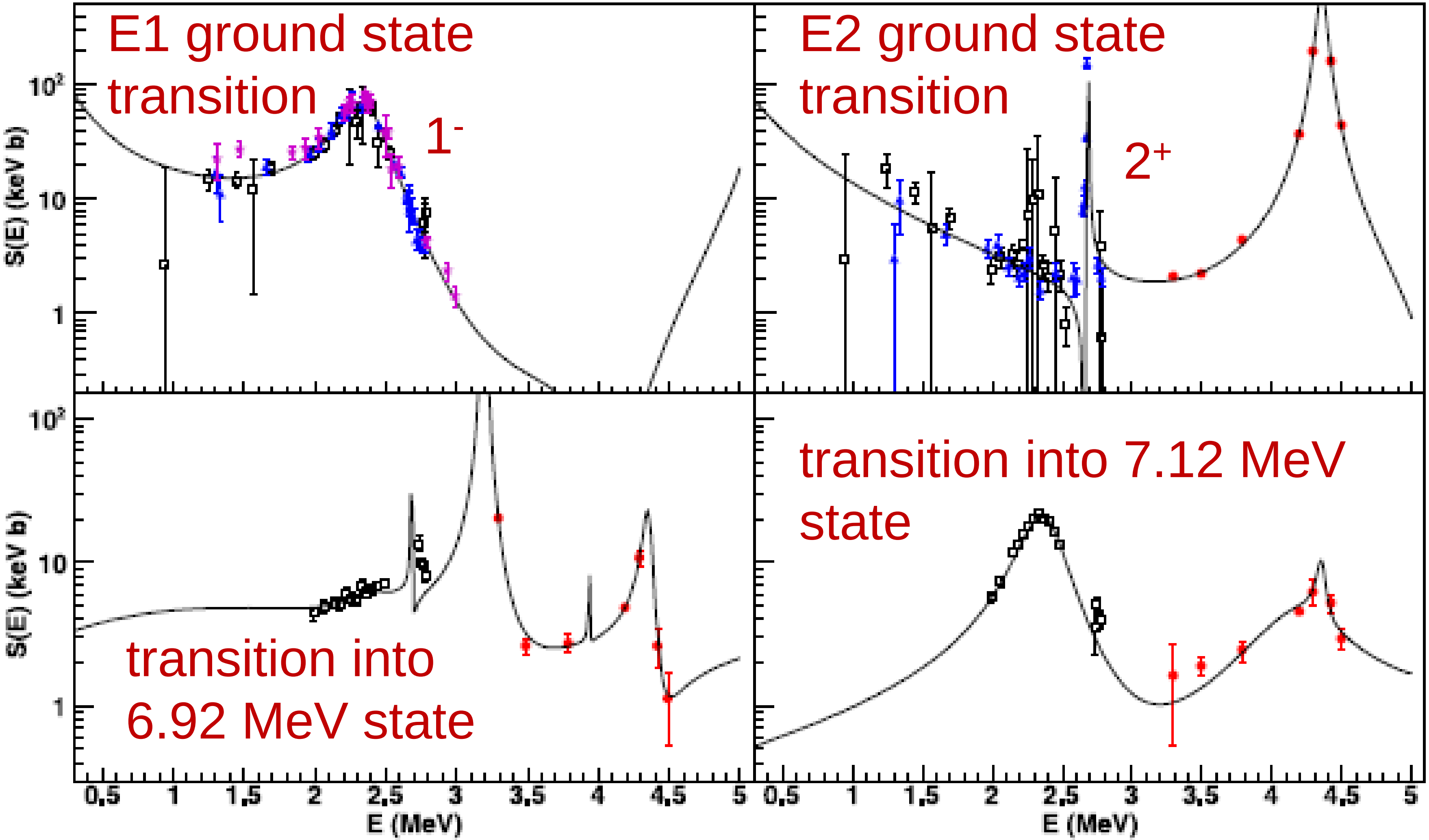
Resonances in the $^{12}C(\alpha,\gamma)^{16}O$ reaction

I have asked myself the question what is the consequences of the nuclear resonances in the proposed experiment in inverse kinematics of the α capture reaction?

So far, the reaction was discussed as it were an s-wave and that a measurement of the total astrophysical S factor (= sum of all partial waves) at a single kinematics would fully constrain it.

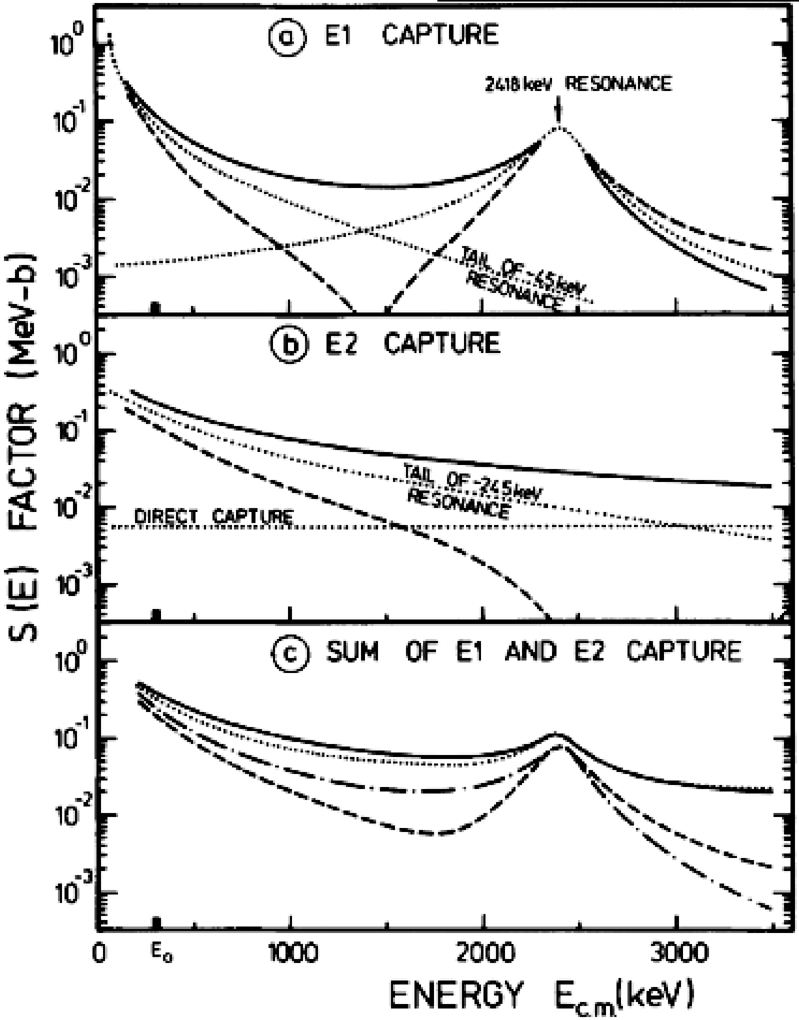
Can one find “the holy grail of astrophysics” [C. Rolfs] by a measurement with one spectrometer and α detector setting?

Existing S factor data



D. Schürmann, L. Gialanella, R. Kunz, F. Strieder: The astrophysical *S* factor of $^{12}C(\alpha,\gamma)^{16}O$ at stellar energy, Phys. Lett. B 711, 35 (2012)

Schematic S factor curves



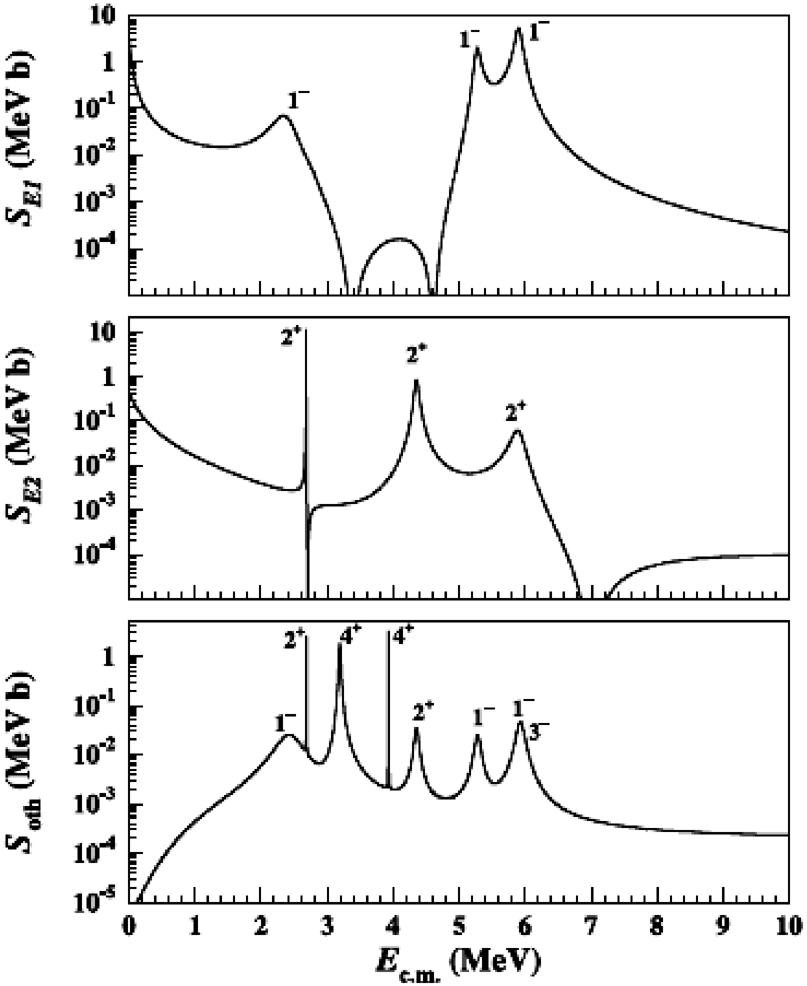
C. E. Rolfs & W. S. Rodney: Cauldrons in the Cosmos, Chicago: Univ. Chicago Press (1988)

the cross section at stellar energies is, most likely, dominated by the tails of subthreshold resonances corresponding to the bound states at 7.12 MeV and 6.92 MeV, whereas in the experimentally accessible region it is dominated by the resonance corresponding to a 9.6 MeV state and by direct capture

constructive or destructive interference may occur.

the total cross section is incoherent sum of E1 and E2 leading to four possible curves depending on the sign of the interference effects.

Extrapolated S factor curves



recent calculations for the different contributions to the S factor of the reaction and *current* precision.

The final result of $\boxed{S(300) = 161 \pm 19_{stat}{}^{+8}_{-2\,sys}\ \text{keV b}}$ represents the most precise analysis of the $^{12}C(\alpha,\gamma)^{16}O$ S factor at helium burning temperature presently available. This extrapolation is based on a set of complementary data including all available information which in addition have been reviewed according to clear and well-grounded criteria.

→ $\Delta S/S \sim 12$ %

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R. Kunz et al.: Astrophysical Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$, Astrophys. J. 567, 643 (2002)

How to improve?

The excitation function of $^{12}C(\alpha, \gamma)^{16}O$ is formed by several resonant states that show strong interference effects. Two resonances are below the $^{12}C + \alpha$ threshold, but their high-energy tails enhance the cross section above threshold. The α capture leads predominantly to E1 and E2 γ transitions to the ground state of ^{16}O and, to a minor extent, to excited states giving rise to γ cascades. For a proper analysis of this reaction it is necessary to separate the three parts, E1 and E2 capture and capture followed by γ cascades, by

R. Kunz et al.: Astrophysical Reaction Rate of $^{12}C(\alpha,\gamma)^{16}O$, Astrophys. J. 567, 643 (2002)

The two multipoles appear to be of similar importance and arise predominately from the high-energy tails of two subthreshold resonances at $E = -45$ ($J^{\pi} = 1^{-}$) and -245 keV (2^{+}),[1] and their interference with higher energy states of the same J^{π} (Fig. 1). The contribution of a direct capture process has to be considered for the E2 amplitude. Since the capture cross sections of the E1 and E2 multipoles have different energy dependencies, one must have an independent and precise information on each multipole cross section for an extrapolation to E_0. In addition to the ground state contributions cascade transitions have to be considered.

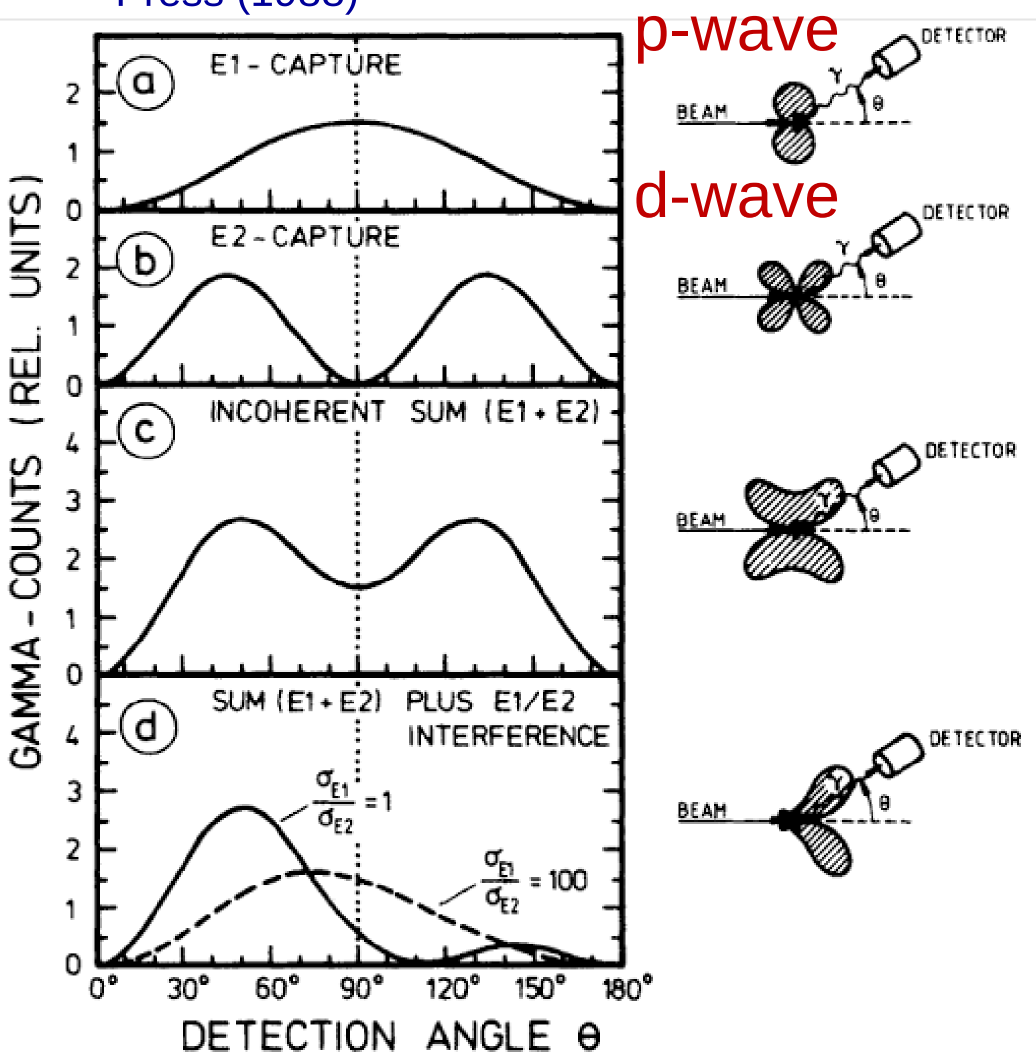
D. Schürmann, L. Gialanella, R. Kunz, F. Strieder: The astrophysical *S* factor of $^{12}C(\alpha,\gamma)^{16}O$ at stellar energy, Phys. Lett. B 711, 35 (2012)

How to approach experimentally?

P. Prati et al.: Nuclear Astrophysics At LUNA: Status And Perspectives:

"The measurement of the $^{12}C(\alpha,\gamma)^{16}O$ reaction should be done in a nearly 4π geometry with an angle-segmented crystal ball detector. The measurement of angular distributions is necessary to separate the E1 and E2 components of both ground-state and cascade transitions."

C. E. Rolfs & W. S. Rodney: Cauldrons in the Cosmos, Chicago: Univ. Chicago Press (1988)



Consequences

It is important to get data of high relevance
with respect to the (complex) properties of the S factor curve:

- What's the impact of a data point on total $d\sigma/d\Omega$ at a specific $\cos\theta$ especially at $E \gg E_0$ where an extrapolation to E_0 is needed?
  - It is not possible to get σ_{total} (and therefore S_{total}) from $d\sigma/d\Omega$.
  - It is not possible to separate multipoles.
  - The cascade γ-decay amplitude is not accessed by the inverse reaction
- Is it crucial to get information on p- or d-waves?
- Requirement to get a measurement with 10-20% accuracy.

Consequences

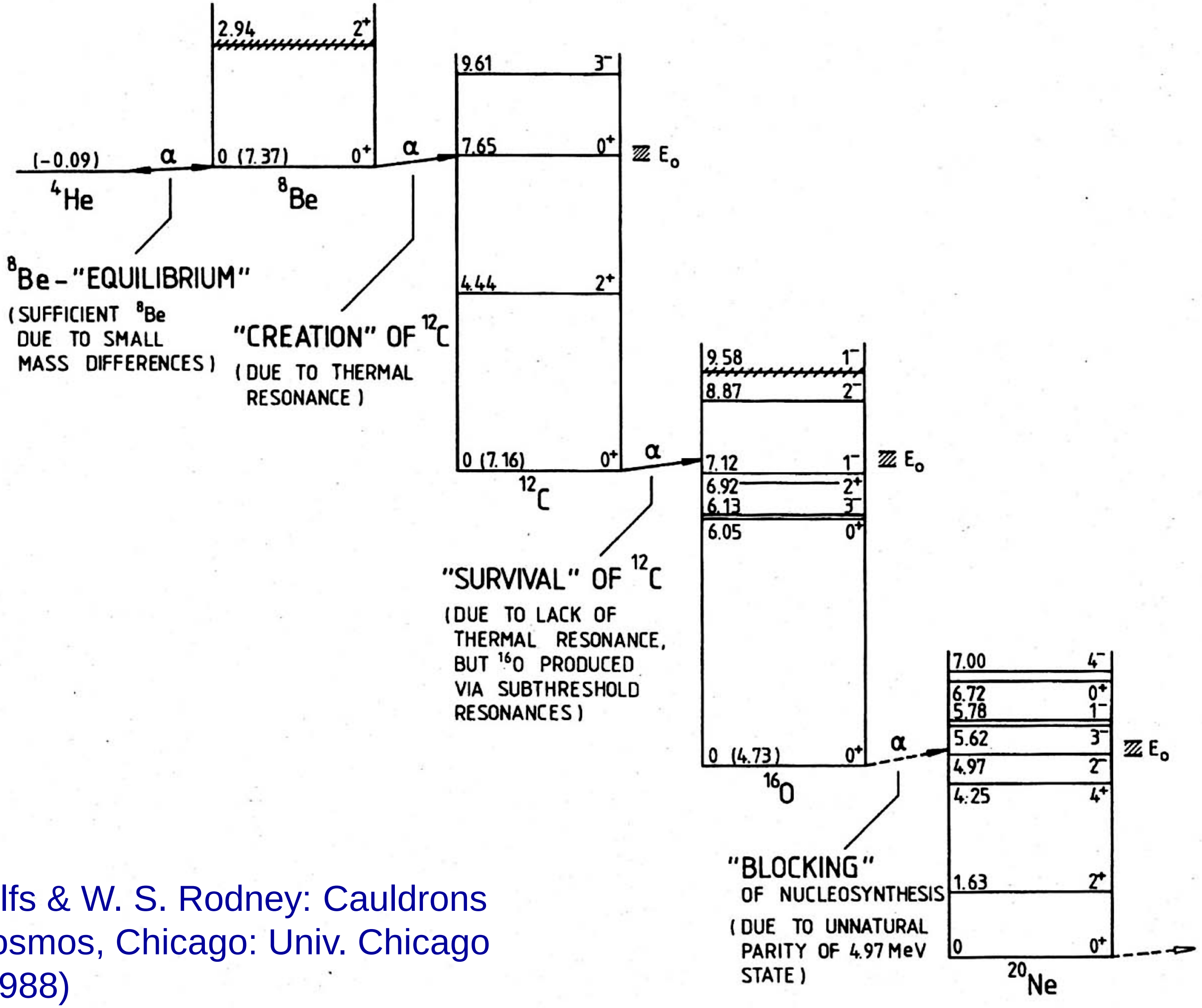
What is the ideal experimental setup?

- A limited (or integrated) detection angle of the α particle leads to an unknown multipolarity of the measured cross section.

- A detector ring or sphere with full angular coverage would have dramatically different background as a function of cosθ.

- Is a gas detector a possible alternative to a detector?
  - A low pressure MWPC or multistep chamber can have a good timing resolution and high efficiency for nuclei while being extreme insensitive to gamma, electron, proton and neutron background
  - 4π acceptance in a 1-3 Torr gas volume
  - see for example: K. Assamagan et al: Time-zero fission-fragment detector based on low-pressure multiwire proportional chambers, Nucl. Instr. Meth. Phys. Res. A 426, 405 (1999)

Helium burning reaction chain



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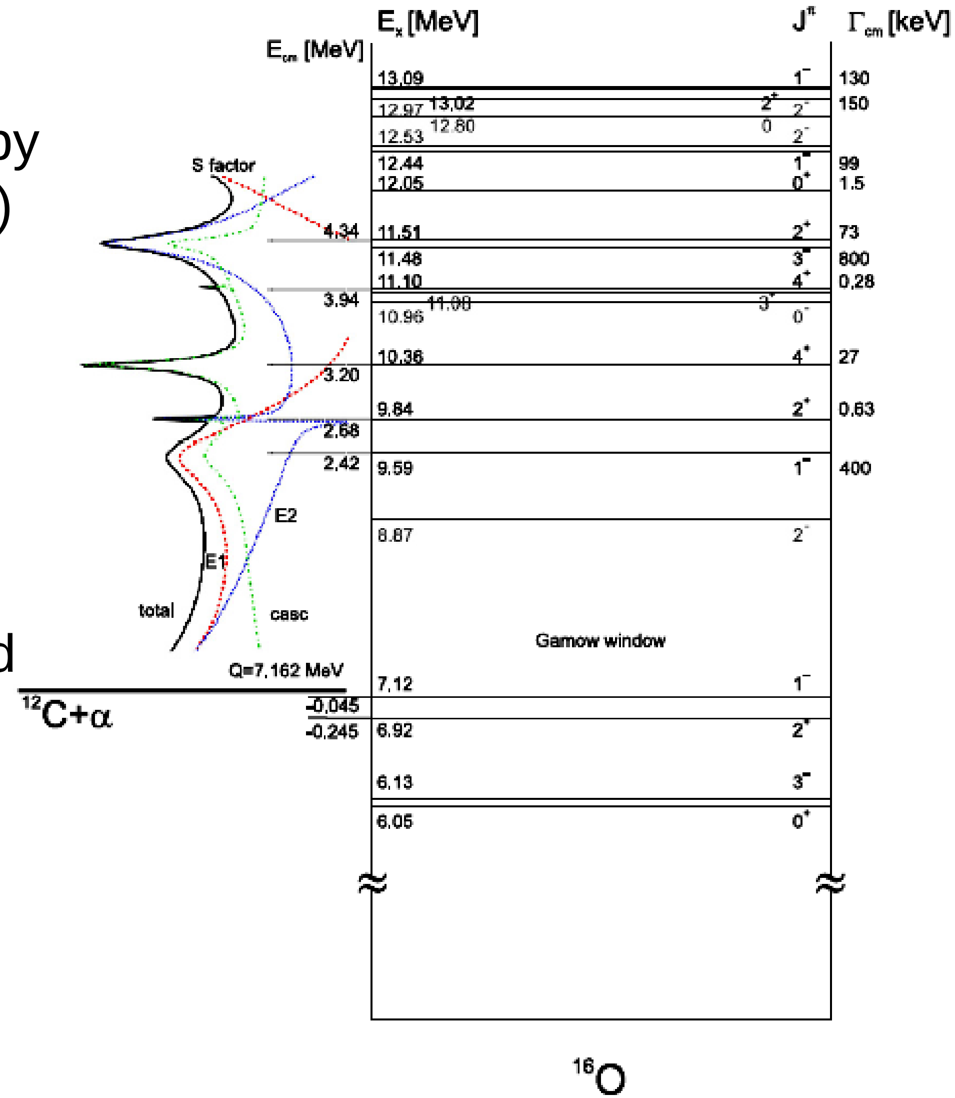
Level scheme of the ^{16}O nucleus

- α ($J^p=0^+$) + ^{12}C ($J^p=0^+$) cross section, $\sigma(E_0)$, is dominated by *p*-wave (E1) and *d*-wave (E2) radiative capture to ^{16}O ground state ($J^p=0^+$)

- Two bound states, at 6.92 MeV ($J^p=2^+$) and 7.12 MeV ($J^p=1^-$), with sub-threshold resonances at E_R=-0.245 and -0.045 MeV, provide most $\sigma(E_0)$ through their finite widths

- Transition $1^- \rightarrow 0^+$ (E1) and transition $2^+ \rightarrow 0^+$ (E2) distinguished by γ-angular distributions



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