Ab initial calculation of the Hoyle state

Xingze Mao

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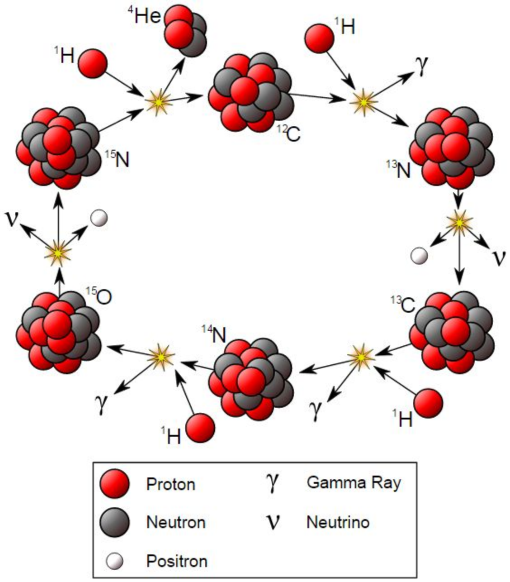
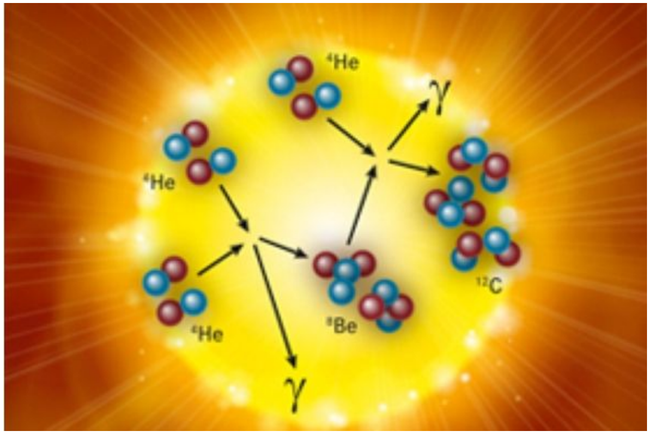
Hoyle state

Carbon-Nitrogen-Oxygen (CNO) cycle:



From Wikipedia

Triple alpha reaction:



Courtesy of Forschungszentrum Jülich GmbH

However, **without additional help** this triple alpha reaction is highly **suppressed** at stellar temperatures.

In order to enhance the fusion of third alpha particle, Hoyle[1] postultated a new excited state of ^{12}C, a spinless even-parity resonance very near 8Be-alpha threshold. Three years later, the state was found at Caltech[2,3]

Theory and method

1)Effective field theory (EFT) is an organizational tool to construct the interactions of particles as a systematic expansion in powers of particle momenta. Chiral EFT provides a systematic hierarchy ot the forces among protons and neutrons

2) Lattice effective field theory: Space is discretized as a periodic cubic lattice with spacing **a** and length **L** (≈10fm). The time step is $\mathbf{a_t}$ with total propagation time $\mathbf{L_t}$.

E. Epelbaum *et al.,* Phys. Rev. Lett. 104,142501 (2010)

Results

Q: is typical momentum of particles, (≈pion mass * light speed)
LO: leading order approximation
NLO: next-to-Leading order
NNLO: next-to-next-to-leading order

TABLE I. Lattice results for the ground state energies for ^{4}He, ^{8}Be, and ^{12}C. For comparison we also exhibit the experimentally observed energies. All energies are in units of MeV.

	^{4}He	^{8}Be	^{12}C
LO [$O(Q^0)$]	−24.8(2)	−60.9(7)	−110(2)
NLO [$O(Q^2)$]	−24.7(2)	−60(2)	−93(3)
IB + EM [$O(Q^2)$]	−23.8(2)	−55(2)	−85(3)
NNLO [$O(Q^3)$]	−28.4(3)	−58(2)	−91(3)
Experiment	−28.30	−56.50	−92.16

E. Epelbaum *et al.,* Phys. Rev. Lett. 104,142501 (2010)

Results

J_n^{π} : J is total spin, π is parity, labels the excitation

starting from 1 for the lowest level

TABLE II. Lattice results for the low-lying excited states of ^{12}C. For comparison the experimentally observed energies are shown. All energies are in units of MeV.

	0_2^+	$2_1^+, J_z = 0$	$2_1^+, J_z = 2$
LO $[O(Q^0)]$	$-94(2)$	$-92(2)$	$-89(2)$
NLO $[O(Q^2)]$	$-82(3)$	$-87(3)$	$-85(3)$
IB + EM $[O(Q^2)]$	$-74(3)$	$-80(3)$	$-78(3)$
NNLO $[O(Q^3)]$	$-85(3)$	$-88(3)$	$-90(4)$
Experiment	-84.51	-87.72	

E. Epelbaum *et al.,* Phys. Rev. Lett. 104,142501 (2010)

Conclusion

In addition to the ground state and excited spin-2 state, a resonance at -85(3) MeV with all of the properties of the Hoyle state is found, and it is in agreement with the experimentally observed energy.

Ref:[1] F.Hoyle, Astrophys. J. Suppl. Ser. **1,** 121 (1954).
[2] D. N. F. Dunbar *et al.*, Phys. Rev. **92**, 649 (1953).
[3] C. W. Cook, *et al.*, Phys. Rev. **107**, 508 (1957).

Thank you