GAMOW SHELL MODEL DESCRIPTION OF NEAR-THRESHOLD RESONANCES IN ^{11}C

Alan Dassie
Marek Płoszajczak
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EuNPC - September 2025 - Caen, France

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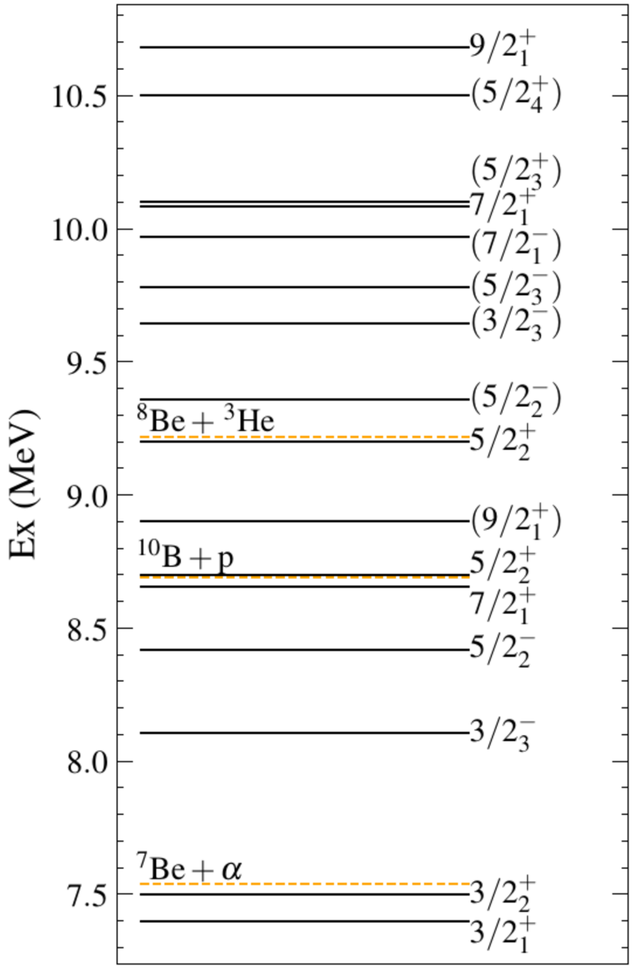
- Motivations
- The Gamow Shell Model
- The coupled-channel representation
- The states above the alpha-thresholds
  - Partial widths
  - Spectroscopic factors
- Conclusions and perspectives

MOTIVATION: ASTROPHYISCAL IMPLICATION

There are two reactions involving ^{11}C that play a role in astrophysics

$$^{10}\mathrm{B}(p,\alpha)^{7}\mathrm{Be}$$

Destruction of ^{10}B in H-rich environment like stars outer layers



Ref: M. Wiescher et al., The Astrophysical Journal 343, 352 (1989).
C. Spitaleri et al., Phys. Rev. C 95, 035801 (2017).

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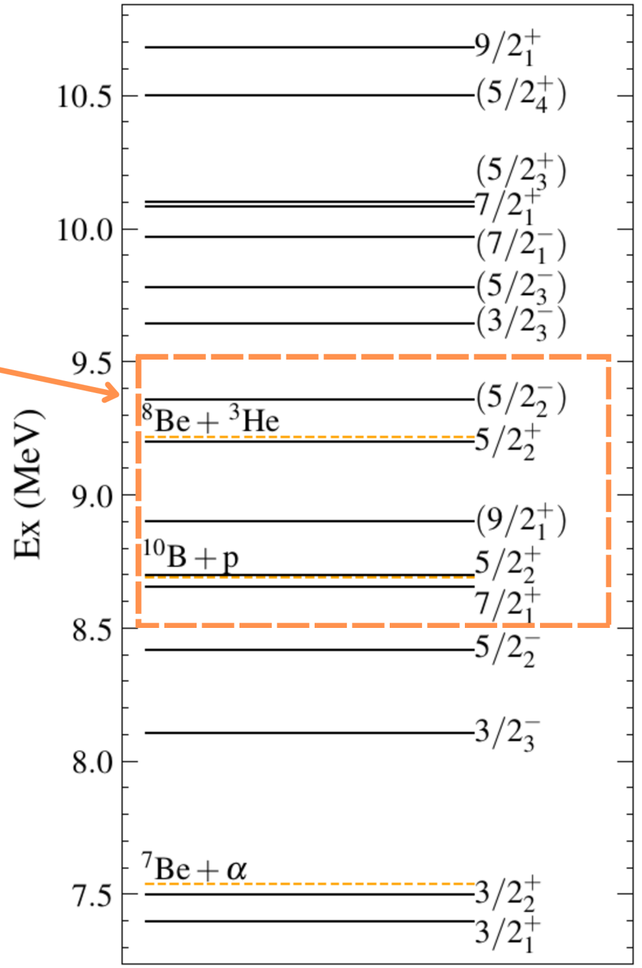

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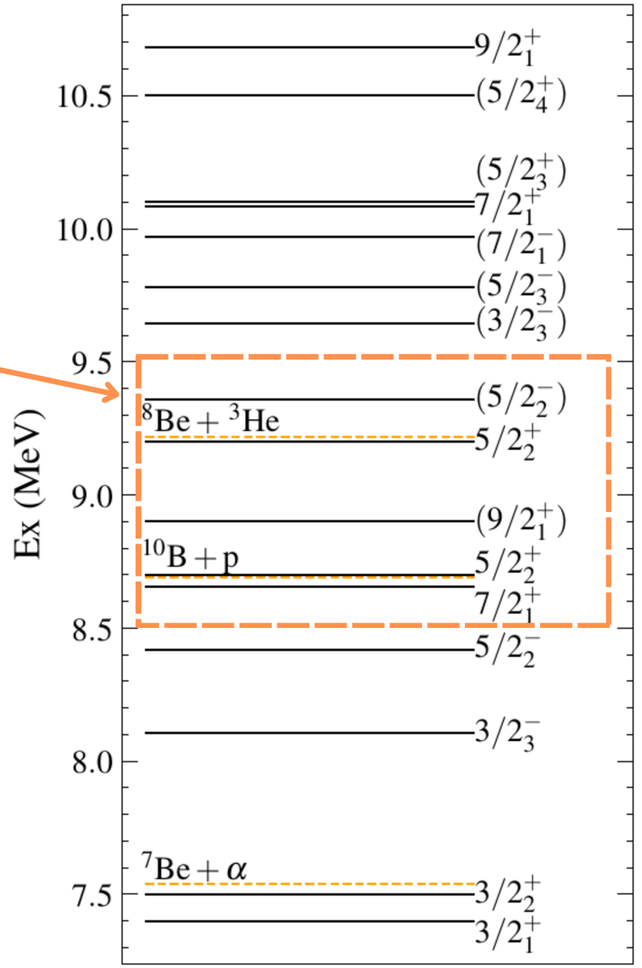
$^{7}\mathrm{Be}(\alpha,\gamma)\,^{11}\mathrm{C}$ → $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\alpha,p)^{14}\mathrm{N}$

hot pp chain that could link A = 7 to the CNO cycle without the triple-alpha process.



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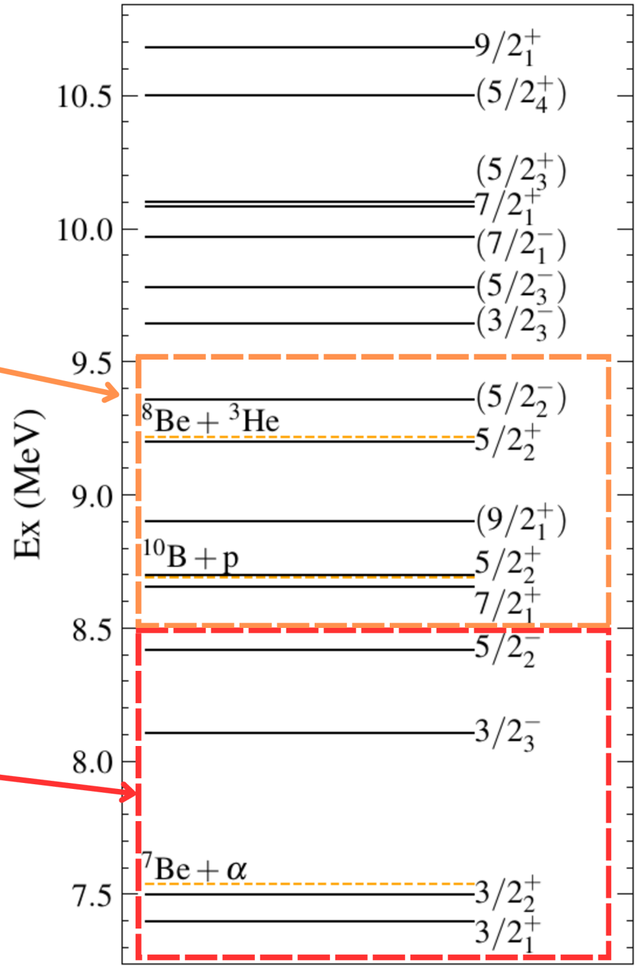

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MOTIVATION: CLEAN ENERGY PRODUCTION

Aneutronic plasma fusion systems have been discussed as possible energy sources without the disadvantage of long-lived radioactive end-products.

$$^{11}\mathrm{B}(p, 2\alpha)^{4}\mathrm{He}$$

Q=8.7 MeV

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Natural boron fuel

19% ^{10}B

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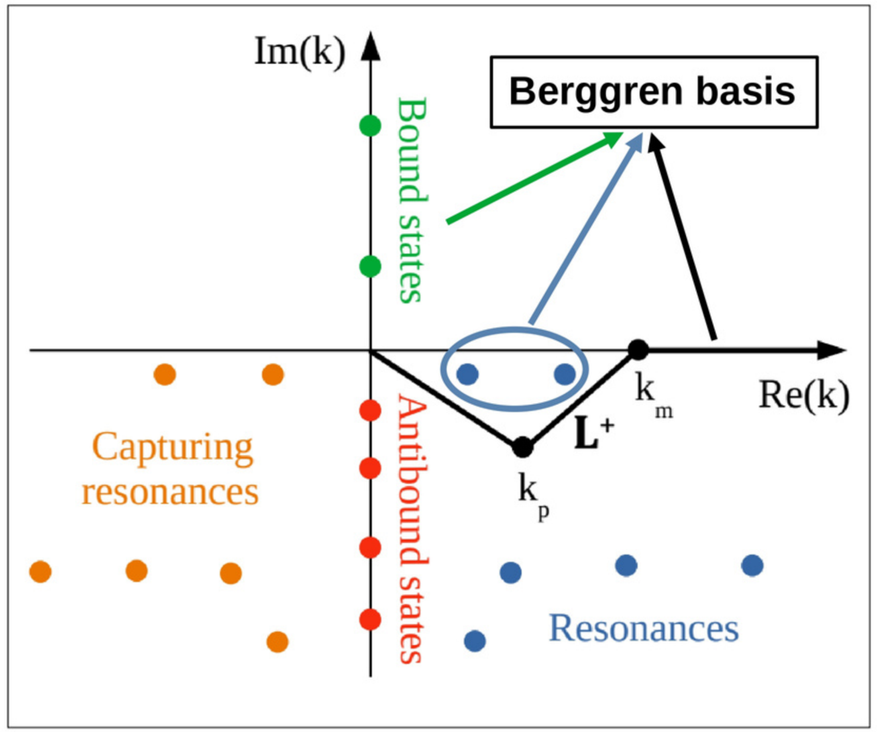
Could serve as an independent test for temperature analysis in the new generation of laser driven hot plasma facilities like *National Ignition Facility, LLNL* *Laser Mégajoule, CEA*

Ref: M. Wiescher et al., Phys. Rev. C 95, 044617 (2017).

THE BERGGREN BASIS

Berggren implemented the resonant states on a basis, with the inclusion of the **scattering** states. This complex states describe the behavior of particles that scatter away from each other and are no longer strongly interacting.

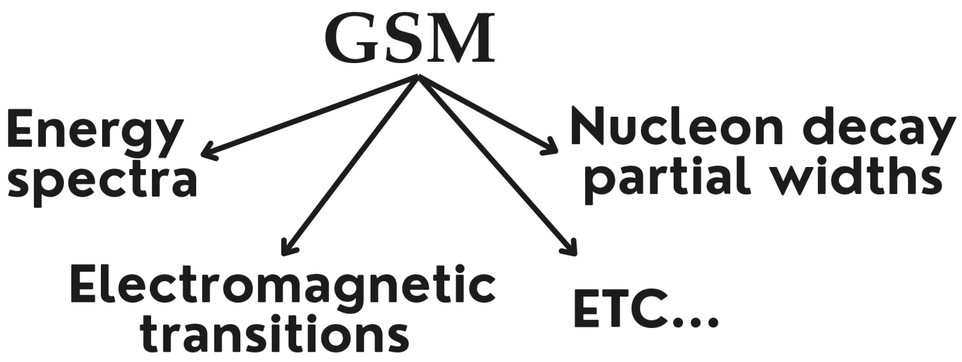
$$\delta(r-r') = \sum_a u_a(r)u_a(r') + \int_{L^+} dk u(r,k')u(r',k')$$



N. Michel, M. Płoszajczak,
The Gamow Shell Model: the unified theory of nuclear structure and reactions,
Lecture Notes in Physics, Springer International Publishing (2021)

GAMOW SHELL MODEL

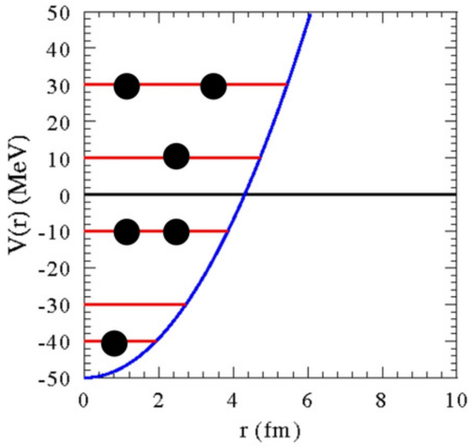
The Gamow Shell Model is the open quantum system formulation of the nuclear shell model.



The GSM many-body eigenfunctions are superposition of Slater determinants

Standard shell model

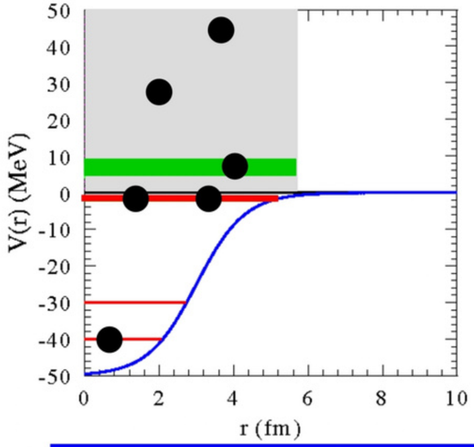
Closed quantum system description



Localized states

Gamow Shell Model

Open quantum system description



Localized states
Weakly bound/resonant states
Scattering states

COUPLED-CHANNEL REPRESENTATION

In the coupled-channel representation of GSM, the A-body state is decomposed into reaction channels defined by the target (T) and the projectile (P)

$$|\Psi^J_M\rangle = \sum_c \int_0^{+\infty} |(c,r)^J_M\rangle \frac{u_c(r)}{r} r^2 dr \qquad |(r,c)^J_M\rangle = \hat{\mathcal{A}} |\{|\Psi^{J_T}_T\rangle \otimes |\Psi^{J_P}_P\rangle\}^J_M\rangle$$

GSM-CC ⟶ unification of the structure and nuclear reactions

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GSM-CC ⟶ unification of the structure and nuclear reactions

TARGET { One-body ⟶ WS + LS + Coul
and
two-body ⟶ FHT: Central+LS+Tensor

+

PROJECTILE { N^3LO for cluster

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GSM-CC ⟶ unification of the structure and nuclear reactions

$|(r,c)^J_M\rangle$

TARGET { One-body → WS + LS + Coul and two-body → FHT

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$\alpha + {}^7\mathrm{Be}$

6 channels
Coupled up to 10 MeV ex. energy

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TARGET { One-body ⟶ WS + LS + Coul and two-body ⟶ FHT

+

PROJECTILE { N³LO for cluster

$\alpha + {}^7\mathrm{Be}$

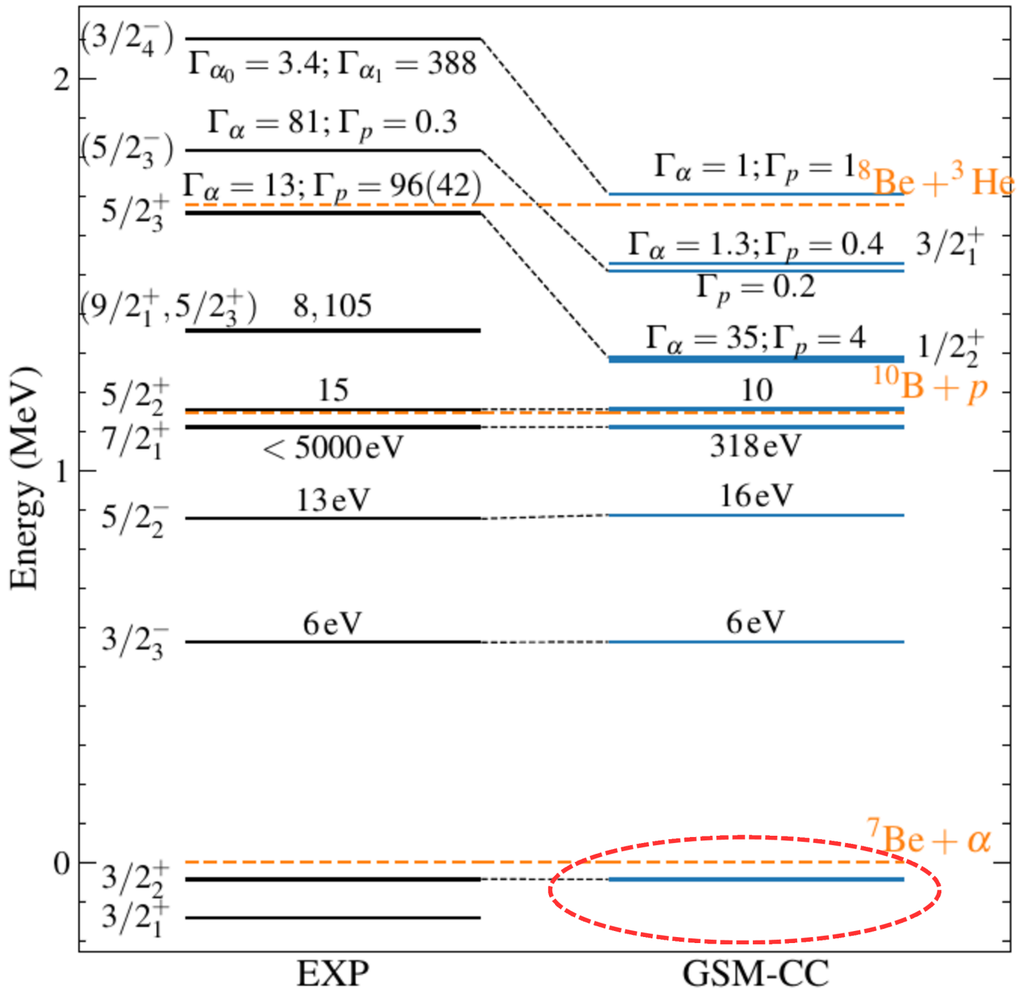
6 channels
Coupled up to 10 MeV ex. energy

+

$p + {}^{10}\mathrm{B}$

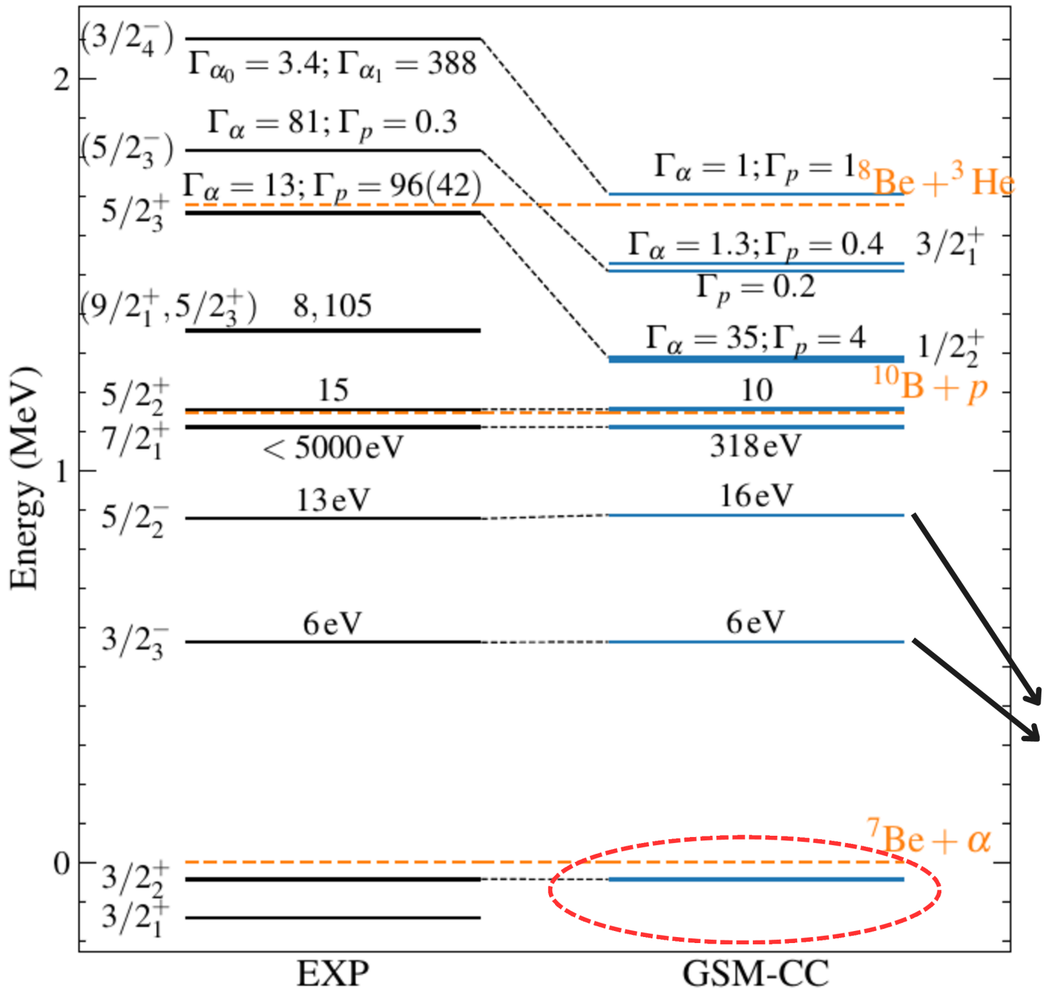
17 channels
Coupled up to 8 MeV ex. energy

ABOVE ALPHA–THRESHOLD STATES



Low energy region

ABOVE ALPHA–THRESHOLD STATES



Low energy region

Resonant alpha capture by ^{7}Be and ^{7}Li

G. Hardie
Physics Department, Western Michigan University, Kalamazoo, Michigan 49008

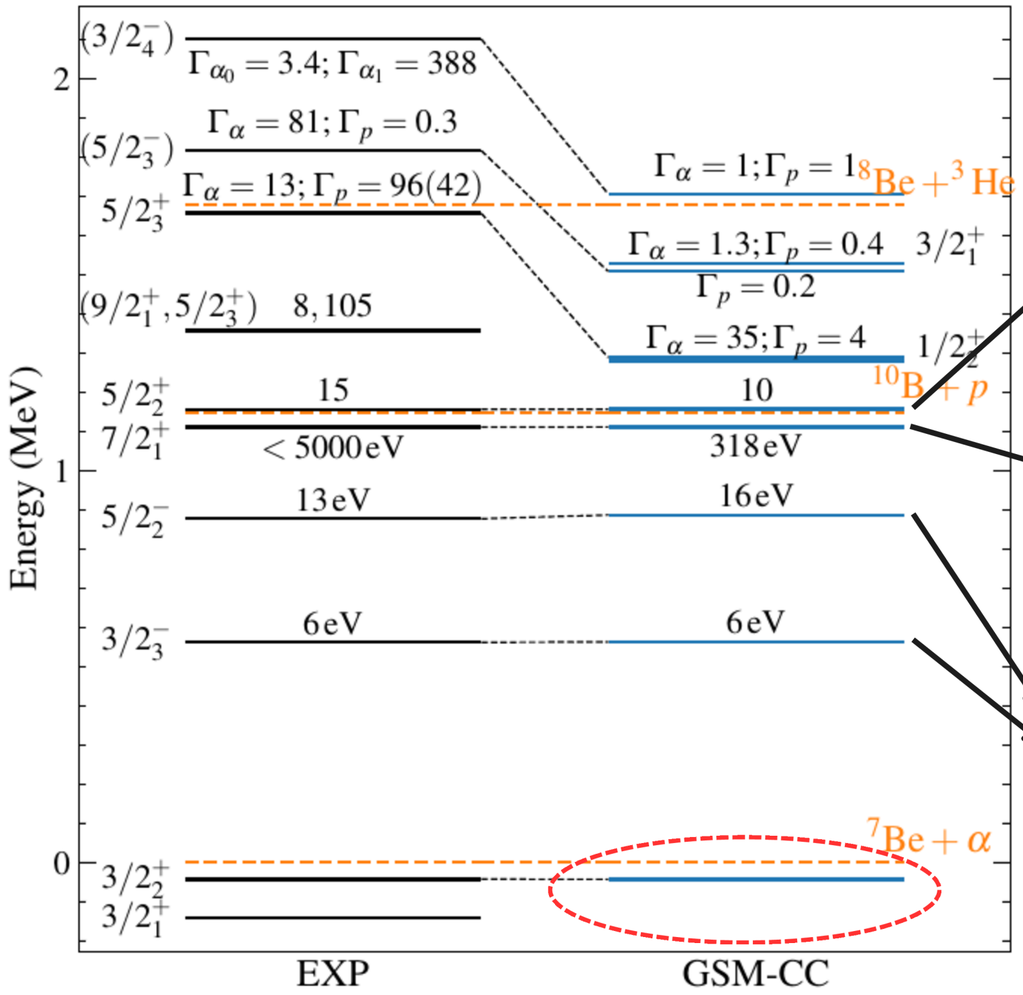
B. W. Filippone* and A. J. Elwyn†
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

M. Wiescher
Physics Department, The Ohio State University, Columbus, Ohio 43210

R. E. Segel
Physics Department, Northwestern University, Evanston, Illinois 60201

(Received 2 December 1983)

ABOVE ALPHA–THRESHOLD STATES



Low energy region

PHYSICAL REVIEW C **95**, 044617 (2017)

Low energy measurements of the ^{10}B$(p,\alpha)^7$Be reaction

M. Wiescher,* R. J. deBoer, and J. Görres
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA

R. E. Azuma
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada

(Received 20 January 2017; published 26 April 2017)

$$\Gamma_\alpha^{5/2_2^+} = 15 \text{ keV}$$

PHYSICAL REVIEW C **105**, 055802 (2022)

Investigation of the ^{10}B$(p,\alpha)^7$Be reaction from 0.8 to 2.0 MeV

B. Vande Kolk,[1] K. T. Macon,[1,2,*] R. J. deBoer,[1] T. Anderson,[1] A. Boeltzig,[1,†] K. Brandenburg,[3] C. R. Brune,[3] Y. Chen,[1] A. M. Clark,[1] T. Danley,[3] B. Frentz,[1] R. Giri,[3] J. Görres,[1] M. Hall,[1] S. L. Henderson,[1] E. Holmbeck,[1] K. B. Howard,[1] D. Jacobs,[3] J. Lai,[1] Q. Liu,[1] J. Long,[1] K. Manukyan,[1] T. Massey,[3] M. Moran,[1] L. Morales,[1] D. Odell,[3] P. O'Malley,[1] S. N. Paneru,[3] A. Richard,[3] D. Schneider,[4] M. Skulski,[1] N. Sensharma,[1] C. Seymour,[1] G. Seymour,[1] D. Soltesz,[3] S. Strauss,[1] A. Voinov,[3] L. Wüstrich,[1,‡] and M. Wiescher[1]

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^{11}C level structure via the ^{10}B(p,γ) reaction

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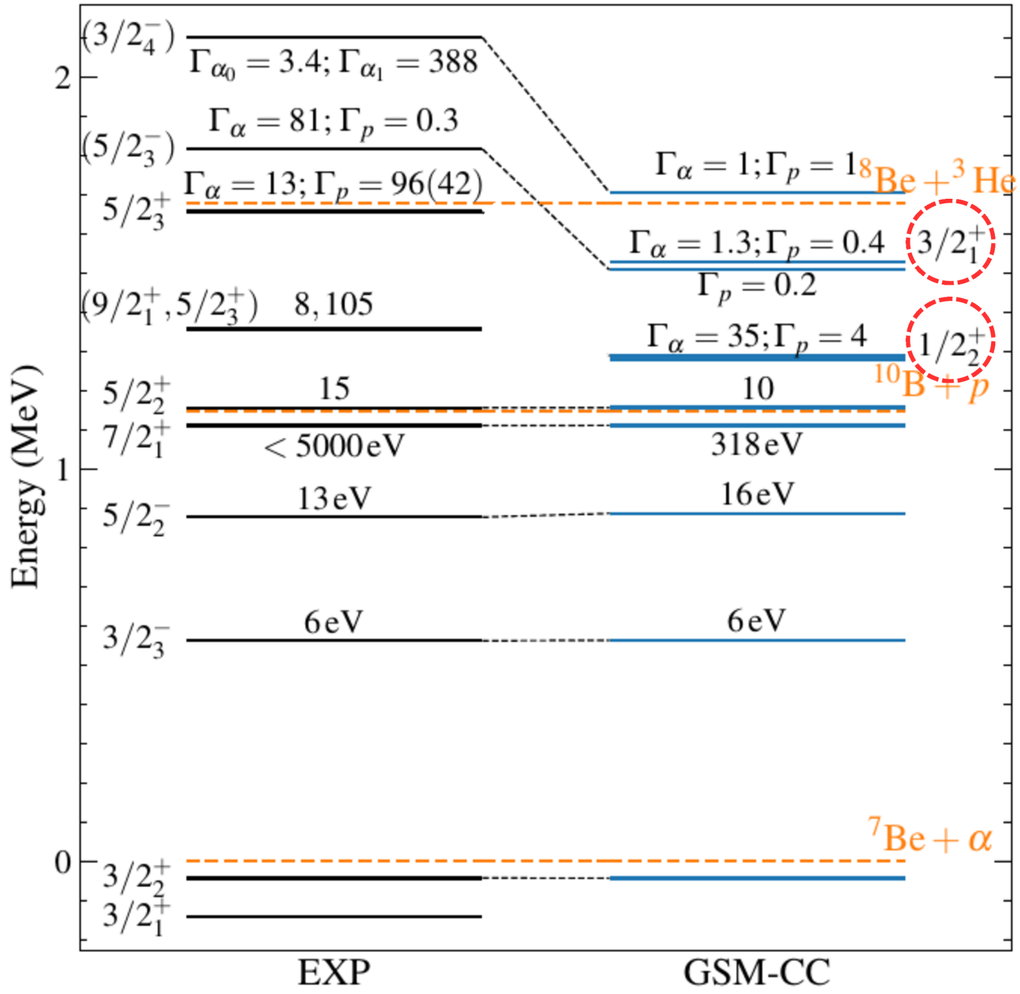
J. Görres, C. Rolfs, and A. Vlieks*
Institut für Kernphysik, Universitat Münster, Münster, Federal Republic of Germany

(Received 12 May 1983)

$$\Gamma^{7/2_1^+} < 5 \text{ keV}$$

ABOVE PROTON–THRESHOLD STATES



These states has been observed in the mirror system 11B.

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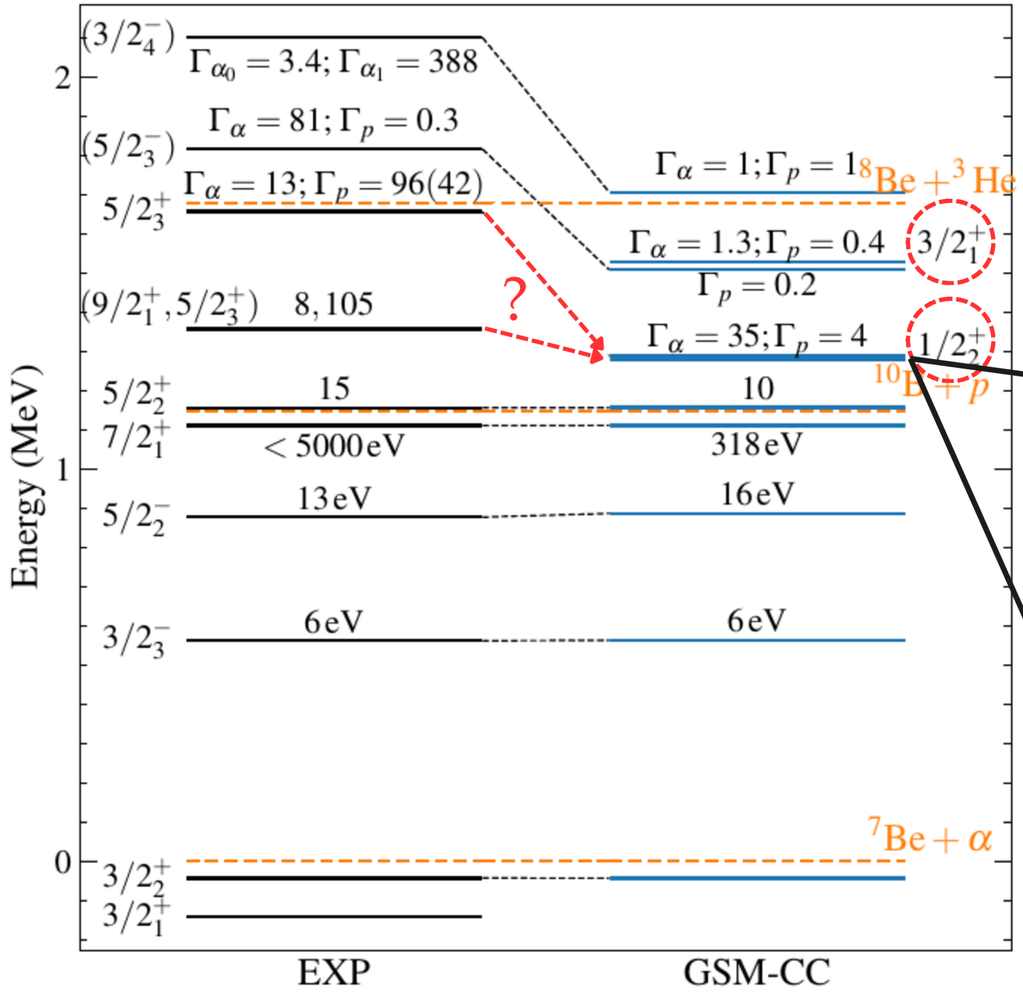

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PHYSICAL REVIEW C **95**, 044617 (2017)

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$$E(5/2_3^+) = 1.33 \text{ MeV}$$
$$\Gamma_\alpha^{5/2_3^+} = 105 \text{ keV}$$

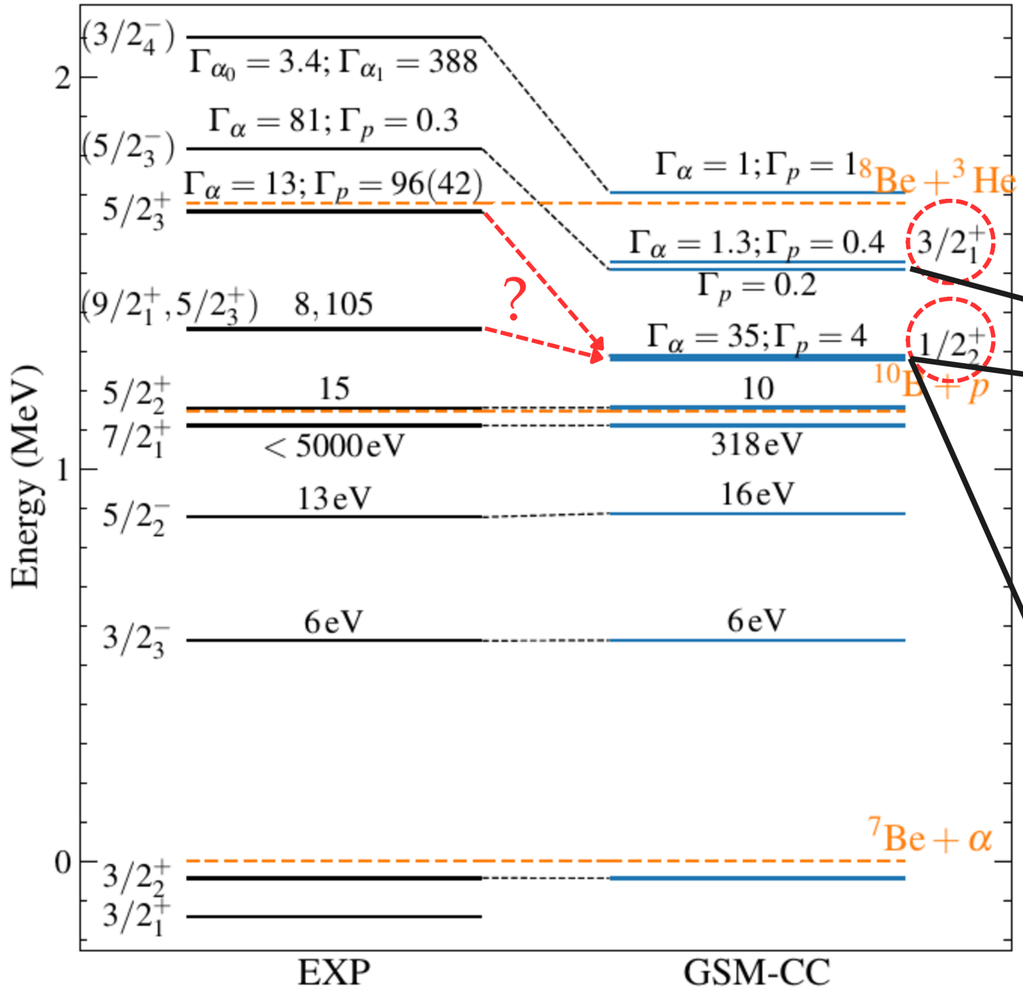
PHYSICAL REVIEW C **87**, 034303 (2013)

α-resonance structure in ^{11}C studied via resonant scattering of $^7\mathrm{Be} + \alpha$ and with the ^{7}Be(α, p) reaction

H. Yamaguchi (山口英斉)* and D. Kahl
Center for Nuclear Study, the University of Tokyo, RIKEN Campus, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

$$E(9/2_1^+) = 1.36 \text{ MeV}$$
$$\Gamma_\alpha^{9/2_1^+} = 8 \text{ keV}$$

ABOVE PROTON–THRESHOLD STATES



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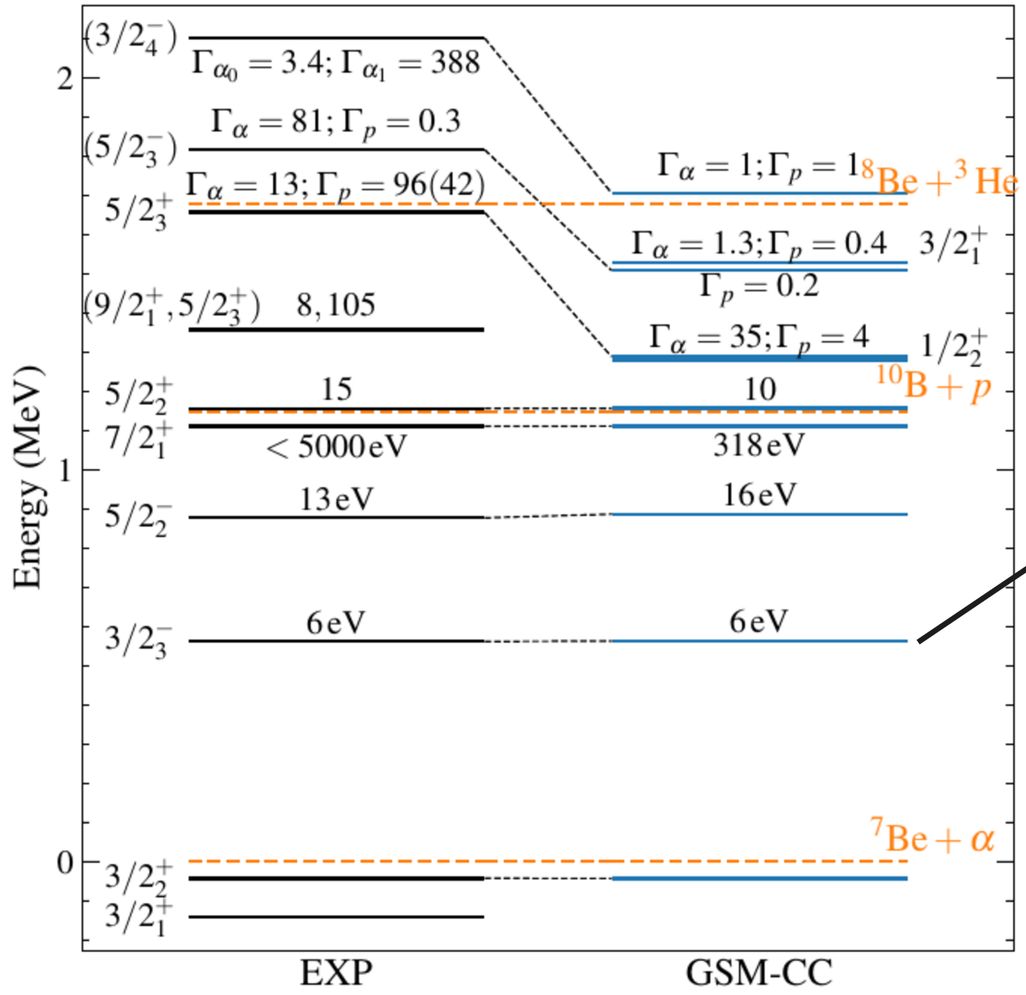
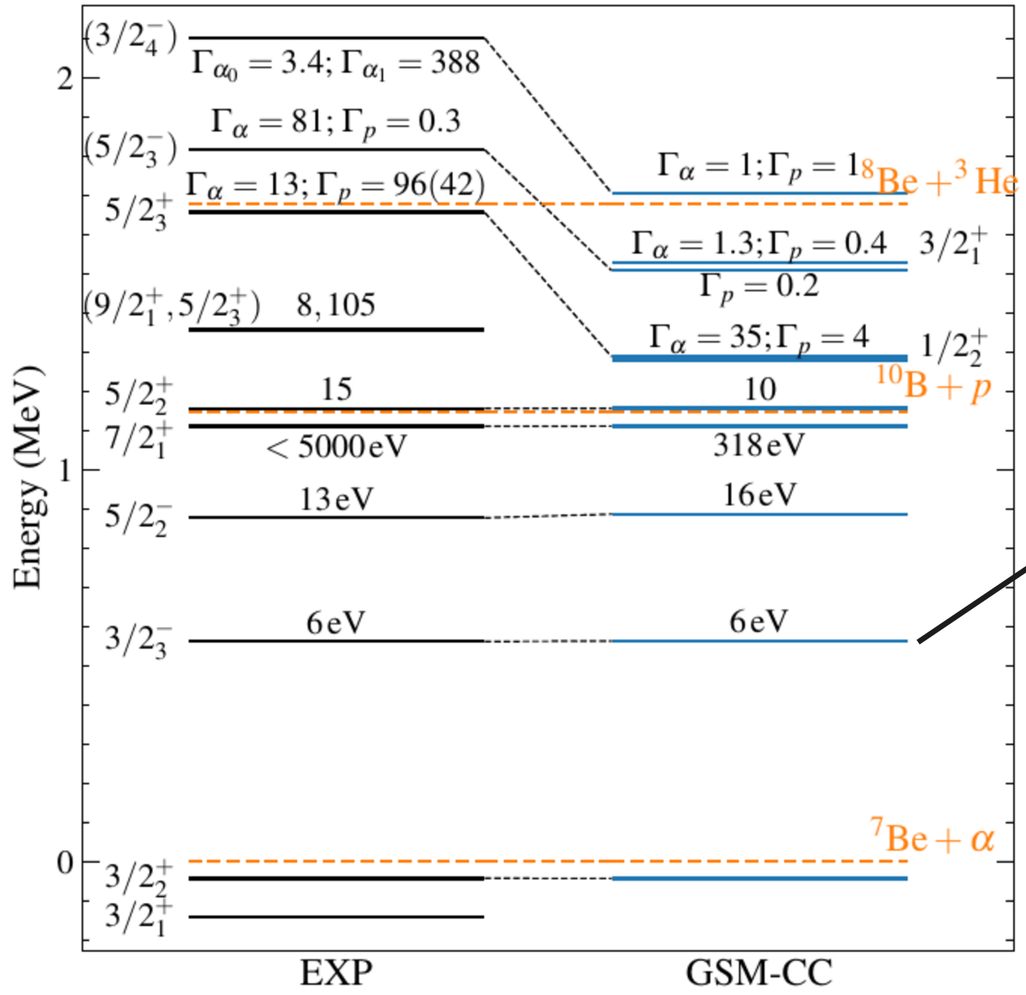
SPECTROSCOPIC FACTORS



$$\mathcal{S}_{L_{\rm cm},J_P} \propto \langle \Psi_A || A^\dagger_{L_{\rm cm},J_P} || \Psi_{A-k} \rangle$$

$\left[J^T \otimes j^p\right]$	SF
$\left[3_1^+ \otimes p_{3/2}\right]^{3/2_3^-}$	0.08
$\left[3/2_1^- \otimes D\right]^{3/2_3^-}$	0.01

SPECTROSCOPIC FACTORS



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$[3_1^+ \otimes p_{3/2}]^{3/2_3^-}$	0.08
$[3/2_1^- \otimes D]^{3/2_3^-}$	0.01

Proton Stripping Strengths for Levels of $^{11}C^\dagger$

J. R. Comfort,* H. T. Fortune,‡ J. V. Maher,§ and B. Zeidman
Argonne National Laboratory, Argonne, Illinois 60439
(Received 13 November 1970)

$$\mathrm{SF}_{p_{3/2}} = 0.07$$

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J. Görres, C. Rolfs, and A. Vlieks*
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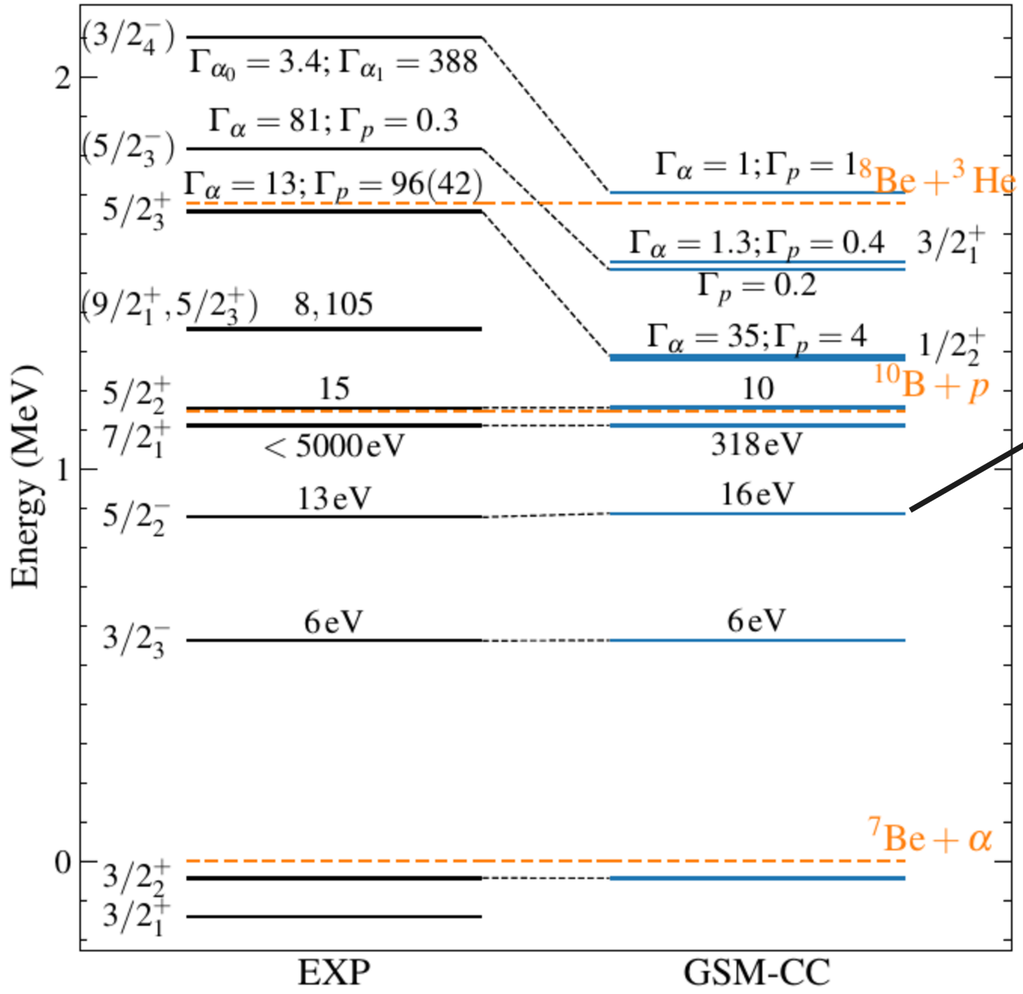
(Received 12 May 1983)

$$\mathrm{SF} < 0.05$$

SPECTROSCOPIC FACTORS



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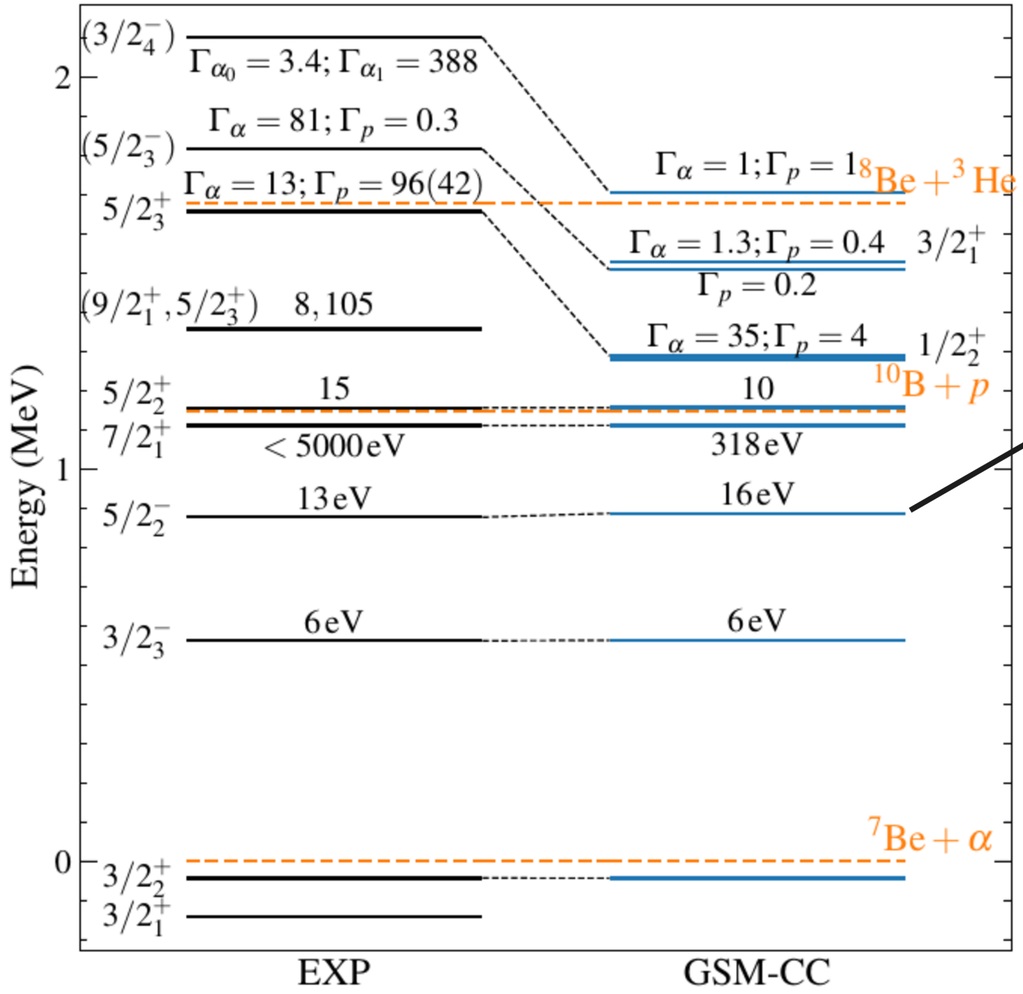
$\left[J^T \otimes j^p\right]$	SF
$\left[3_1^+ \otimes p_{3/2}\right]^{5/2_2^-}$	0.08
$\left[3_1^+ \otimes p_{1/2}\right]^{5/2_2^-}$	0.52

SPECTROSCOPIC FACTORS



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$$\mathrm{SF}_{p_{3/2}} = 0.73; \mathrm{SF}_{p_{1/2}} = 0.79$$

ELASTIC TRANSFER OF A $1p_{\frac{3}{2}}$ HOLE IN THE SCATTERING OF ^{12}C ON ^{11}B

W. BOHNE, C. K. GELBKE, P. BRAUN-MUNZINGER, W. GROCHULSKI†, H. L. HARNEY and H. OESCHLER
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

$$\mathrm{SF}_{p_{3/2}} = 0.46$$

^{11}C level structure via the $^{10}B(p,\gamma)$ reaction

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J. Görres, C. Rolfs, and A. Vlieks*
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(Received 12 May 1983)

$$\mathrm{SF} = 0.39(4)$$

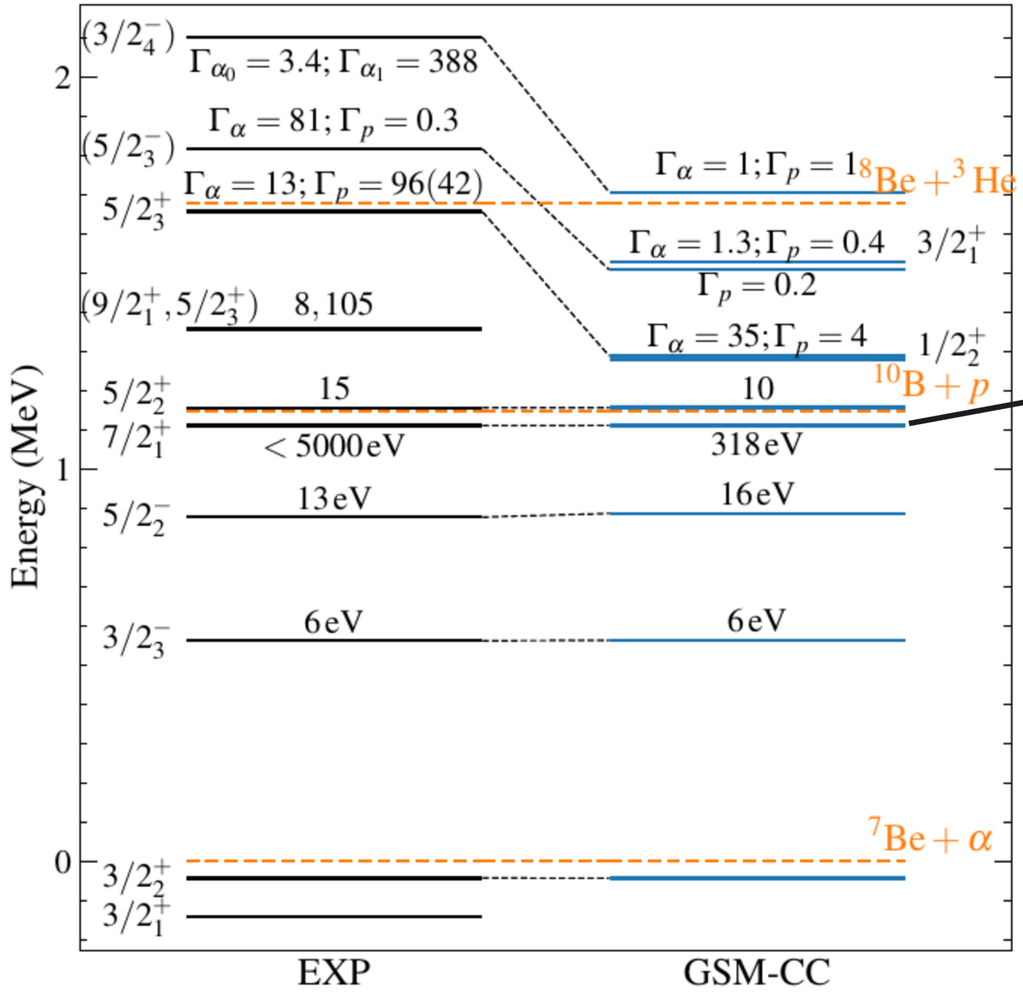
PHYSICAL REVIEW C **68**, 045803 (2003)

The $^{10}B(\vec{p},\gamma)^{11}C$ reaction at astrophysically relevant energies

A. P. Tonchev, S. O. Nelson, K. Sabourov, B. T. Crowley, K. Joshi, and H. R. Weller
Triangle Universities Nuclear Laboratory and Duke University, Durham, North Carolina 27708, USA

$$\mathrm{SF}_p = 0.42$$

SPECTROSCOPIC FACTORS



$$\mathcal{S}_{L_{\rm cm},J_P} \propto \langle \Psi_A || A^\dagger_{L_{\rm cm},J_P} || \Psi_{A-k} \rangle$$

$[J^T \otimes j^p]$	SF
$[3^+_1 \otimes s_{1/2}]^{7/2^+_1}$	0.74
$[3^+_1 \otimes d_{5/2}]^{7/2^+_1}$	0.01

Proton Stripping Strengths for Levels of $^{11}C^\dagger$

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(Received 13 November 1970)

$$\mathrm{SF}_{s_{1/2}} < 0.35; \mathrm{SF}_{d_{5/2}} = 0.41$$

^{11}C level structure via the ^{10}B(p,γ) reaction

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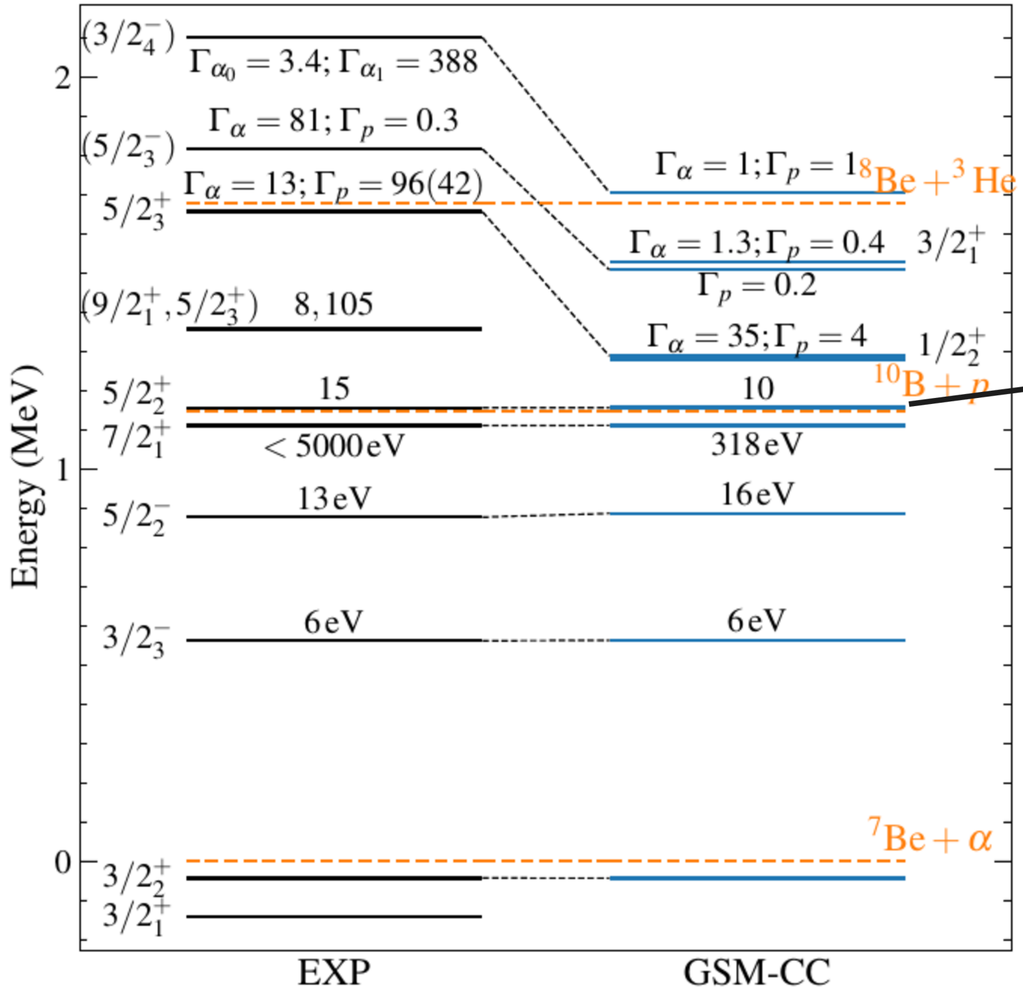
(Received 12 May 1983)

$$\mathrm{SF} = 0.26(3)$$

SPECTROSCOPIC FACTORS



$$\mathcal{S}_{L_{\mathrm{cm}},J_P} \propto \left\langle \Psi_A \middle|\middle| A^\dagger_{L_{\mathrm{cm}},J_P} \middle|\middle| \Psi_{A-k} \right\rangle$$

$\left[J^T \otimes j^p\right]$	SF
$\left[3_1^+ \otimes s_{1/2}\right]^{5/2_2^+}$	0.18
$\left[3_1^+ \otimes d_{5/2}\right]^{5/2_2^+}$	0.01

Proton Stripping Strengths for Levels of $^{11}C^\dagger$

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$$\mathrm{SF} < 0.8$$

^{11}C level structure via the ^{10}B(p,γ) reaction

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$$\mathrm{SF} = 0.31(3)$$

CONCLUSION AND PERSPECTIVES

- GSM-CC has demonstrated its capabilty to describe the structure of $^{11}\mathrm{C}$, and the partial widths and spectroscopic factors of near thresholds resonances.
- The state 5/2+(3) has an energy E=-8.8 MeV, in agreement with the R-matrix fit of M. Wiescher et al., Phys. Rev. C 95, 044617 (2017).
- SF of positive parity states around the p-threshold indicates that the poisoning reaction $^{10}\mathrm{B}(p,\alpha)^{7}\mathrm{Be}$ might not be as important as the $^{10}\mathrm{B}(p,\gamma)^{11}\mathrm{C}$ reaction at low energy.
- The future calculations of the (α,γ), (p,γ) and (p,α) cross sections are expected to confirm the conclusions of this study
- Future applications on triton-induced reactions such as $^{6,7}\mathrm{Li}(t,n)^{7,8}\mathrm{B}$ could help us to understand the impact of tritium in the early universe environments.

THANK YOU