MSFC-048

Nuclear Fragmentation Processes Relevant for Human Space Radiation Protection

ZI-WEI LIN

Space radiation from cosmic ray particles is one of the main challenges for human space explorations such as a moon base or a trip to Mars. Models have been developed in order to predict the radiation exposure to astronauts and to evaluate the effectiveness of different shielding materials, and a key ingredient in these models is the physics of nuclear fragmentations. We have developed a semi-analytical method to determine which partial cross sections of nuclear fragmentations most affect the radiation dose behind shielding materials due to exposure to galactic cosmic rays. The cross sections thus determined will require more theoretical and/or experimental studies in order for us to better predict, reduce and mitigate the radiation exposure in human space explorations.

MSFC-032

Nuclear Fragmentation Processes Relevant for Human Space Radiation Protection

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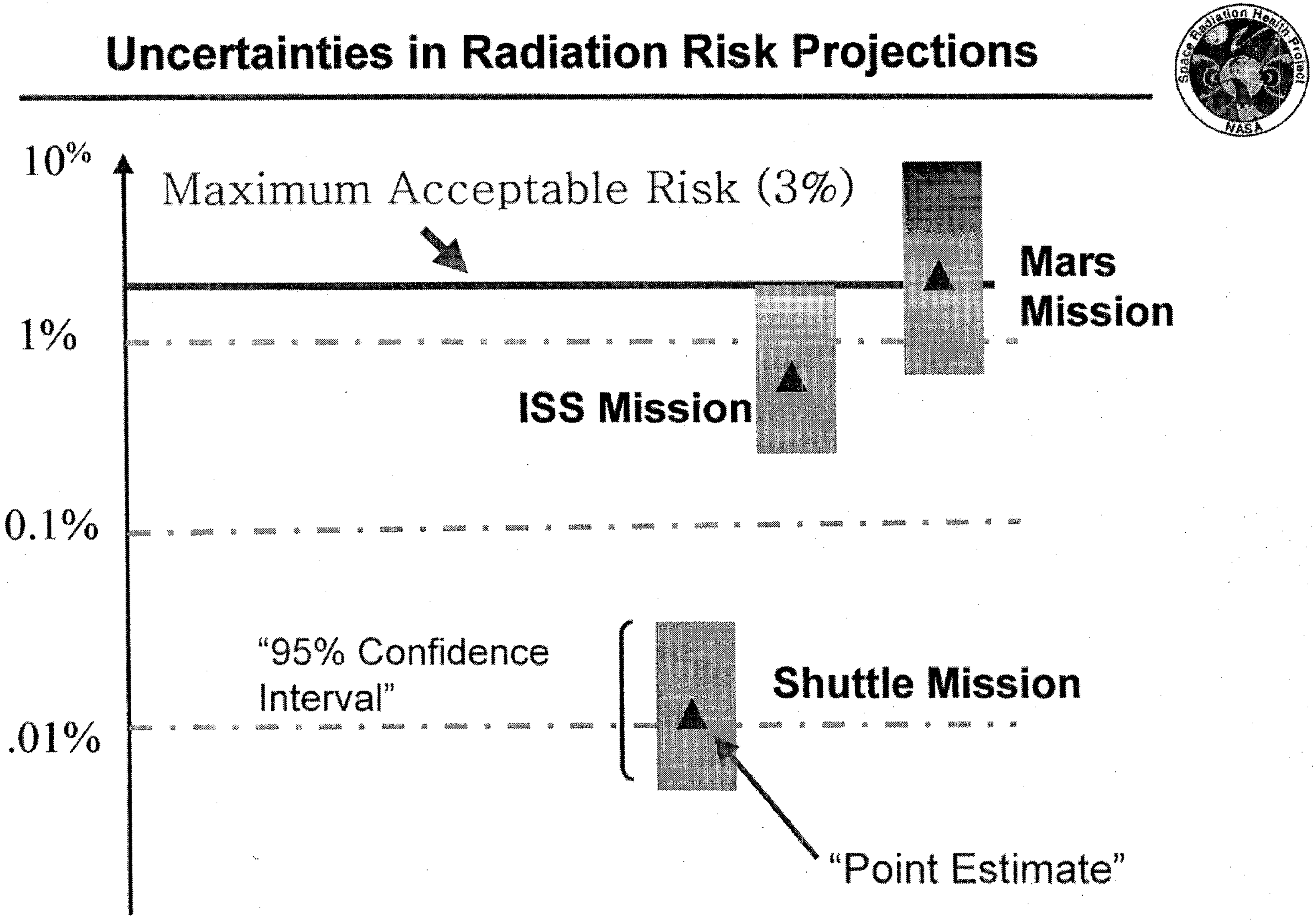
Outline

- Why do we need to address this problem?
- Semi-analytical results
- Constraint from baryon number conservation
- Conclusions

For details, see ZWL, PRC75, 034609 (2007)

Space Radiation Risks in Human Space Explorations

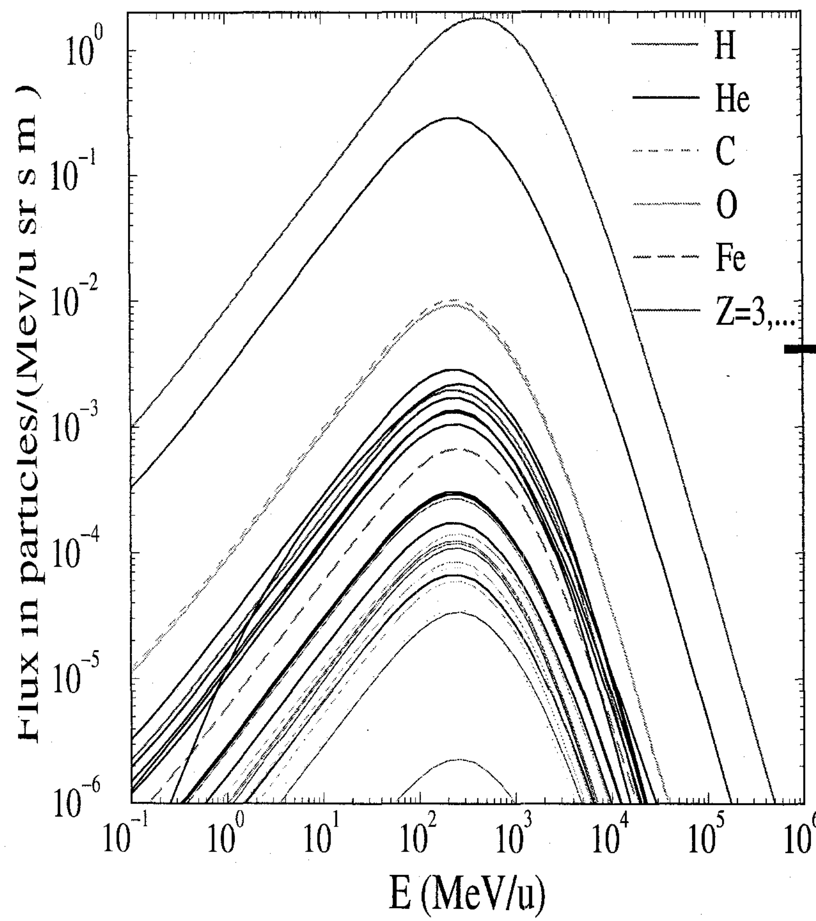


Individual's Excess Fatality Risk

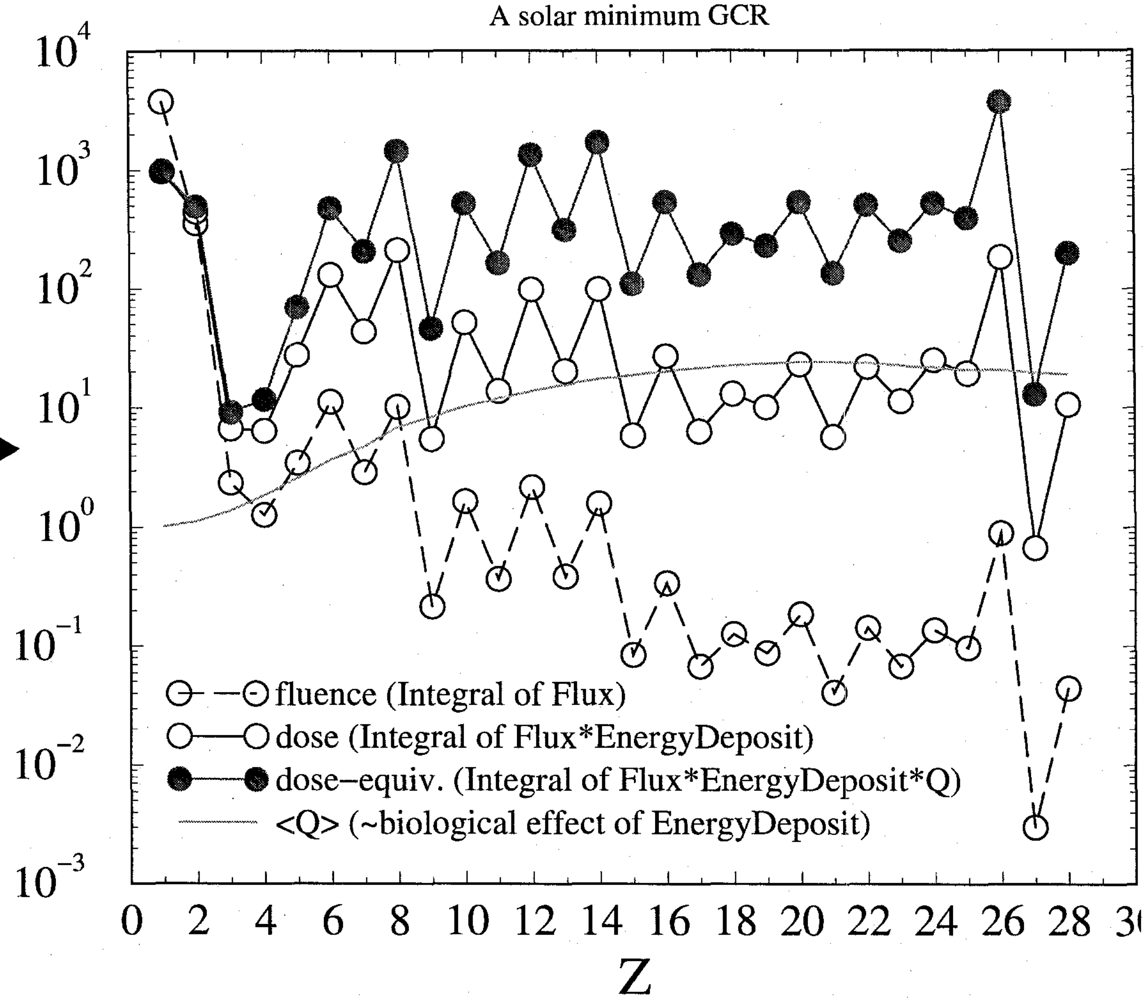
from Cucinotta/JSC

Heavy Ions:
small in abundance, but important for radiation effects

Galactic Cosmic Rays
(at a solar minimum)



Fluence, dose, dose–equivalent of different elements



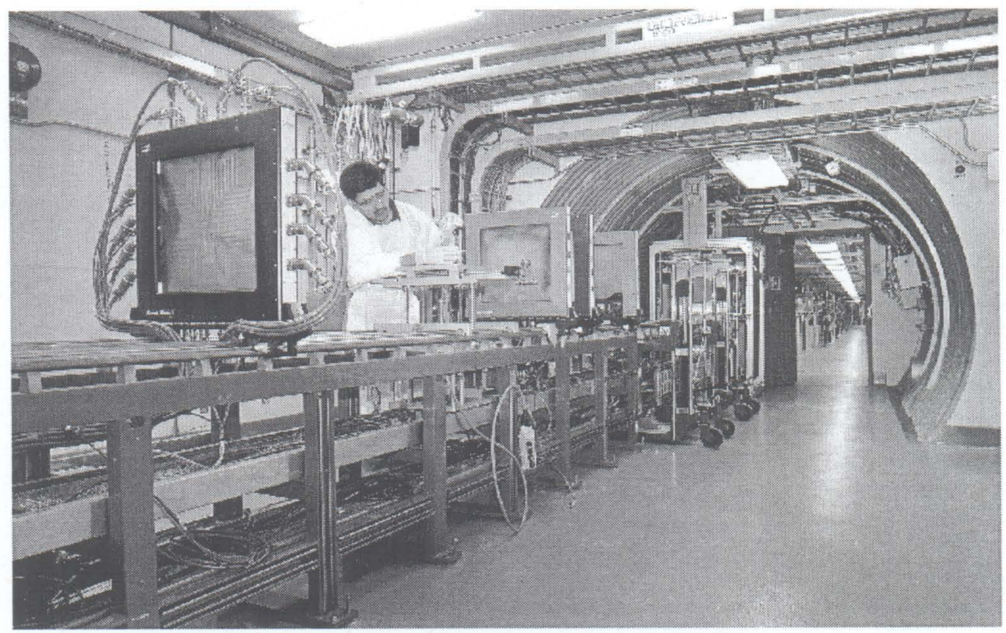
Questions to answer

Which fragmentation processes are more important?
projectile(beam), fragment, energy, target, ...

Townsend et al., NASA-TM 4386 (1992)
Heinbockel et al., Rad. Meas. 41 (2006)
ZWL, Radiat. Res. 167 (2007)

How to best use NSRL to study space radiation physics?

NASA Space Radiation Laboratory (NSRL) at BNL



Radiation transport in one dimension

Under the straight-ahead approximation:

$$\frac{\partial J_k(E,x)}{\partial x} = -\frac{\partial J_k(E,x)}{\Lambda_k(E)} + \sum_j \frac{\partial J_j(E,x)}{\Lambda_{kj}(E)} + \frac{\partial[w_k(E)J_k(E,x)]}{\partial E}$$

Flux of particle species k

ionization energy loss

m.f.p. $\Lambda_k = 1/(n^*\sigma_k)$
total inelastic Xsection
of nuclear fragmentation

gain of k from j, $\Lambda_{kj} = 1/(n^*\sigma_{kj})$
partial fragmentation Xsection ($j \rightarrow k$)

E.g., Letaw et al., ApJS 56, 369 (1984)

Results in the thin-shielding limit (1)

ZWL, PRC75, 034609 (2007)

$$\Rightarrow J_k(E, x \to 0) \approx J_k(E,0)\left[1 + w_k'(E)x + \frac{J_k'(E,0)}{J_k(E,0)} w_k(E)x - \frac{x}{\Lambda_k(E)}\right] + \sum_j \frac{J_j(E,0)}{\Lambda_{kj}(E)} x$$

Affected by cross section uncertainties, but not by energy loss

Radiation hazard is often represented by **dose equivalent**:

$$H(x) = \frac{1}{\rho_T} \sum_k \int J_k(E,x) L_k(E) Q(L_k(E)) dE$$

LET in water

ICRP60(91) quality factor

When σ_{kj} changes:

$$\longrightarrow \quad \delta H(x) = \frac{nx}{\rho_T} \sum_j \int J_j \left[-L_j Q(L_j) \delta\sigma_j + \sum_k L_k Q(L_k) \delta\sigma_{kj} \right] dE$$

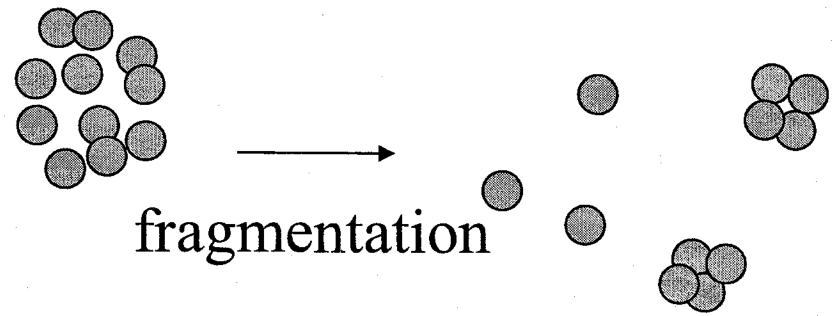
Unitarity constraint from baryon number conservation

Assuming no anti-baryon productions (exact below ~6GeV/u), we have

$$A_j \sigma_j(E) = \sum_k A_k \sigma_{kj}(E)$$

$\longrightarrow$ σ_j (total) and σ_{kj} (partial) are strictly correlated

$\Rightarrow A_j = \sum_k A_k N_k$ This means: getting the same number of nucleons before & after a projectile fragmentation:



Not respecting unitarity means *the violation of baryon number conservation*

Goal of our study is:

evaluate effects on radiation hazard from uncertainty of each ***single*** *partial cross section* σ_{kj}

→ *do not change all the other partial cross sections whenever possibl*

The unitarity constraint from **baryon number conservation**

$$\longrightarrow \quad A_j \delta\sigma_j(E) = \sum_k A_k \delta\sigma_{kj}(E)$$

→ The only way is to adjust σ_j (total) according to unitarity:

when one σ_{kj} (partial) is changed to study its effect, σ_j (total) needs to be changed accordingly.

$$\frac{\partial J_k(E,x)}{\partial x} = -\frac{\partial J_k(E,x)}{\Lambda_k(E)} + \sum_j \frac{\partial J_j(E,x)}{\Lambda_{kj}(E)} + \frac{\partial[w_k(E)J_k(E,x)]}{\partial E}$$

Results in the thin-shielding limit (2): include unitarity

When σ_{kj} changes:

$$\delta H(x) = \rho x \sum_{j,k} U_{jk} \delta\sigma_{kj},$$

sensitivity matrix elements

$$U_{jk} = \frac{n}{\rho_T \rho} \int L_1 J_j \left[-Z_j^{\,2} Q(Z_j^{\,2} L_1) \frac{A_k}{A_j} + Z_k^{\,2} Q(Z_k^{\,2} L_1) \right] dE$$

$\longrightarrow$

- $U_{jk} \to 0$ when $Z_k \to Z_j$ or $Z_k \to 0$
- In the limit of same Q_k and same A_k/Z_k (for all k):

$$-U_{jk} \sim Z_j^{\,2} \frac{A_k}{A_j} - Z_k^{\,2} \approx Z_k (Z_j - Z_k)$$

$\Rightarrow U_{jk}$ peaks at $Z_k \approx Z_j / 2$

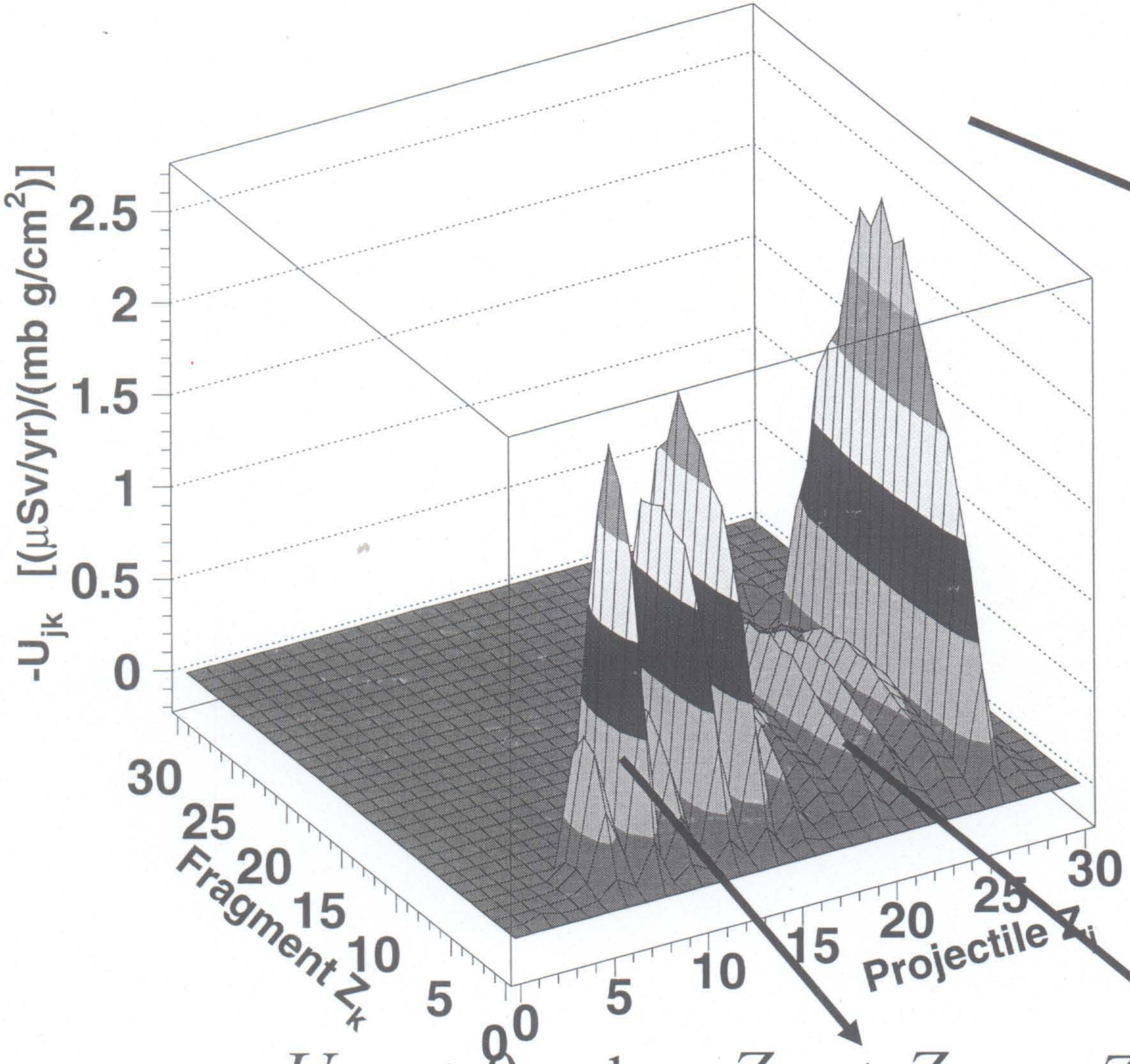
fragment Z

projectile Z

$$-U_{jk} \sim Z_k(Z_j - Z_k)$$

sensitivity matrix elements

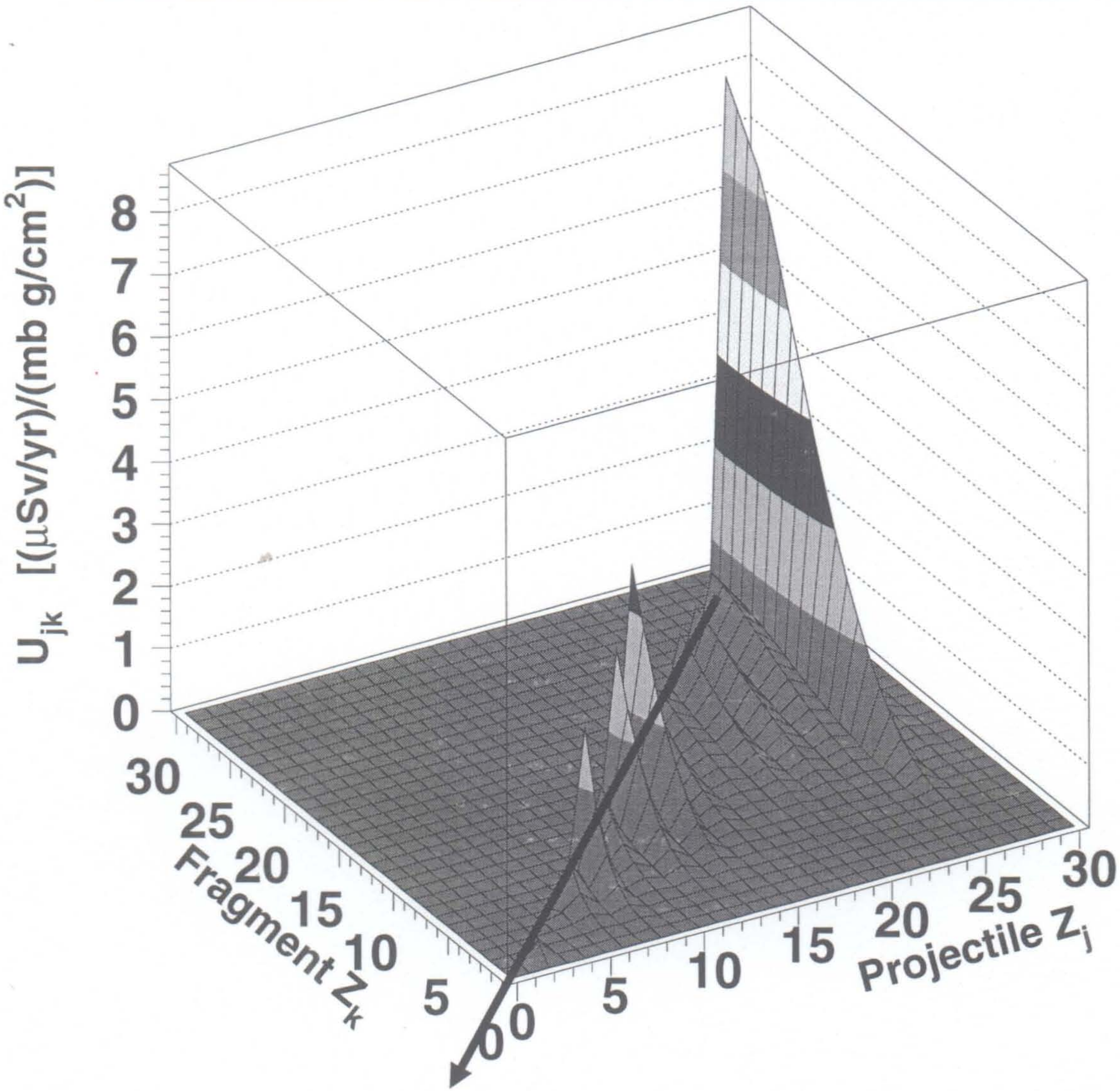
for 1977 solar minimum GCR



Fragment peaks at mid-Z $Z_k \approx Z_j / 2$

$U_{jk} \to 0$ when $Z_k \to Z_j$ or $Z_k \to 0$

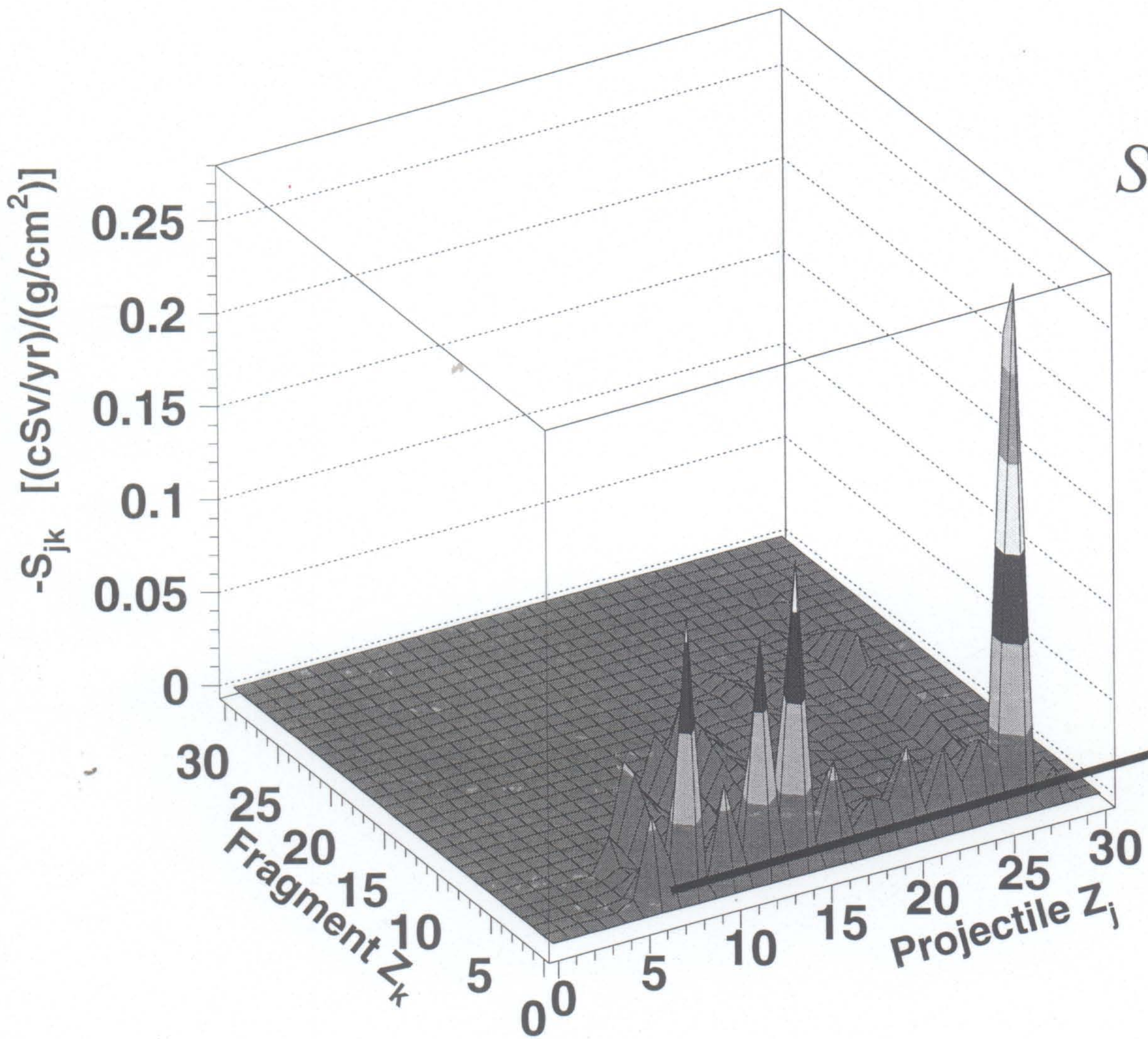
sensitivity matrix elements
without the unitarity constraint $U_{jk} \sim Z_k^2$



Fragment peaks at high-Z $Z_k \approx Z_j$

Sensitivity matrix for relative change in σ_{kj} (e.g. 10%)

$$\delta H(x) = \rho x \sum_{j,k} S_{jk} \frac{\delta\sigma_{kj}}{\sigma_{kj}}, \qquad S_{jk} = U_{jk}\sigma_{kj}$$

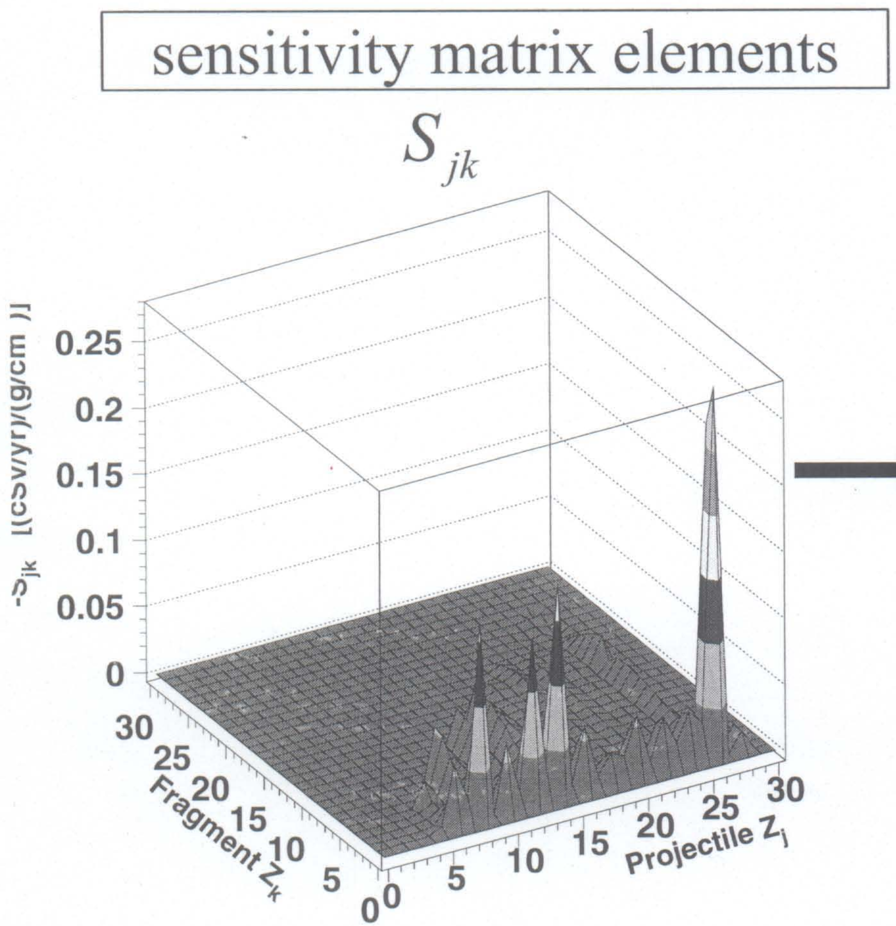


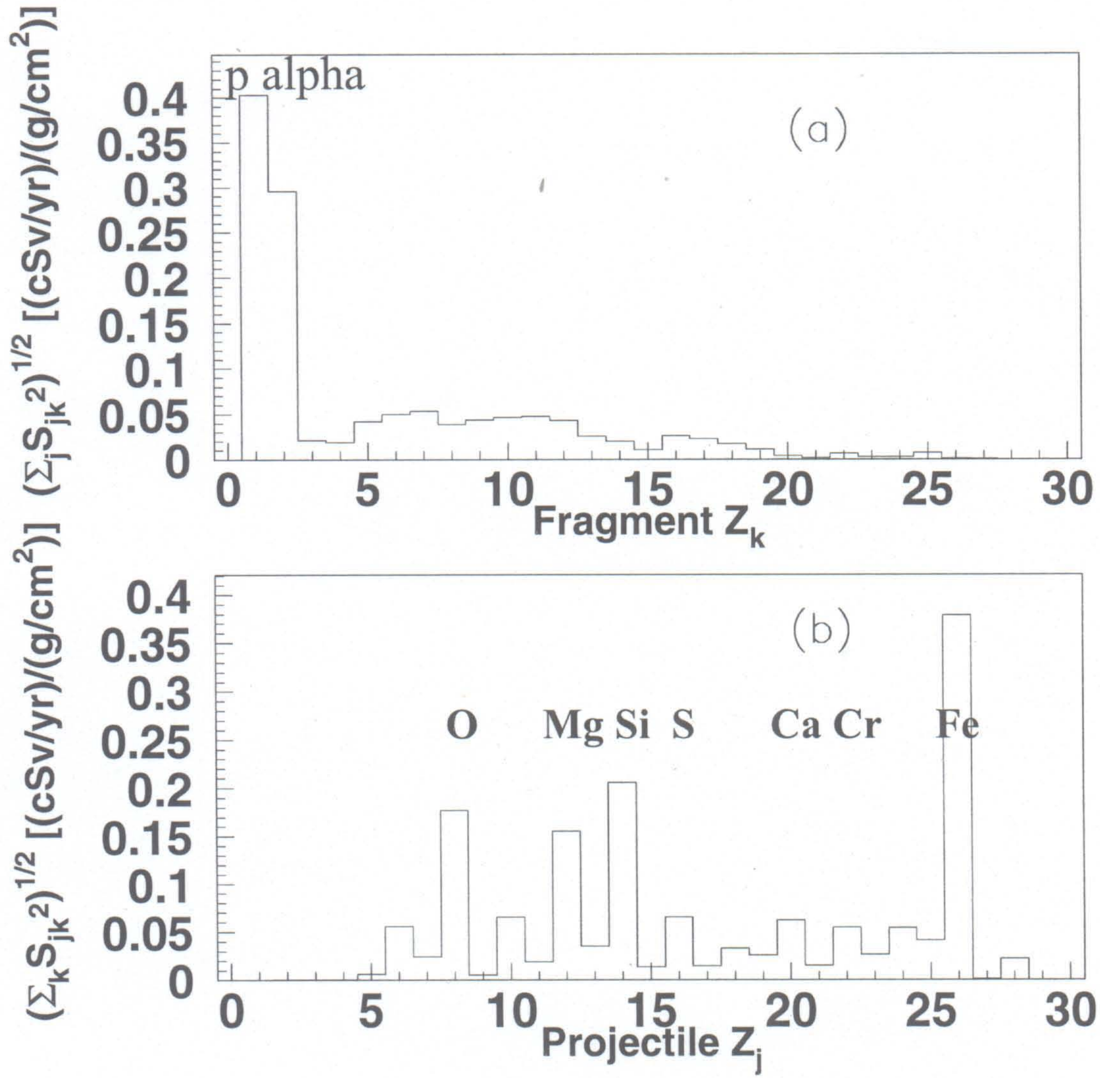
sensitivity matrix elements

S_{jk} for water target and 1977 solar min GCR

Light fragments are the most important

1-d plots: projectile or fragment distributions



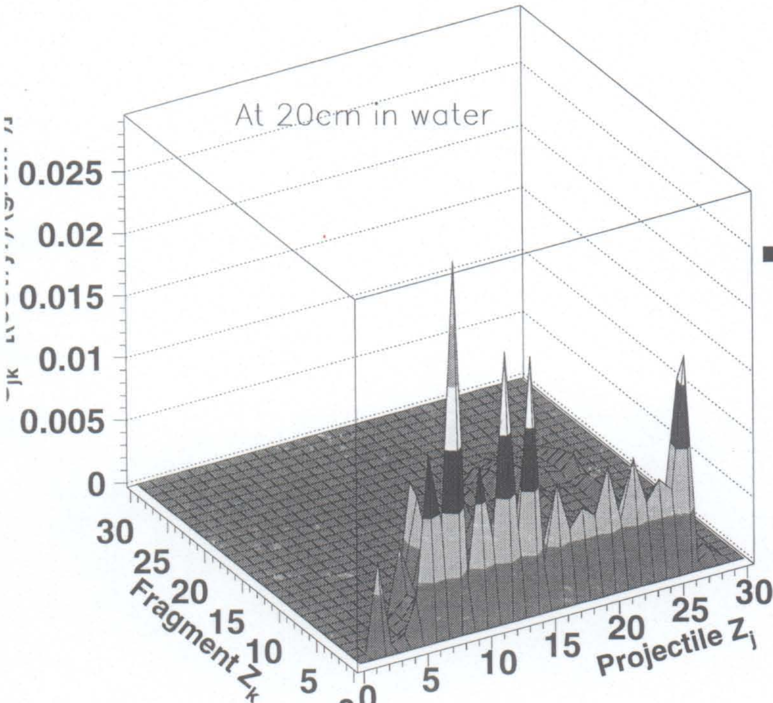


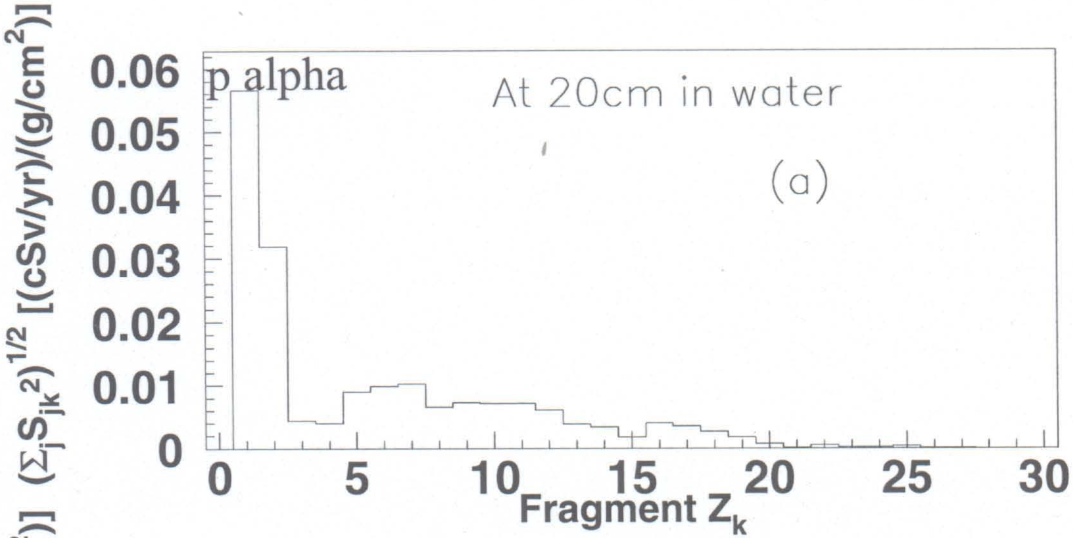
→ Light fragments (p & alpha) are the most important; many projectiles are important (Fe, Si, Mg, O)

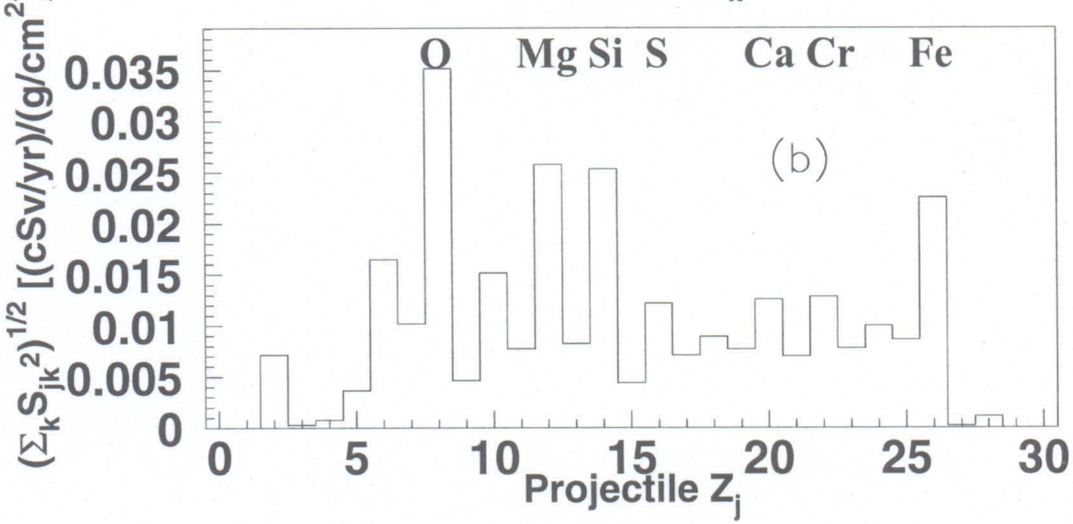
Thick shielding

sensitivity matrix elements

S_{jk}







→ Medium-sized projectiles (O, Mg, Si) may become more important than Fe

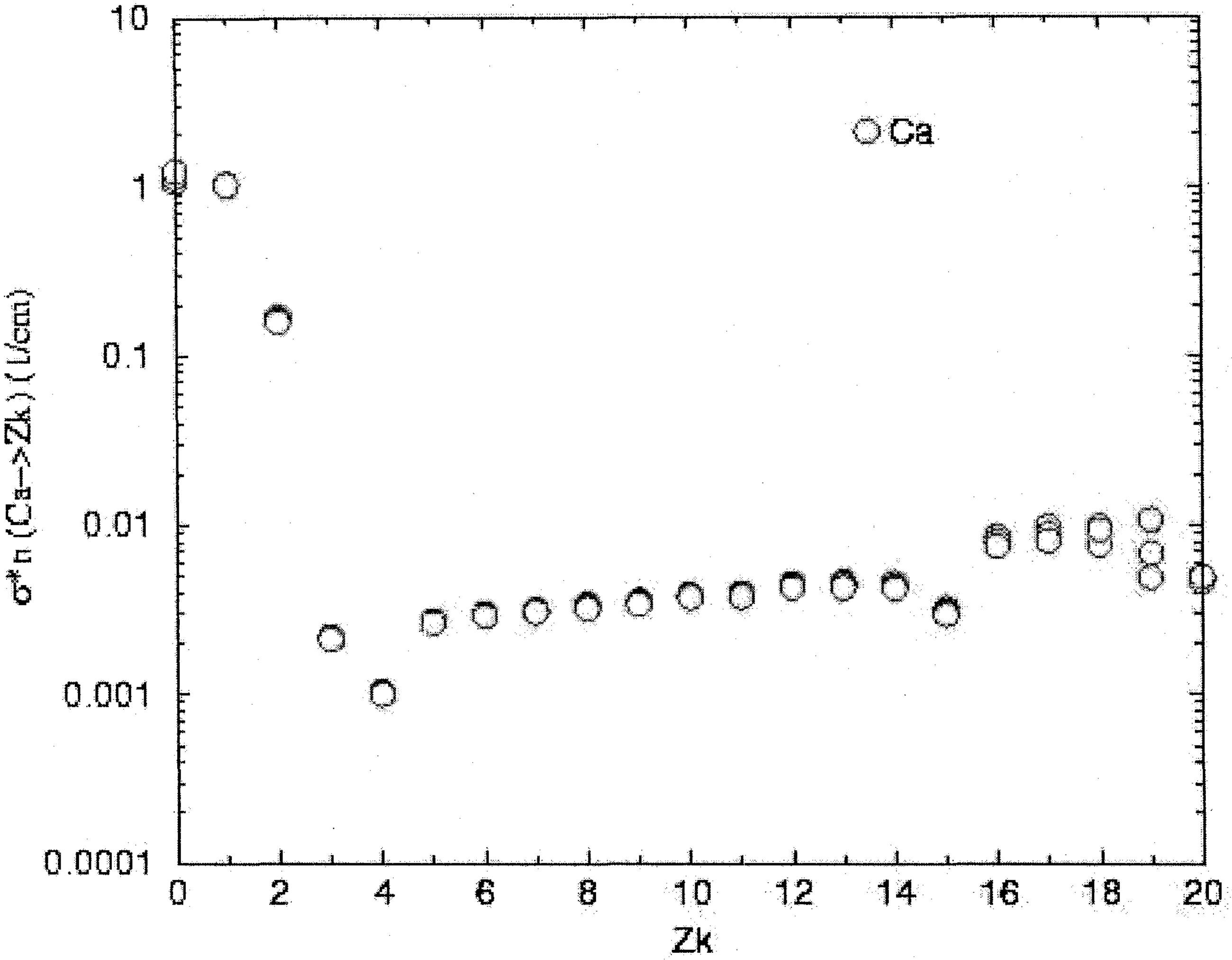
Conclusions

- Semi-analytical results show:
  Light fragments (p & alpha) are the most important;
  Many projectiles are important (Fe, Si, Mg, O)

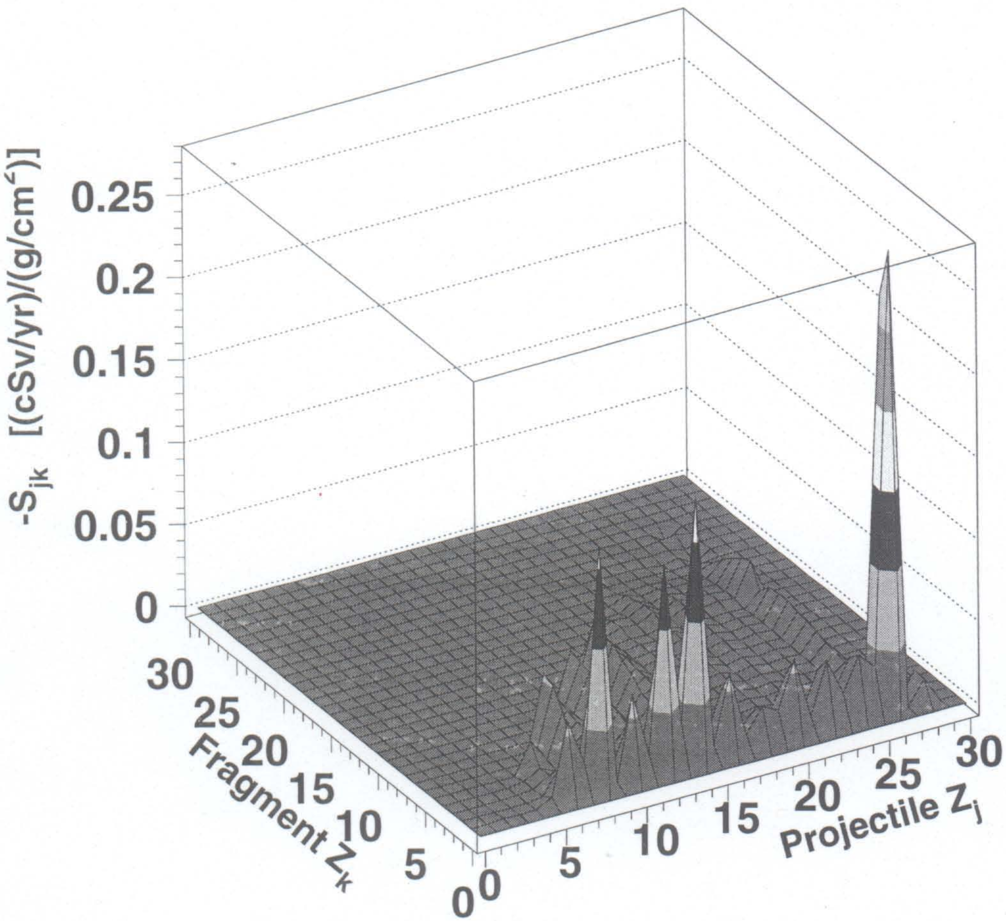
- Focused study on these projectiles and fragments
  will most efficiently reduce uncertainty
  in evaluation of radiation hazard in human space explorations

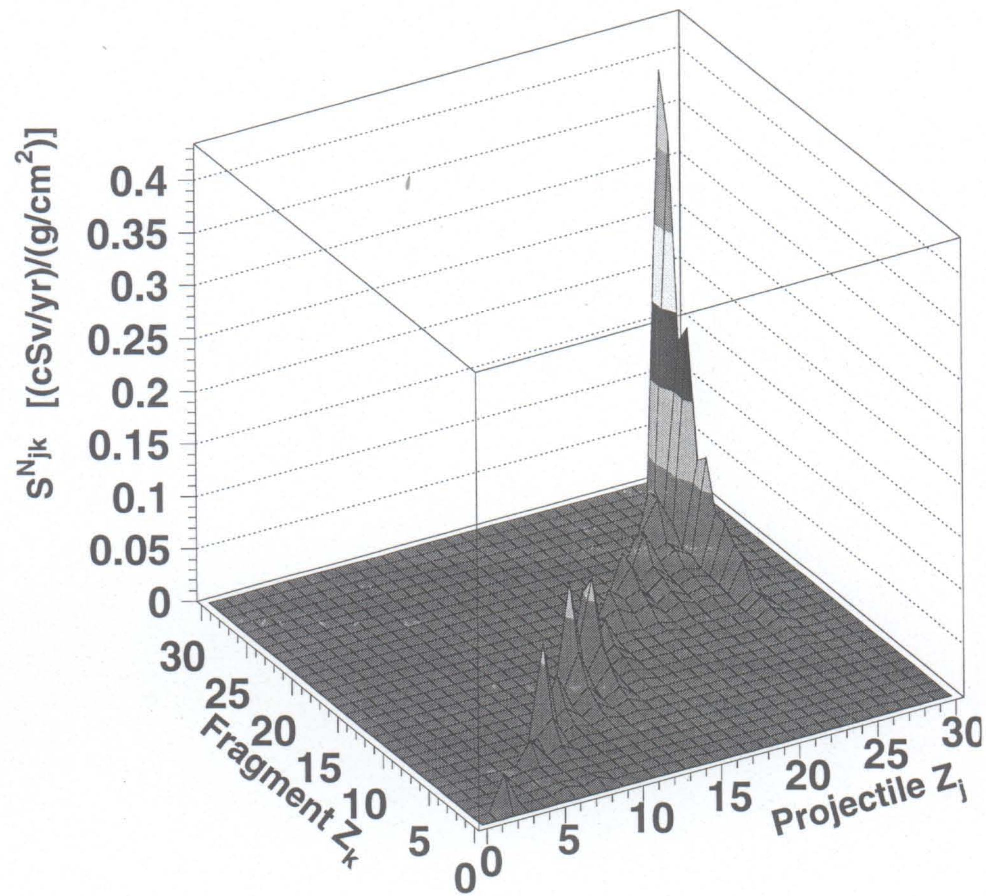
Partial cross sections of fragmentation

Ca projectile (1.2GeV/u) in Al target:



Effect of unitarity on sensitivity matrix S_{jk}





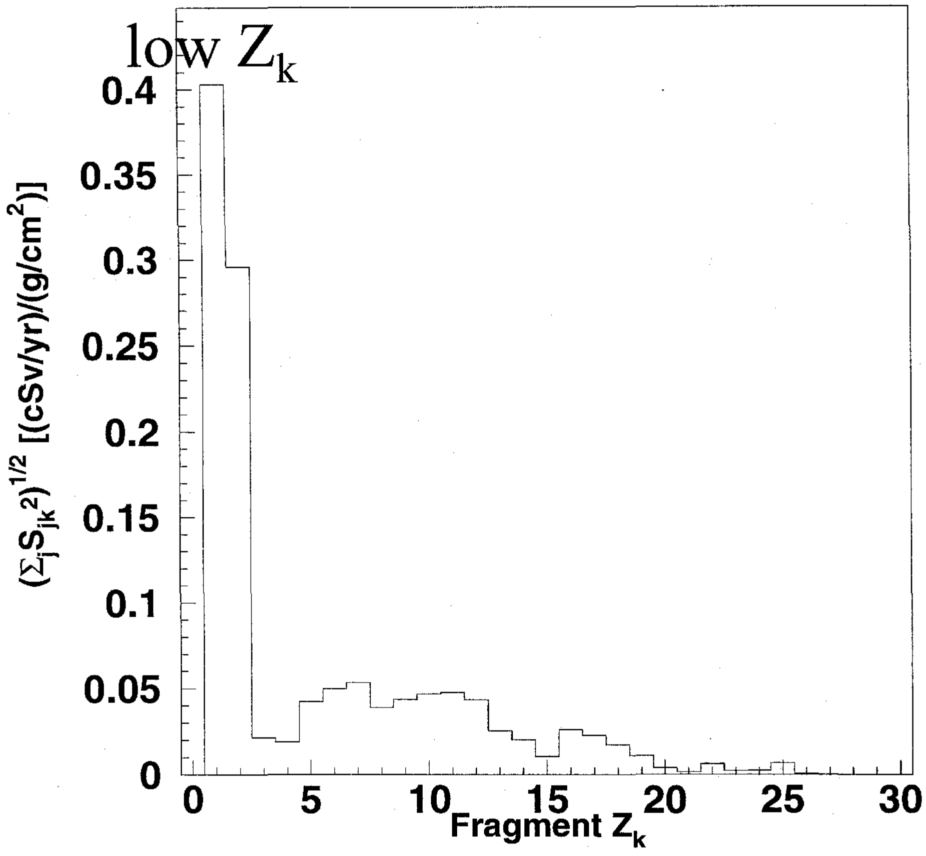
with unitarity

$$A_j \delta\sigma_j(E) = \sum_k A_k \delta\sigma_{kj}(E)$$

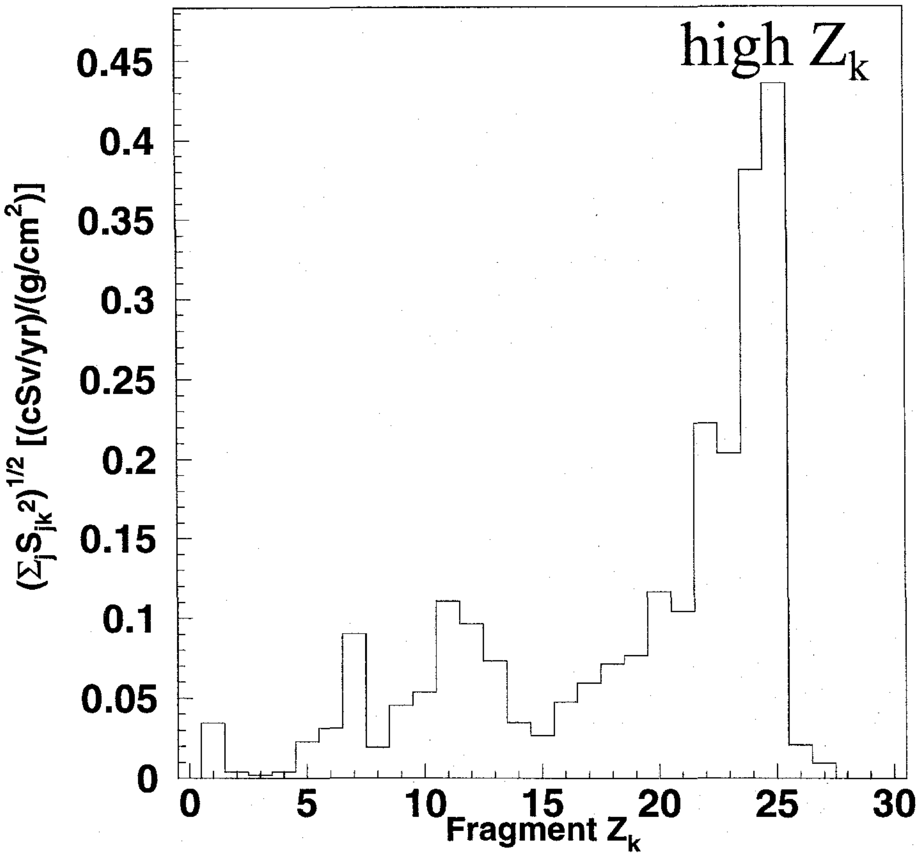
without unitarity

Unitarity constraint is critical for fragment distributions

Effect of unitarity on fragment distributions



with unitarity



without unitarity

Different implementation of unitarity

- The only way to have a **well-defined** sensitivity study:
  adjust σ_j (total) according to unitarity after changing a σ_{kj} (partial).

- Correlations among σ_{kj} uncertainties in data:
  make the sensitivity study ill-defined,
  may require different implementation of unitarity

Example1: *if σ_j (total) is much more accurately determined than σ_{kj} (partial)*

$\longrightarrow$ *Keep σ_j the same and make correlated changes on at least 2 σ_{kj}*

$\longrightarrow$ *Results will be different depending on choice of other σ_{kj}*

Example2: *experimental systematic errors correlate several σ_{kj}*

- Need to investigate experimental data to determine how to implement unitarity