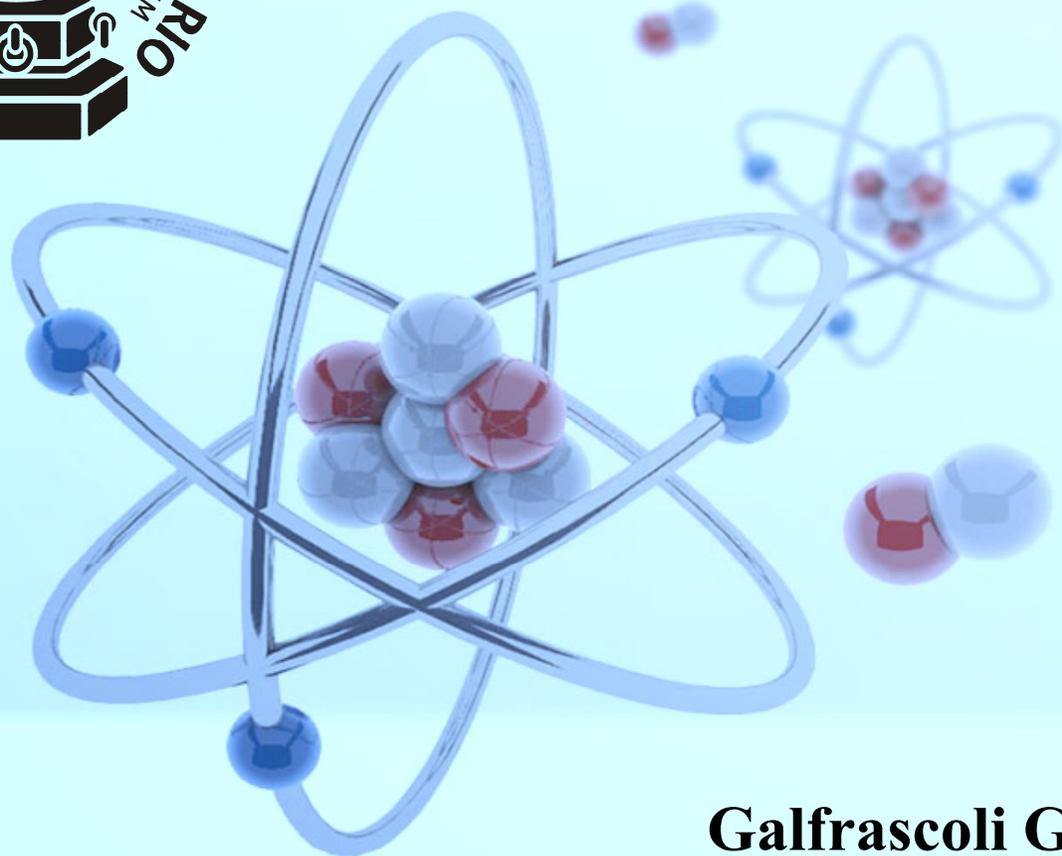


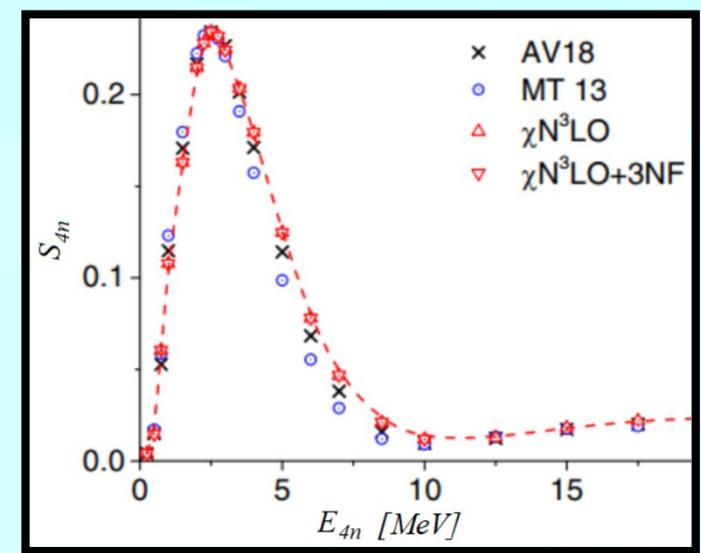
Estructuras de baja energía en reacciones con ^4n en el estado final



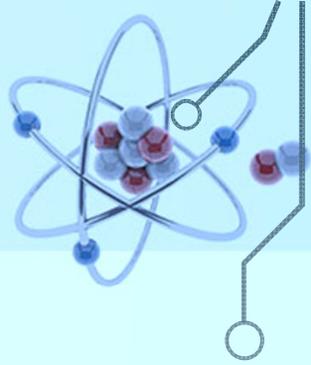
Sobre la existencia de estructuras neutrónicas de baja energía.
Desafiando la comprensión teórica de las fuerzas nucleares.

Galfrascoli Gabriel Mateo
mateo_galfrascoli10@hotmail.com

20/12/2023



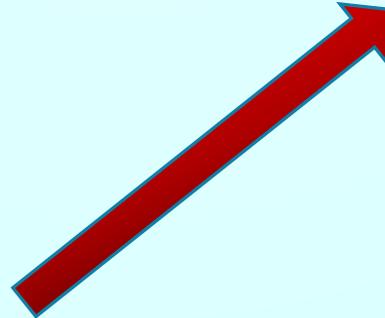
Índice



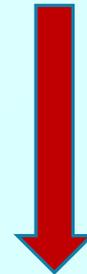
1) Introducción
1.1) Preliminares
1.2) Estados ligados y resonancia



2) Estudios teóricos
2.1) Disyuntivas

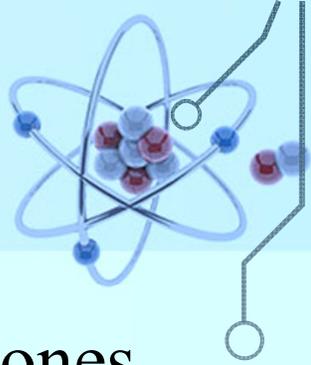


3) Experimento en RIKEN y observación directa



4) Modelo realista de reacción por Lazauskas, Hiyama y Carbonell.

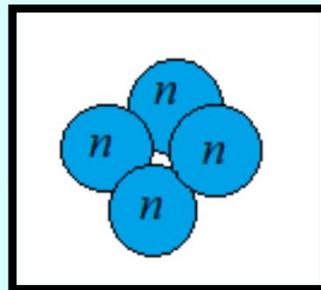
Introducción



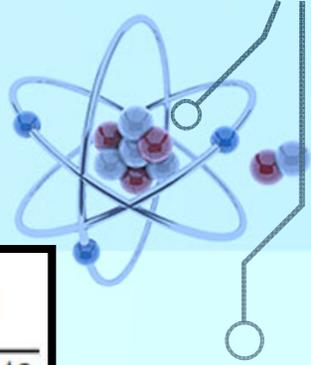
- **Incógnita:** existencia de sistemas nucleares hechos solo de neutrones.



- **Reto:** búsqueda experimental de sistemas multineutrónicos aislados.



Introducción



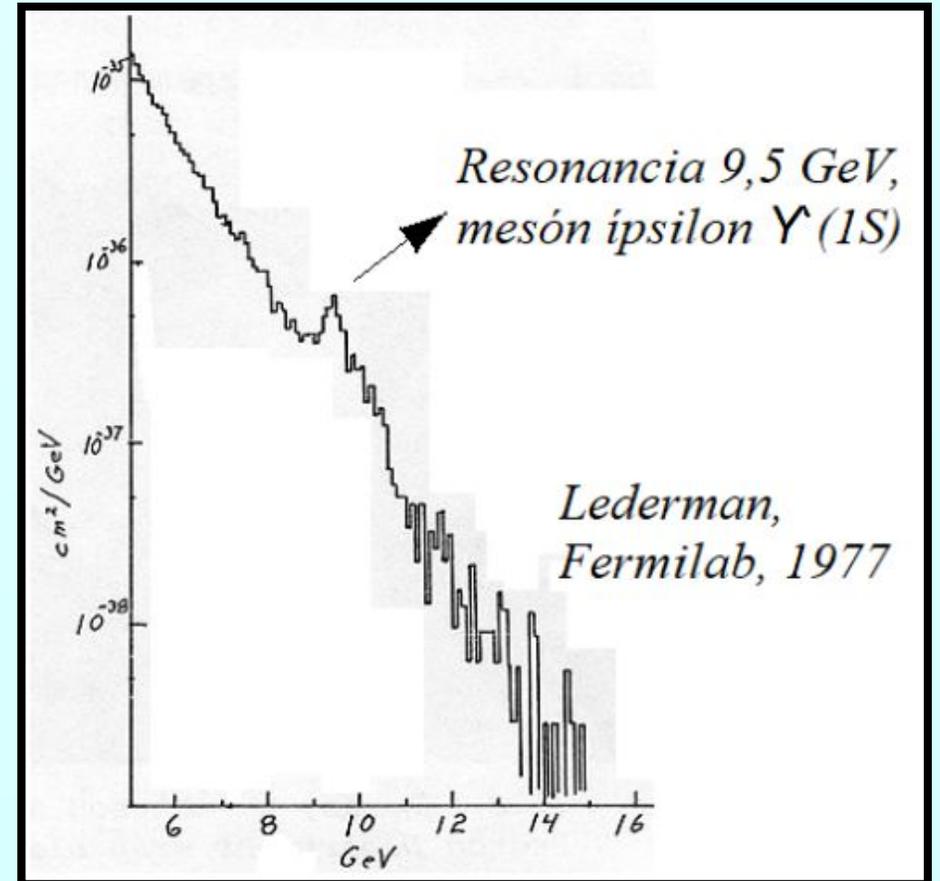
Fórmula de **Weizsäcker**:

$$B(0, A) = a_v A - a_s A^{2/3} + a_p \frac{1 + (-1)^N}{2} \frac{1}{A^{1/2}}$$

Resonancias: pico situado alrededor de cierto valor de energía E_R localizado en las secciones eficaces diferenciales $\sigma(\theta)$.

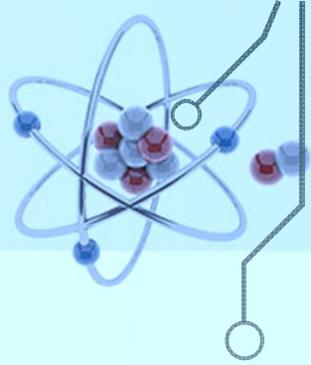
$$E = E_R - i \frac{\Gamma}{2}$$

$$T_{1/2} = \frac{\hbar}{\Gamma} \ln 2$$



Representación de **Berggren**...

Introducción

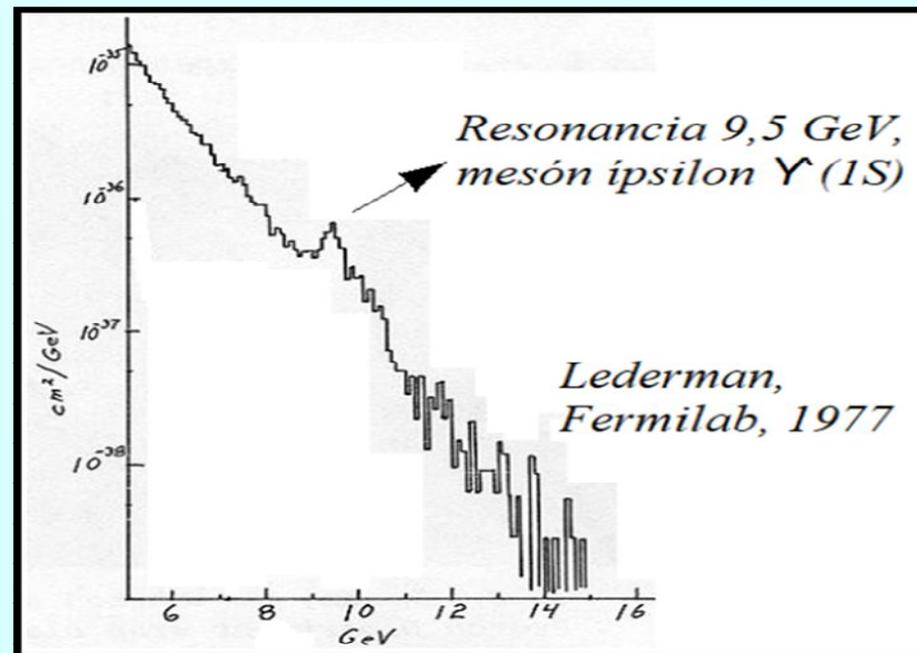


Recordemos...

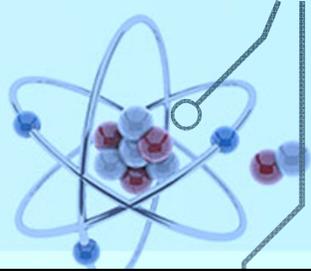
$$\sigma = \int_{\Omega} \sigma(\theta) d\Omega = \frac{4\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) \sin^2 \delta_l = \sum_{l=0}^{\infty} \sigma_l$$

Se puede demostrar...

$$\sigma_l = \frac{4\pi}{k^2} (2l+1) \sin^2 \delta_l = \frac{4\pi}{k^2} (2l+1) \frac{\Gamma^2}{4(E - E_R)^2 + \Gamma^2}$$



Introducción

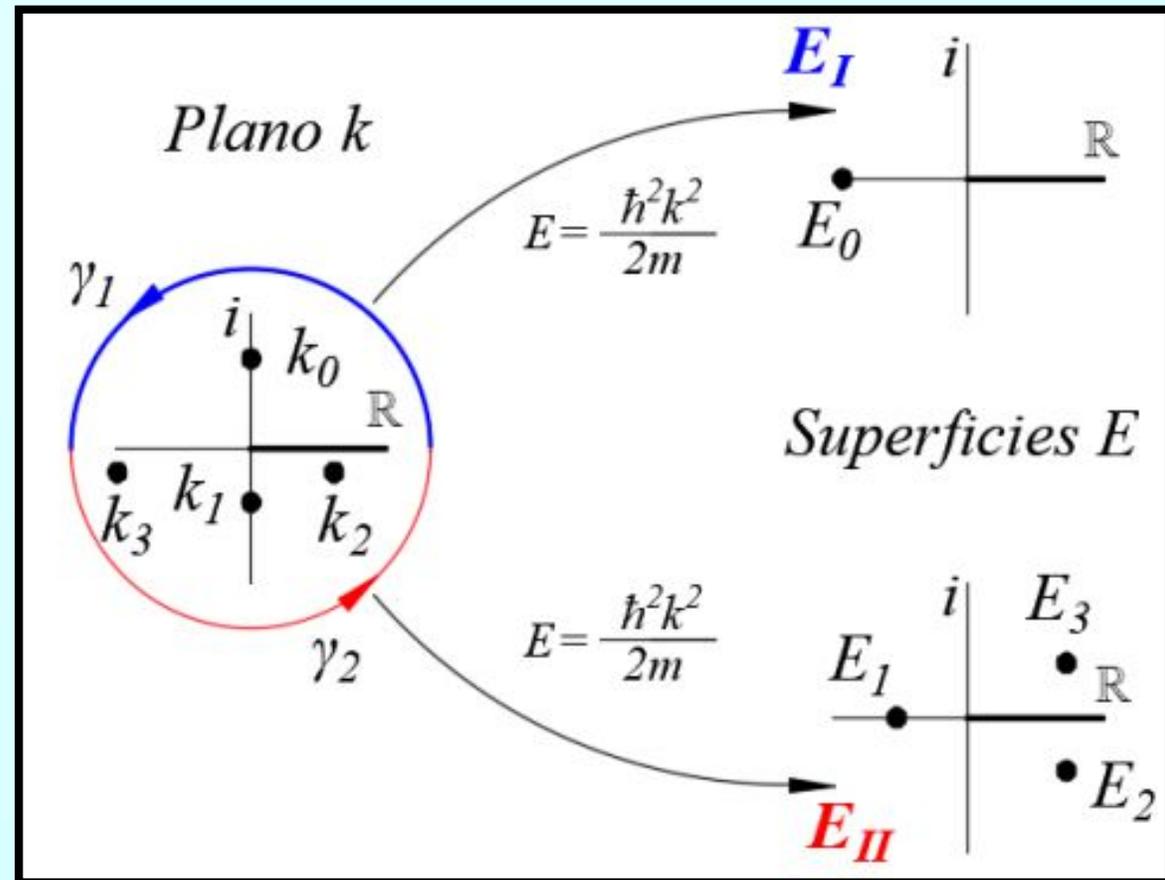


$$\left[-\frac{d^2}{dr^2} + \frac{l(l+1)}{r^2} + \frac{2\mu}{\hbar^2}V(r) - k^2 \right] u_l(r) = 0$$

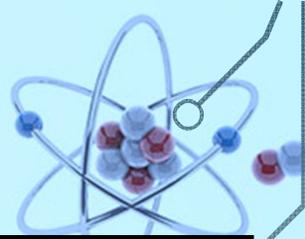
$$k_n \equiv \kappa_n - i\gamma_n$$

$$E = E_R - i\frac{\Gamma}{2}$$

- Estados ligados: k_0
- Estados antiligados: k_1
- Resonancias Gamow: k_2
- Antiresonancias: k_3



Estudios teóricos



Se suele proponer **interacciones** V_{ij} más bien **fenomenológicas** (realistas) basadas en interacciones fundamentales.

Difícil encontrar soluciones. Consenso en **descartar** estados **ligados**.

The NN potential is written as a sum of an electromagnetic (EM) part, a one-pion-exchange (OPE) part, and an intermediate- and short-range phenomenological part:

$$v(NN) = v^{EM}(NN) + v^{\pi}(NN) + v^R(NN) . \quad (2)$$

The EM interaction is the same as that used in the Nijmegen partial-wave analysis, with the addition of short-range terms and finite-size effects [17,18,19]. (Values for the masses and other physical constants used in the following formulae are given in Table I.) For pp scattering we include one- and two-photon Coulomb terms, the Darwin-Foldy term, vacuum polarization, and the magnetic moment interaction, each with an appropriate form factor:

$$v^{EM}(pp) = V_{C1}(pp) + V_{C2} + V_{DF} + V_{VP} + V_{MM}(pp) . \quad (3)$$

Here

$$V_{C1}(pp) = \alpha' \frac{F_C(r)}{r} , \quad (4)$$

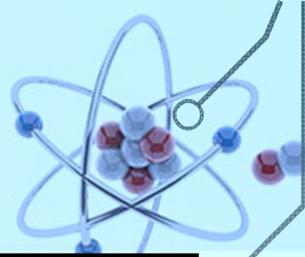
$$V_{C2} = -\frac{\alpha}{2M_p^2} \left[(\nabla^2 + k^2) \frac{F_C(r)}{r} + \frac{F_C(r)}{r} (\nabla^2 + k^2) \right] \approx -\frac{\alpha\alpha'}{M_p} \left[\frac{F_C(r)}{r} \right]^2 , \quad (5)$$

$$V_{DF} = -\frac{\alpha}{4M_p^2} F_{\delta}(r) , \quad (6)$$

$$V_{VP} = \frac{2\alpha\alpha'}{3\pi} \frac{F_C(r)}{r} \int_1^{\infty} dx e^{-2m_e r x} \left[1 + \frac{1}{2x^2} \right] \frac{(x^2 - 1)^{1/2}}{x^2} , \quad (7)$$

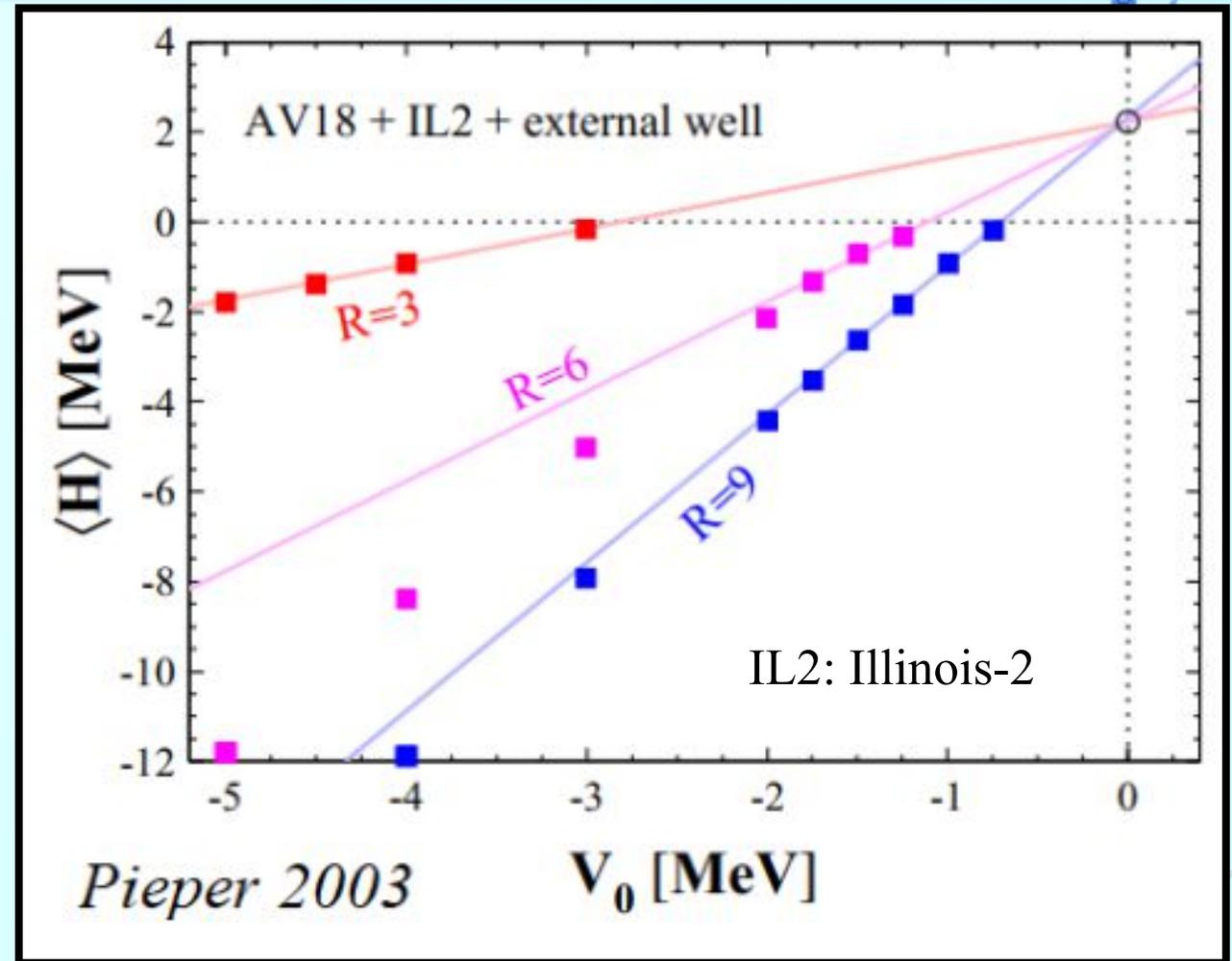
$$V_{MM}(pp) = -\frac{\alpha}{4M_p^2} \mu_p^2 \left[\frac{2}{3} F_{\delta}(r) \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j + \frac{F_t(r)}{r^3} S_{ij} \right] - \frac{\alpha}{2M_p^2} (4\mu_p - 1) \frac{F_{ls}(r)}{r^3} \mathbf{L} \cdot \mathbf{S} . \quad (8)$$

Estudios teóricos



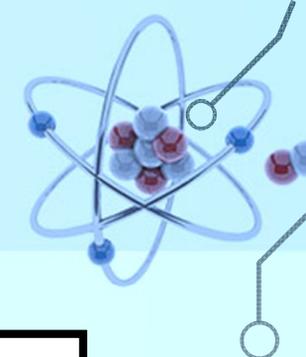
“A mano” puedo encontrar estados ligados, agregando alguna trampa de confinamiento $V_0 V_T(\mathbf{r}_i)$.

Como pozo externo usó un potencial Wood-Saxon $V(V_0, R, a)$, con $a = 0,65\text{fm}$.

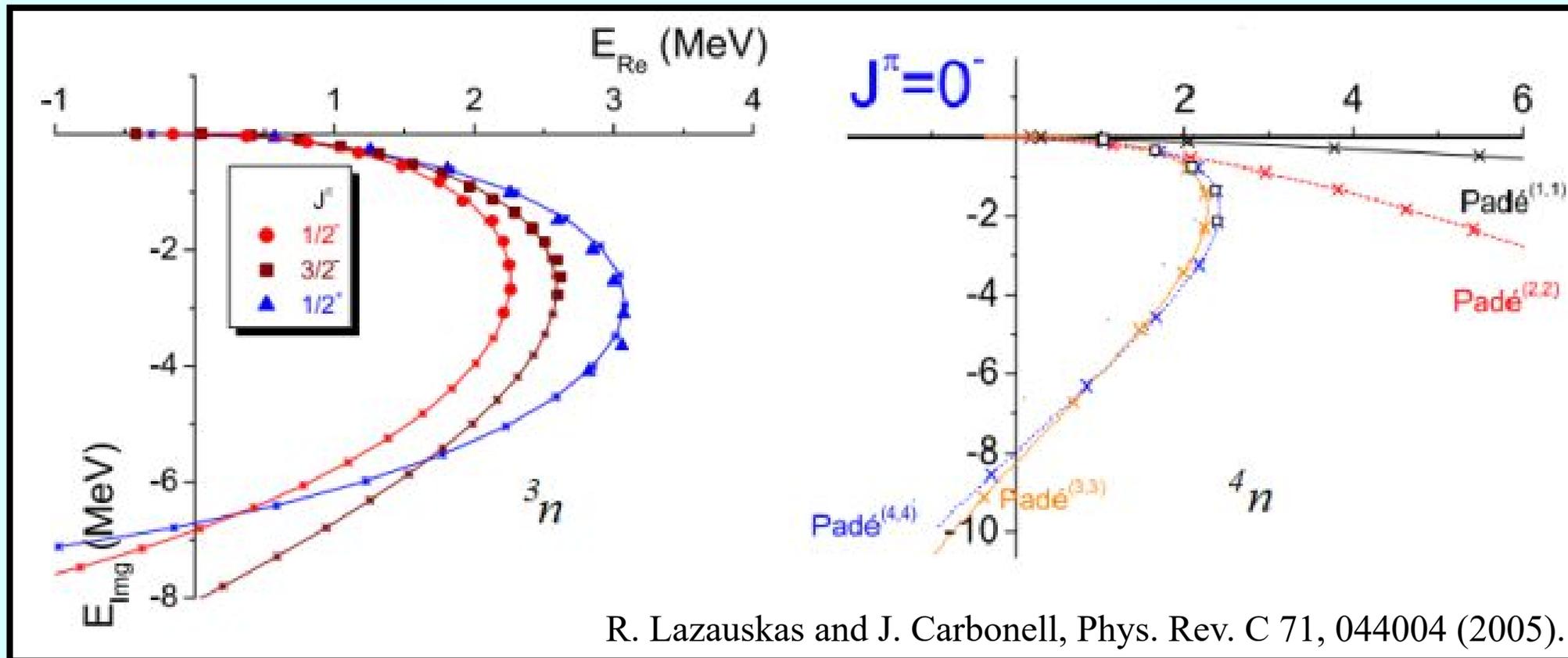


S.C. Pieper, Phys. Rev. Lett. 90, 252501 (2003)

Estudios teóricos



Interacción Reid93, ecuaciones Faddeev-Yakubovsky.



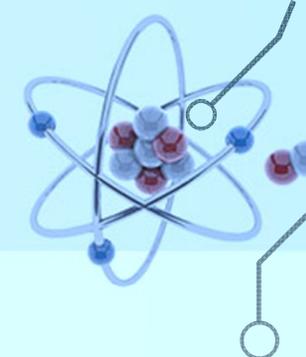
R. Lazauskas and J. Carbonell, Phys. Rev. C 71, 044004 (2005).

Padé (N, M) : $k(\lambda) = i \frac{\sum_{j=0}^N c_j z^j}{1 + \sum_{j=1}^M d_j z^j}$

$$z = \sqrt{\lambda - \lambda_c}$$

$E(\lambda)$ av. de $H_\lambda = H + \lambda W$

Estudios teóricos



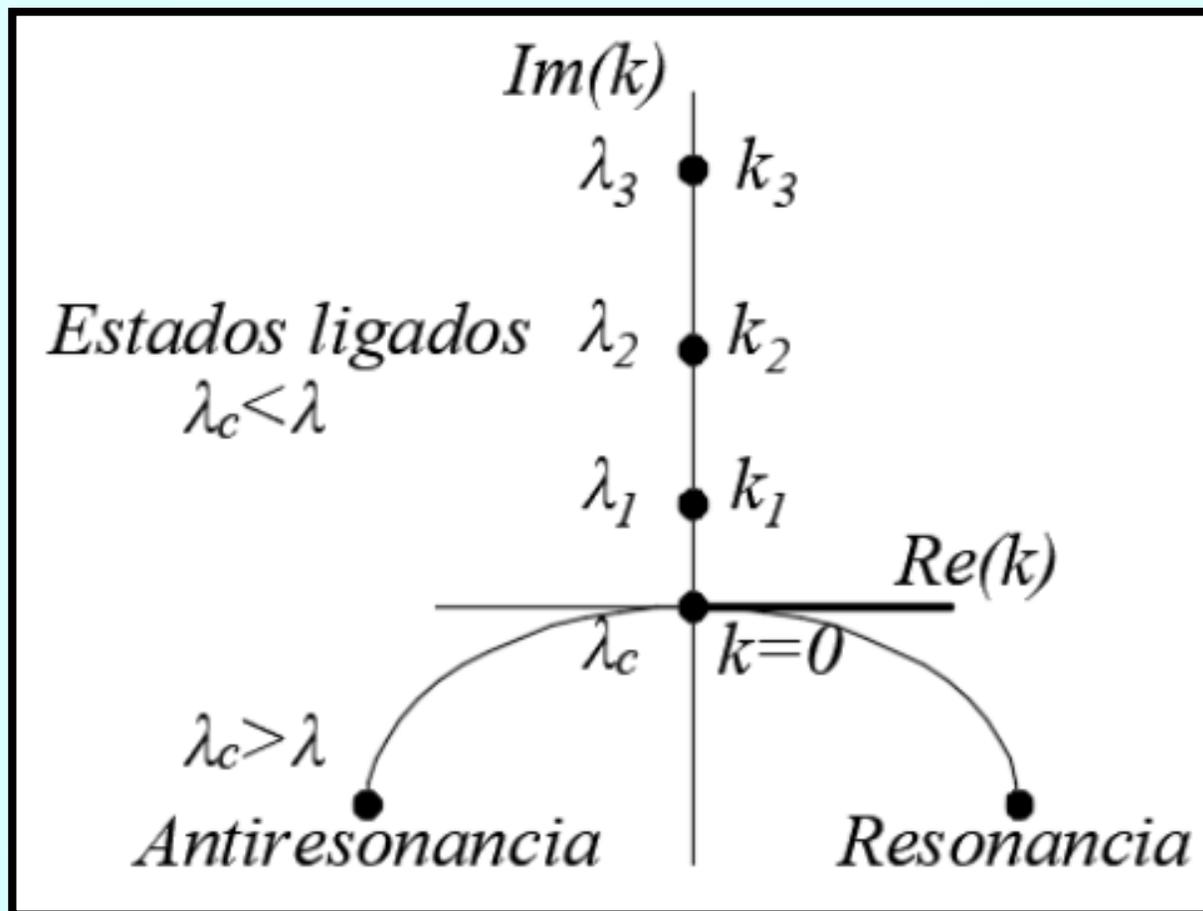
Padé (N, M) :

$$k(\lambda) = i \frac{\sum_{j=0}^N c_j z^j}{1 + \sum_{j=1}^M d_j z^j}$$

$$z = \sqrt{\lambda - \lambda_c}$$

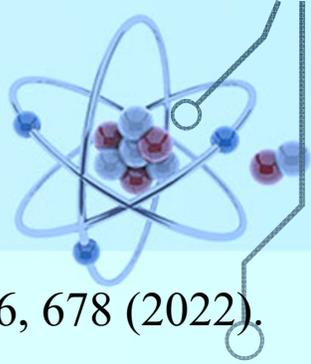
$E(\lambda)$ av. de:

$$H_\lambda = H + \lambda W$$

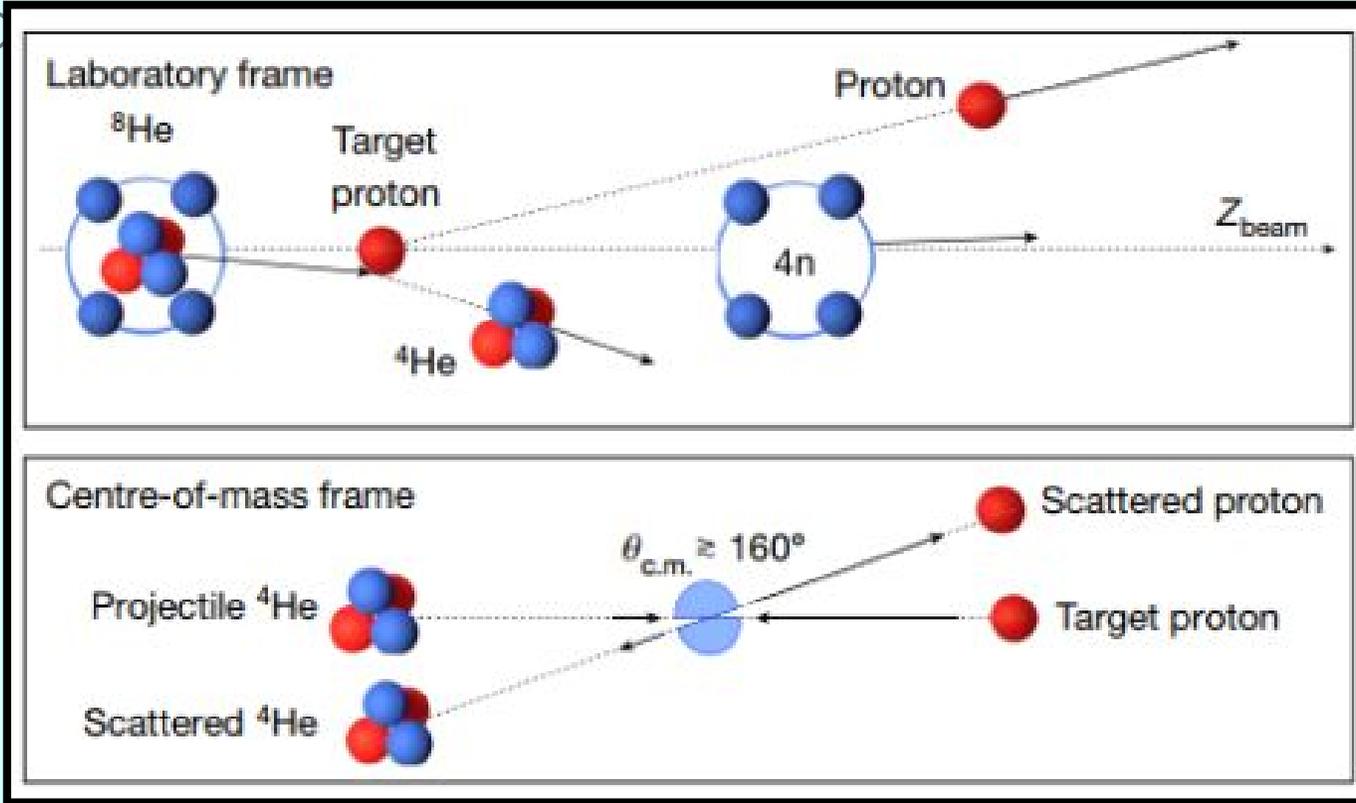


$\lambda \rightarrow 0 ?$

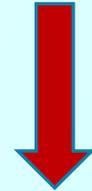
Experimento en RIKEN



M. Duer et al., Nature (London) 606, 678 (2022).



$$E_{4n} = \sqrt{E_{\text{miss}}^2 - p_{\text{miss}}^2 c^2} - 4m_n c^2$$

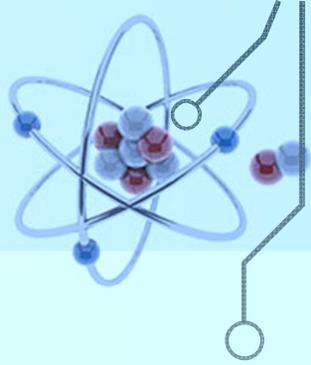


- $E_{4n} > 0$ resonancia
- $E_{4n} < 0$ ligado

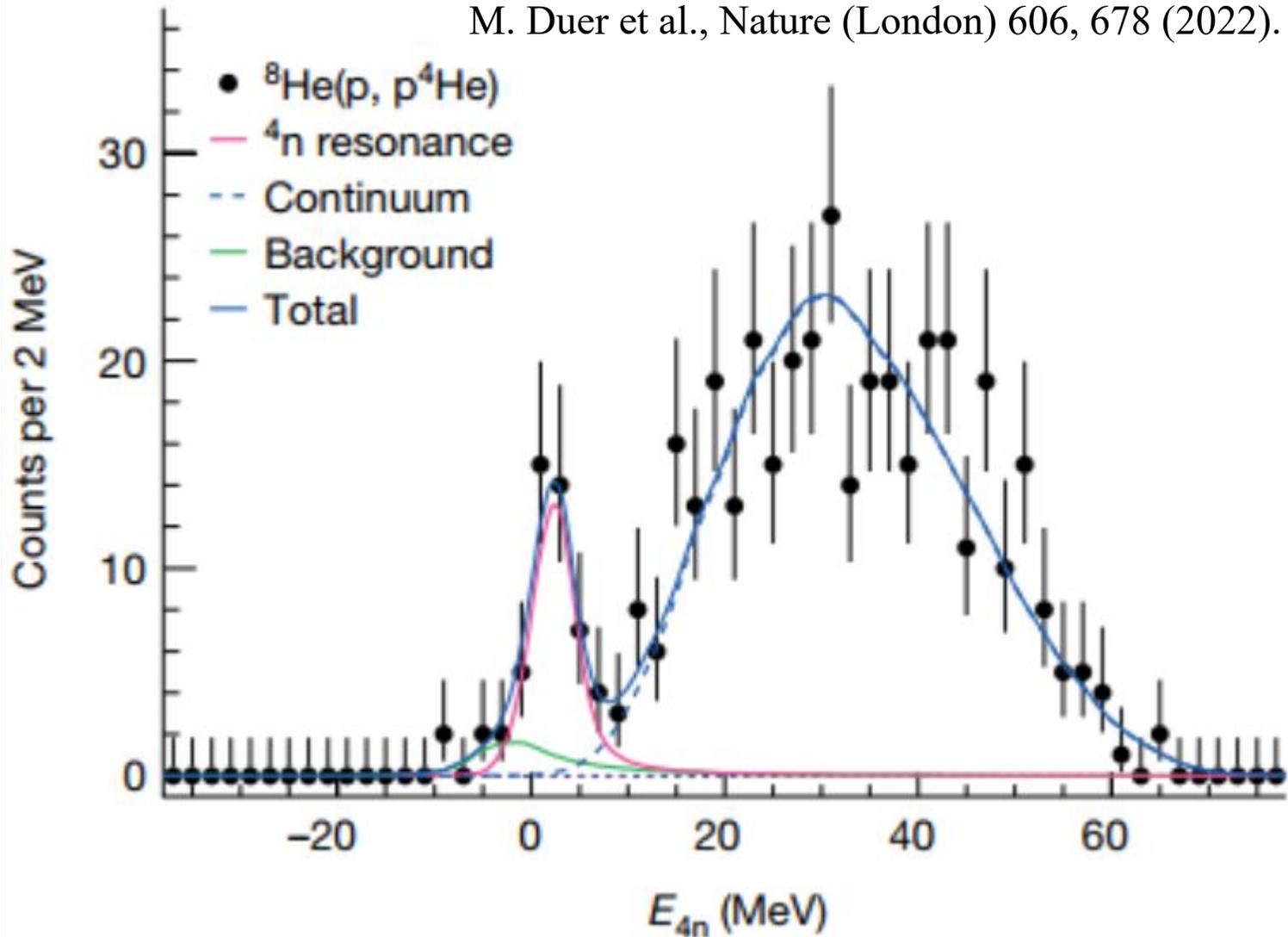
$$E^2 = m^2 c^4 + p^2 c^2, \quad E = \gamma m c^2, \quad \mathbf{P} = \left(\frac{E}{c}, \mathbf{p} \right) = \left(\frac{E}{c}, \gamma m \mathbf{v} \right)$$

$$\mathbf{P}_{\text{miss}} = \mathbf{P}_{^8\text{He}} + \mathbf{P}_{\text{p(tgt)}} - \mathbf{P}_{^4\text{He}} - \mathbf{P}_{\text{p}}$$

Experimento en RIKEN



M. Duer et al., Nature (London) 606, 678 (2022).



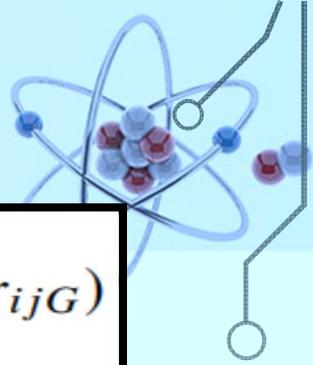
$$P_R = 18,7 \pm 2,3 \%$$

$$E_R = 2,37 \pm 0,38(\text{estad.}) \pm 0,44(\text{sis.}) \text{ MeV}$$

$$\Gamma = 1,75 \pm 0,22(\text{estad.}) \pm 0,30(\text{sis.}) \text{ MeV}$$

Modelo propuesto

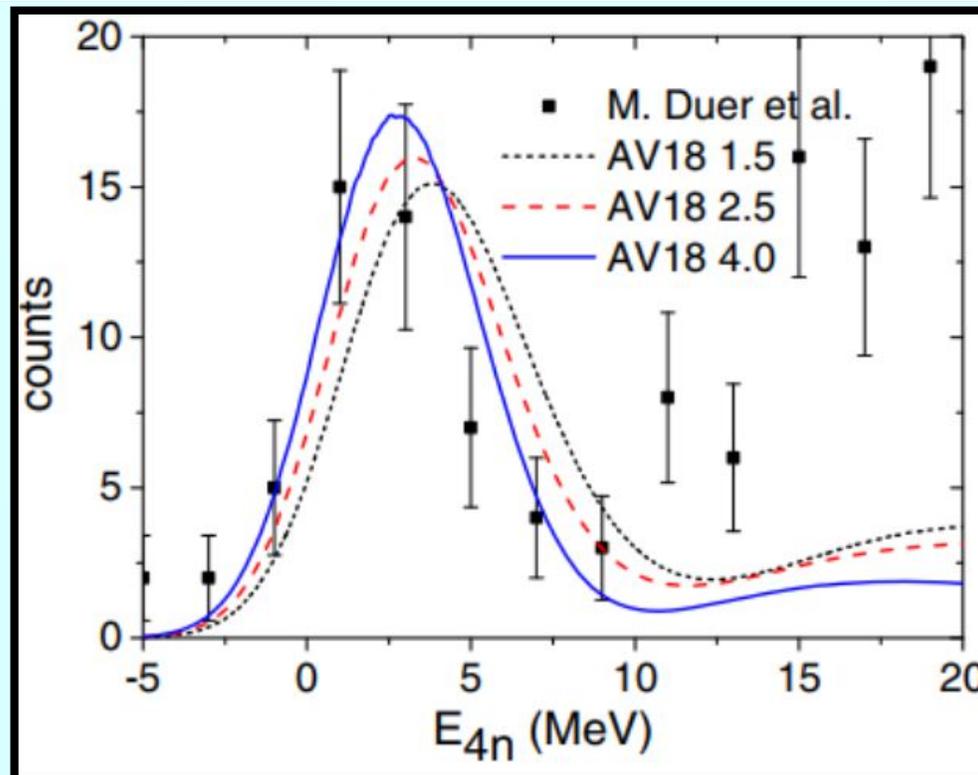
Lazauskas, R., Hiyama, E., Carbonell J., Physical Review Letters 130, 102501 (marzo de 2023).



$$H_i = H_0 + \lambda \sum_{i=1}^4 |\psi_\alpha(r_i)\rangle \langle \psi_\alpha(r_i)| + \sum_{i<j=1}^4 V_{nn}(r_{ij}) + \sum_{i=1}^4 V(r_{iG}) + \sum_{i<j=1}^4 W_{ij}(\rho, r_{ijG})$$

$$r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|, \quad r_{ijG} = |(\mathbf{r}_i + \mathbf{r}_j)/2 - \mathbf{r}_G|$$

$$V(r_{iG}) = V_0 e^{-(r_{iG}/\rho_0)^2}, \quad W_{ijG}(\rho, r_{ijG}) = r_{ijG} W_0 e^{-(\rho/\rho_0)^2}, \quad \rho^2 = \frac{1}{16} r_{ij}^2 + \frac{1}{2} r_{ijG}^2$$



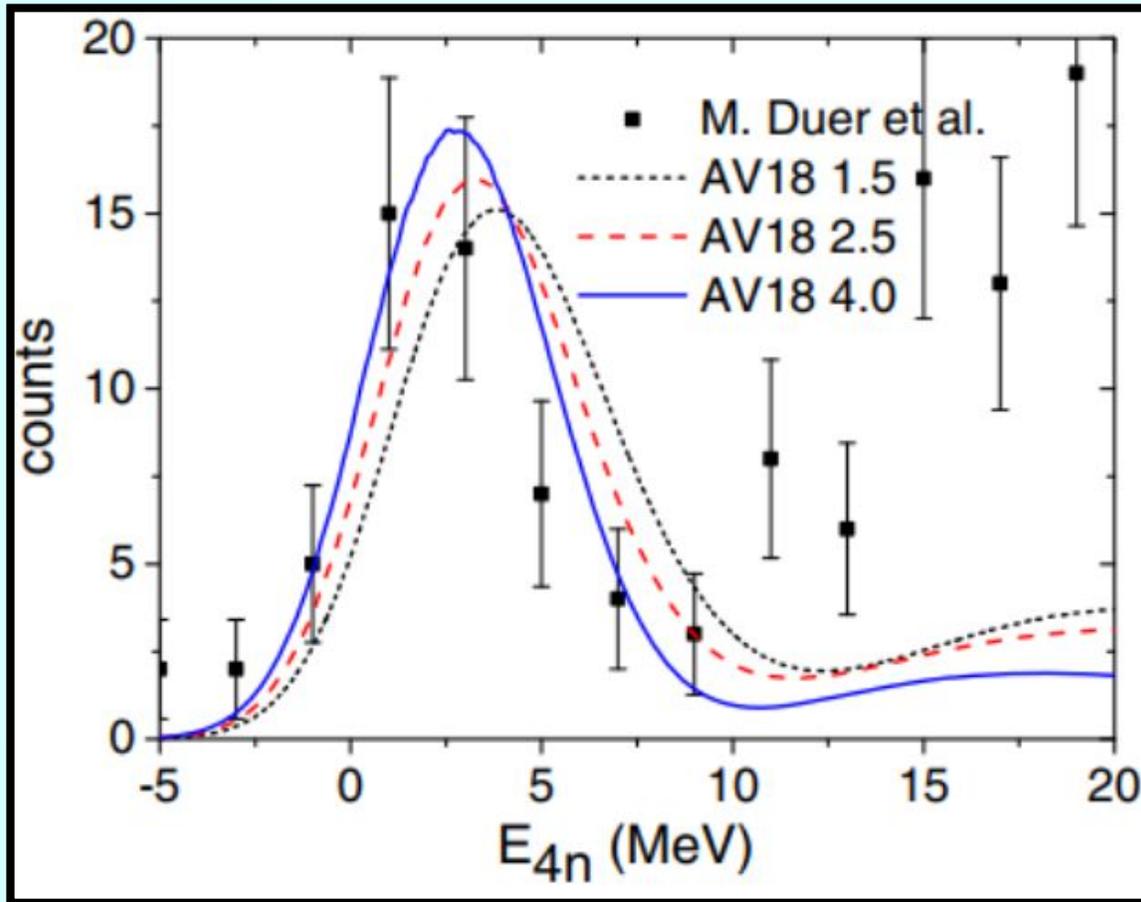
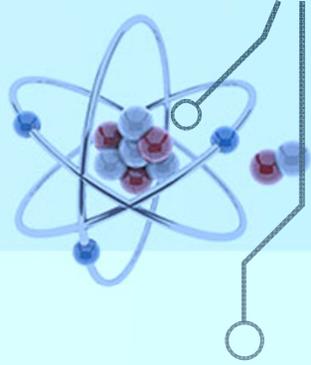
Interacciones V_{nn} AV18 para distintos valores ρ_0 . El valor 4fm aproxima mejor al experimento.

OMG!



Modelo propuesto

Lazauskas, R., Hiyama, E., Carbonell J., Physical Review Letters 130, 102501 (marzo de 2023).



Ellos solo reportan $E_{4n} \approx 2,5\text{MeV}$



Logró reconocimiento la existencia de un estado resonante 4n agregando comprensión a los sistemas neutrónicos y abriendo paso a nuevos estudios.

Gracias...

