implement on ITER and hardware is robust*

- for solid targets, use a pneumatic target transfer system similar to that used on TFTR and JET

- for gas and liquid targets, can use a valve and pumping system, all moving parts would be outside biological shield

## Cons

- *Limited time resolution* –Results are integrated over target exposure times (~ seconds), although any knock-on approach is inherently limited to time scale for fast ion slowing-down (~ few seconds in ITER)

- *Delayed results* - long half-lives of some of the activation products will delay availability of data

- *Background reactions* between the much larger flux of DT neutrons below the desired energy threshold and other isotopes or with impurities in the activation target will require careful selection and handling of the target

# Finding Suitable Threshold Activation Targets Is Difficult

- *"Background" reactions between the much larger flux of DT neutrons below the desired energy threshold and all of the isotopes and any impurities present in the activation target will require careful selection and handling of the targets*

  *- there are a large number of possible neutron reactions, including (n,2n) (n,3n) (n,p) (n,d) (n,t) (n,He$^3$) (n,$\alpha$) (n,n') (n,n+p) (n,n+d) (n,n+t) (n,n+$\alpha$) reactions, that can create "background" decay products that will prevent observation of the knock-on tail induced "signal" reactions*

  *- impurity concentrations as low as parts per billion can also prevent observation of the knock-on signal*

- *Initial studies of some of the possible targets are presented that illustrate techniques that can be employed to reduce these background decays*

# Activation Targets With Energy Thresholds of 15 - 20 MeV

| Target Reaction | Threshold Energy (MeV) | Decay Half-Life | Decay Modes | Gamma Energies |
|---|---|---|---|---|
| $Au^{197}$ (n, 3n) $Au^{195m}$ | 14.79 | 30.6 sec | IT | 0.20, 0.262 MeV |
| $Au^{197}$ (n, 3n) $Au^{195}$ | 14.79 | 183 days | EC | 0.10 MeV |
| $S^{32}$ (n, 2n) $S^{31}$ | 15.52 | 2.6 sec | $\beta^+$ | 0.511 MeV |
| $Ne^{20}$ (n, t) $F^{18}$ | 15.54 | 110 min | $\beta^+$, EC | 0.511, 1.04 MeV |
| $Ca^{40}$ (n, 2n) $Ca^{39}$ | 16.0 | 0.86 sec | $\beta^+$ | 0.511 MeV |
| $Be^{9}$ (n, d) $Li^{8}$ | 16.31 | .84 sec | $\beta^-$ | ~13 MeV $\beta^-$ directly |
| $O^{16}$ (n, 2n) $O^{15}$ | 16.65 | 2 min | $\beta^+$ | 0.511 MeV |
| $La^{138}$ (n, 3n) $La^{136}$ | 16.75 | 9.5 min | EC, $\beta^+$ | 0.511, 0.83, 1.32, 2.13 MeV |

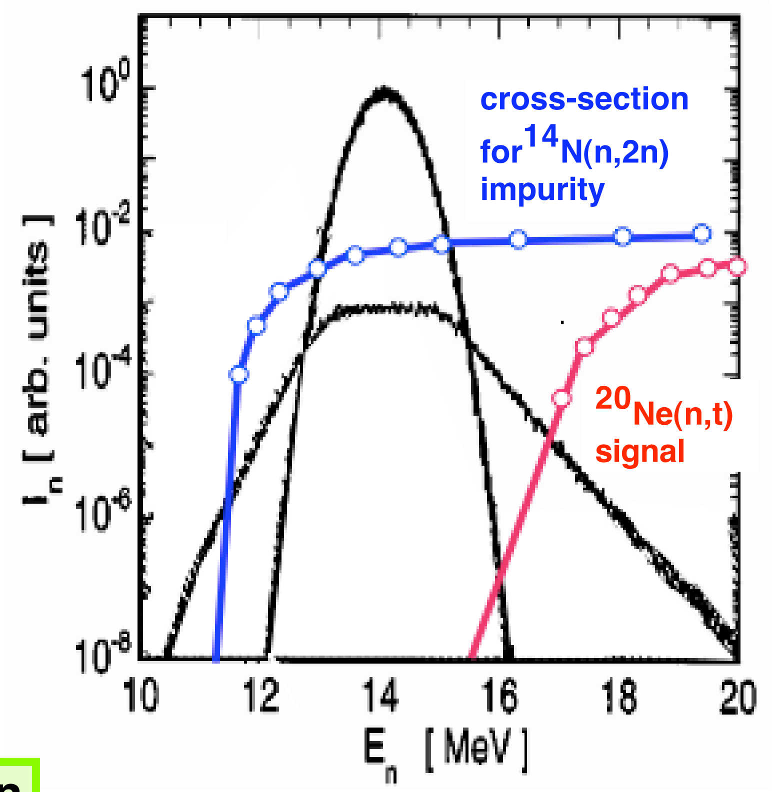
| | | | | |
|---|---|---|---|---|
| **$Mg^{24}$ (n, 2n) $Mg^{23}$** | **17.2** | **11.3 sec** | **$\beta^+$** | **0.511 MeV** |
| **$Pr^{141}$ (n, 3n) $Pr^{139}$** | **17.46** | **4.5 hrs** | **EC, $\beta^+$** | **1.35, 1.63 MeV** |
| **$Ne^{20}$ (n, 2p) $O^{19}$** | **17.74** | **27 sec** | **$\beta^+$, EC** | **0.2, 1.55, 2.6, 4.2 MeV** |
| **$Si^{28}$ (n, 2n) $Si^{27}$** | **17.8** | **4.1 sec** | **$\beta^+$** | **0.511 MeV** |
| **$C^{12}$ (n, 2n) $C^{11}$** | **20.3** | **20.4 min** | **$\beta^+$, EC** | **0.511 MeV** |

# Background Due To Impurities In Activation Targets

- Impurities in the activation target are a significant concern:

  - the impurity activation cross-sections can be 100 to 1000 times larger since their threshold energies will be well below 14 MeV

  - the neutron flux for impurity activation is $10^3$ to $10^6$ times larger than the small fraction of neutrons above the knock-on signal threshold



- **Impurity concentrations in the activation target at parts per million to even parts per billion can lead to problematic background signals**

Research grade Ne gas has < 1 ppm of $N_2$ and other impurities

# Techniques Available To Overcome Background Reactions

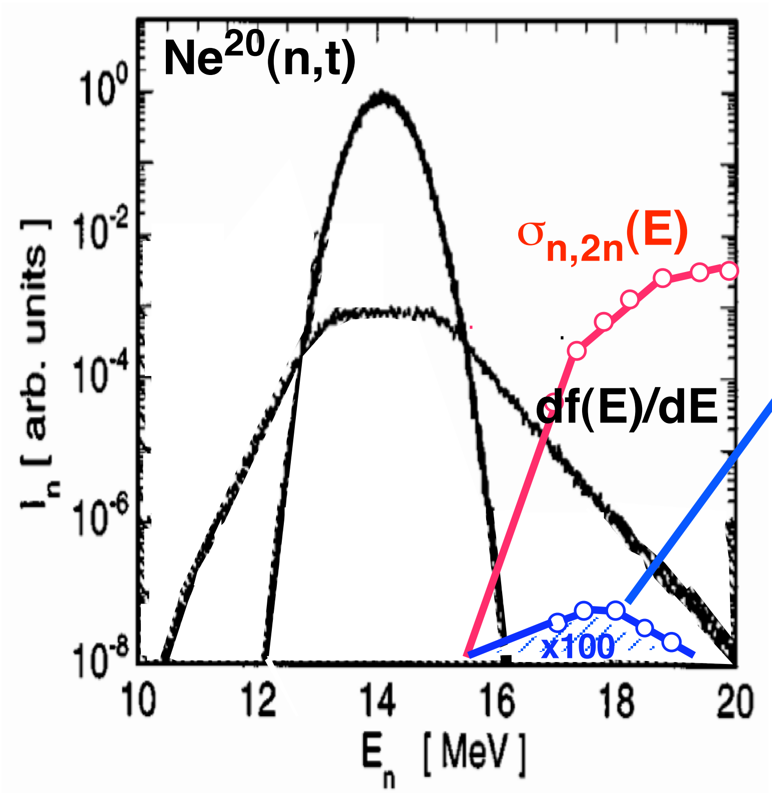
| Method | Examples |
|---|---|
| ● Choose a signal reaction with a long half-life and wait for the shorter lived backgrounds to decay away | 110 min for $Ne^{20}(n,t)F^{18}$<br>4.4 hrs for $Pr^{141}(n,3n)Pr^{139}$ |
| ● Use coincident detection to detect 511 keV annihilation gammas from $\beta+$ decay | $Ne^{20}(n,t)F^{18}$<br>$Pr^{141}(n,3n)Pr^{139}$<br>$La^{138}(n,3n)Pr^{136}$ |
| ● Reduce the low energy gamma backgrounds using thin absorbers | $Pr^{141}(n,3n)Pr^{139}$<br>$La^{138}(n,3n)Pr^{136}$ |
| ● Choose a target with a high energy gamma decay so it can be observed in a much higher flux of lower energy background gammas | 3.51 MeV for $S^{32}(n,2n)S^{31}$ |
| ● Use chemistry after exposure to remove elements causing background, and increase SNR<br>e.g. remove $N^{13}$ from $H_2O$ using ion exchange resin beds | $O^{16}(n,2n)O^{15}$ signal<br>$O^{16}(p,\alpha)N^{13}$ background |

# $Ne^{20}(n,t)\ F^{18}$ Activation on ITER

- Expected decay signal $dN_{decay}/dt$ from an activation target containing $N_a$ atoms of $Ne^{20}$ and exposed to a neutron fluence of $\Phi_n$ is

$$dN_{decay}/dt \;=\; N_a\,\sigma_{eff}\;\Phi_n\;/\;\tau_{decay}$$

where $\sigma_{eff} = \int df(E)/dE\ \sigma(E)\ dE$ ; with $df(E)/dE$ = fraction of DT neutrons in the knock on tail times and $\sigma(E)$ is the activation cross-section



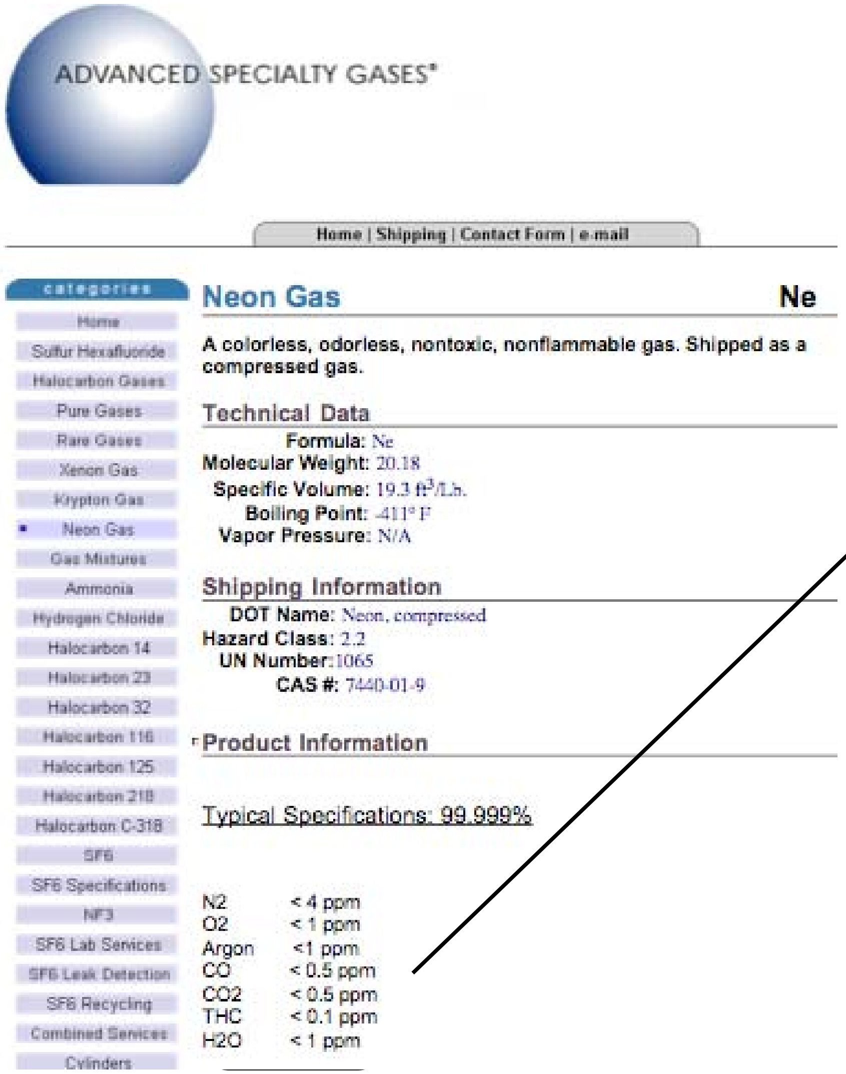
$\Phi_n \sim 2.4 \cdot 10^{13}$ n/cm$^2$-sec at target

for 500MW ITER DT plasma

$\sigma_{eff} \sim 1.2 \cdot 10^{-9}$ barns

- $dN_{decay}/dt \sim 0.1$ decays/sec or ~1,150 total decays due to $Ne^{20}(n,t)$ reactions in a 1 atm. 16 cm$^3$ target exposed for 100 sec to the ITER n-flux; much larger signals possible with high pressure targets

# Sufficiently High Purity Neon Is Commercially Available



**Neon Gas** **Ne**

A colorless, odorless, nontoxic, nonflammable gas. Shipped as a compressed gas.

**Technical Data**

Formula: Ne
Molecular Weight: 20.18
Specific Volume: 19.3 ft³/Lb.
Boiling Point: -411° F
Vapor Pressure: N/A

**Shipping Information**

DOT Name: Neon, compressed
Hazard Class: 2.2
UN Number: 1065
CAS #: 7440-01-9

**Product Information**

Typical Specifications: 99.999%

| | |
|---|---|
| N2 | < 4 ppm |
| O2 | < 1 ppm |
| Argon | <1 ppm |
| CO | < 0.5 ppm |
| CO2 | < 0.5 ppm |
| THC | < 0.1 ppm |
| H2O | < 1 ppm |

| | |
|---|---|
| **N2** | **< 4 ppm** |
| **O2** | **< 1 ppm** |
| **Argon** | **< 1 ppm** |
| **CO** | **< 0.5 ppm** |
| **CO2** | **< 0.5 ppm** |
| **THC** | **< 0.1 ppm** |
| **H2O** | **< 1 ppm** |

***Largest source of background is $N^{14}(n,2n)N^{13}$ which is negligible ~ 70 minutes after exposure due to much longer half-life of $Ne^{20}(n,t)F^{18}$ signal***

# Overcoming Background Reactions in $Ne^{20}$(n,t) Targets

| Reaction | Neutron Threshold | Half-Life Decay | Decay Gamma Energies | Initial Decay Rate from 16cm$^3$ target at 1 atm. exposed for 100 sec on ITER |
|---|---|---|---|---|
| $Ne^{20}(n,t)F^{18}$<br>Signal | 15.54 MeV | 110 min<br>$\beta$+, EC | 0.511 MeV (100%) | 0.12/sec<br>signal can be increased by using larger high-pressure target |
| $Ne^{20}(n,p)F^{20}$<br>Background | 6.55 MeV | 11 sec<br>$\beta$- | 1.63 MeV (100%) | $3.4 \cdot 10^{11}$/sec<br>but negligible after 7min |
| $N^{14}(n,2n)N^{13}$<br>Impurity | 11.31 MeV | 9.5 min<br>$\beta$+ | 0.511 MeV (100%) | 9 /sec at 1 ppm $N_2$<br>but negligible after 1 hr |

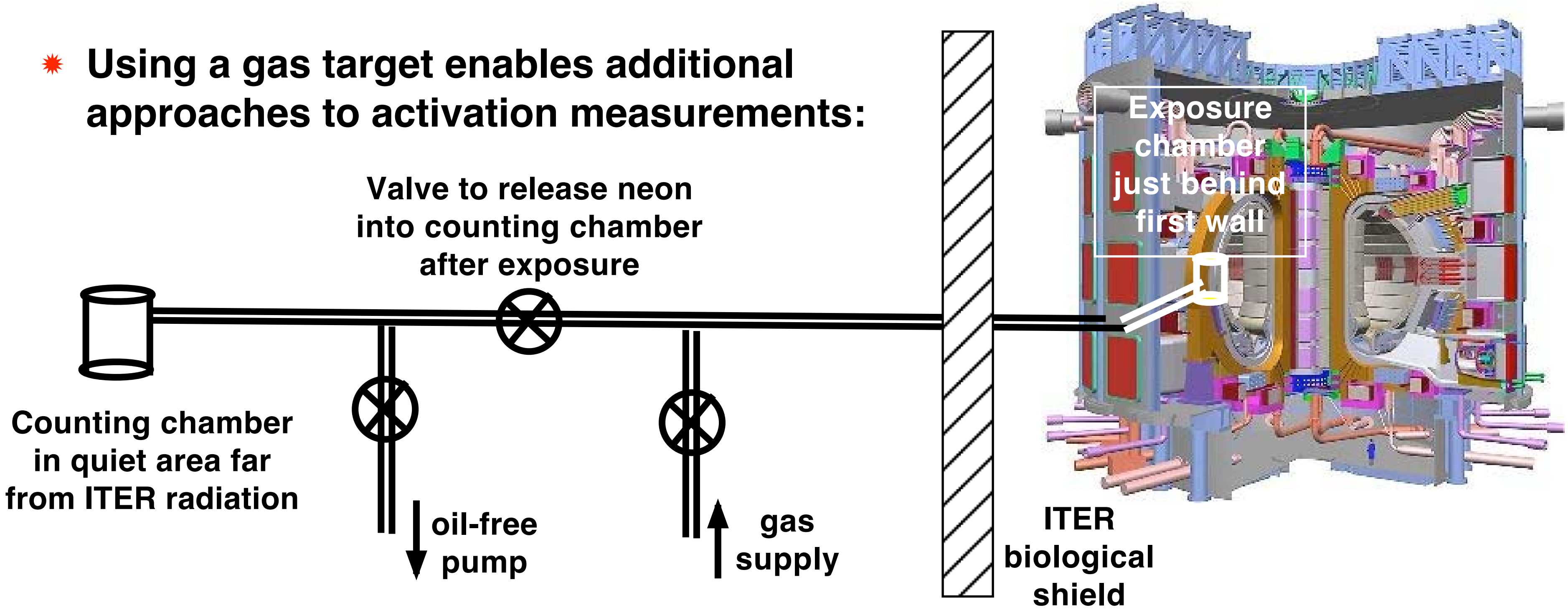
- ***The 0.511 MeV gamma rays should be observable based on the longer lifetime of the signal decay compared to any of the expected background decays***

  ***- the 110 min half-life will require several hours to analyze the data, delaying availability of the results***

# Possible Approaches to $Ne^{20}$(n,t) Activation on ITER

- Can use gas-filled capsule "rabbit" in a pneumatic transport system similar to that used on JET and TFTR

- Using a gas target enables additional approaches to activation measurements:



Valve to release neon
into counting chamber
after exposure

Exposure
chamber
just behind
first wall

Counting chamber
in quiet area far
from ITER radiation

oil-free
pump

gas
supply

ITER
biological
shield

- allows larger exposure chamber and hence larger signals
- avoids background gammas from activation of transport capsule
- no moving parts inside ITER; no "jammed" transport capsules

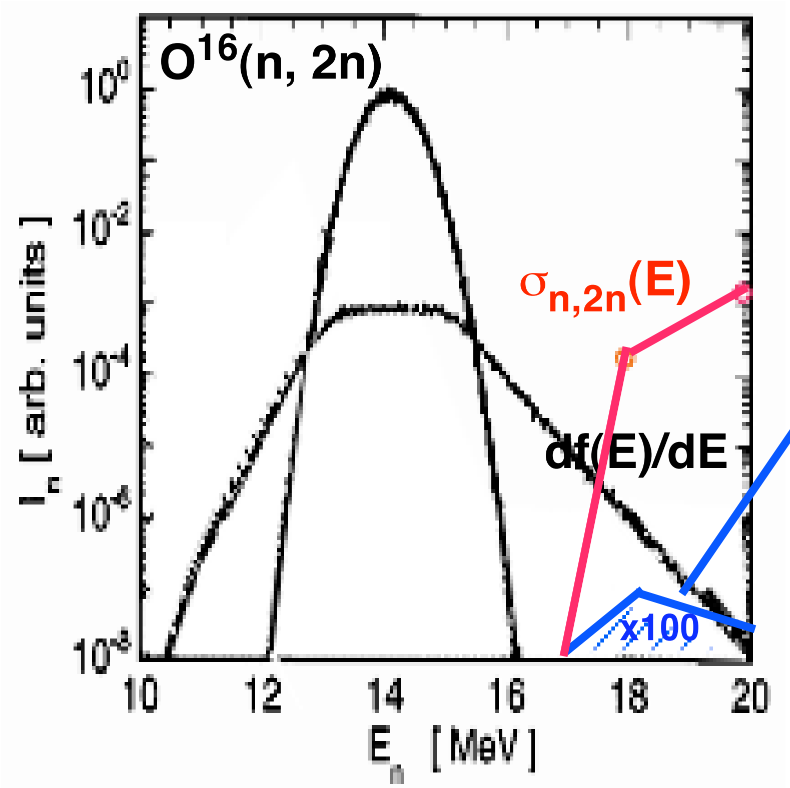
- Can measure ratio of $Ne^{20}$(n,t) to $Ne^{20}$(n,p) activation to determine fraction of neutrons in alpha knock-on tail

# $O^{16}(n, 2n)\ O^{15}$ Activation on ITER

- Expected decay signal $dN_{decay}/dt$ from an activation target containing $N_a$ atoms of $O^{16}$ and exposed to a neutron fluence of $\Phi_n$ is

$$dN_{decay}/dt \;=\; N_a\, \sigma_{eff}\, \Phi_n \,/\, \tau_{decay}$$

where $\sigma_{eff} = \int df(E)/dE\ \sigma(E)\ dE$ ; with $df(E)/dE$ = fraction of DT neutrons in the knock on tail times and $\sigma(E)$ is the activation cross-section



$\Phi_n \sim 2.4 \cdot 10^{13}$ n/cm$^2$-sec at target

for 500MW ITER DT plasma

$\sigma_{eff} \sim 1.3 \cdot 10^{-9}$ barns

- $dN_{decay}/dt \sim 7 \cdot 10^{3}$ decays/sec due to $O^{16}(n,2n)$ reactions in a 15 gm target exposed for 10 sec to the ITER neutron flux

# Overcoming Background Reactions in $O^{16}$(n,2n) Targets

| Reaction | Neutron Threshold | Half-Life Decay | Decay Gamma Energies | Initial Decay Rate from 100 gm target exposed for 10 sec on ITER |
|---|---|---|---|---|
| $O^{16}(n,2n)O^{15}$<br>Signal | 16.7 MeV | 2 min<br>$\beta+$ | 0.511 MeV (100%) | $7 \cdot 10^3$ /sec |
| $O^{16}(n,p)N^{16}$<br>Background | 11 MeV | 7 sec<br>$\beta-$ | 6.13 MeV (68%) | ~$10^{13}$ /sec<br>but negligible after 3 min |
| $O^{16}(p,\alpha)N^{13}$<br>Background<br>(water target) | 5.6 MeV | 10 min<br>$\beta+$ | 0.511 MeV (100%) | $10^7$ /sec<br>must reduce using chemistry |

- ***The 0.511 MeV gamma rays should be observable based on the longer lifetime of the signal decay compared to the $O^{16}(n,p)N^{16}$ background***
- ***Ultrapure water (semiconductor industry) avoids impurity backgrounds***

  ***- but n-p scattering in $H_2O$ target creates proton-induced background which requires removal of $N^{13}$ using ion exchange resin beds after n-exposure***

# Summary and Conclusions

- Knock-on measurements can provide important information on the confinement and slowing-down of energetic confined alphas in ITER

- Measurement of the energetic neutron tail will yield information on the alpha physics in the hot plasma core where the neutron emission is largest

- Neutron activation measurements with energy thresholds between 15.5 and 20 MeV look attractive for measuring the size and shape of the alpha knock-on tail

  - targets exposed to the high neutron flux ( >$10^{13}$n/cm$^2$/sec) near the first wall of ITER should provide signal levels large enough to allow alpha particle physics studies

  - background reactions between the much larger flux of neutrons below the desired energy threshold and the isotopes and any impurities in the activation target will require careful selection and handling of the targets

  - initial studies of some candidate targets are presented that illustrate techniques that can be employed to reduce these background decays

# Possible Approaches to ITER Knock-On Diagnostics

| ***Approach*** | ***Advantages*** | ***Disadvantages*** |
|---|---|---|
| **Magnetic Proton Recoil Spectrometer** | **DT n-tail observed on JET; proven technique** | **small signals in ITER unless allowed large aperture** |
| ***Neutron Threshold Activation*** | ***larger signals; no below threshold response*** | ***lack of time resolution; need high purity targets*** |
| **Bubble Neutron Detectors** | **larger signals using new high efficiency detectors** | **need for accurate temperature control** |
| **Proton Tracks in Emulsions** | **larger signals; no below threshold response** | **lack of time resolution; many tracks to analyze** |
| **Passive CX Neutral Spectroscopy** | **K-O deuterium ion tail observed on JET** | **line integral measurement; don't know source profile** |
| **CX Neutrals Using 1 MeV Beams** | **spatial profile possible?** | **need small observation angle w.r.t. beam?** |