INVESTIGATIONS OF THE BASIC DOUBLE-PIONIC FUSION IN THE REGION OF THE ABC EFFECT*

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In this contribution, we deal with the fusion to the light nuclei ^{2}H, ^{3}He and ^{4}He. However, different from the conventional fusion processes in the primordial nucleosynthesis and those taking place in star burning, we invstigate here the fusion process to light nuclei in the case that two pions are produced associatedly. In such cases, the peculiar so-called ABC effect was already observed more than fifty years ago. New exclusive and kinematically complete measurements with the WASA detector reveal this ominous effect to be correlated with a narrow resonance in the *pn* system constituting the first solid evidence for the existence of resonances in the system of two baryons.

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1. Introduction

The lightest nuclei in the cosmos were formed within the first three minutes after the Big Bang in the era of the so-called primordial nucleosynthesis. Since in this period there were abundant neutrons available, the fusion processes were driven in a straightforward manner by the strong interaction part of the nucleon–nucleon interaction. Since the pion–nucleon–nucleon coupling constant is strong enough to produce a bound deuteron, but simultaneously still too weak to form stable $A = 5$ and $A = 8$ systems, the Big Bang nucleosynthesis ended after production of the light nuclei.

The nuclear fusion in stars — driven in first instance by gravitational attraction — set in millions of years later. Since there are no longer free neutrons available, this fusion process starts from a bottleneck, the $pp \rightarrow$

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$de^+\nu_e$ reaction, which is finally driven by the weak interaction. Thanks to this circumstance, the sun is a very slowly burning star, where hydrogen is fused finally to helium. Compared to typical nuclear reaction times, the sun is a very slowly glowing nuclear fusion reactor working for billions of years at about constant temperature — just right to allow the development of life on earth.

For energy production on earth, the solar fusion reactions are not useful due to the above mentioned bottleneck. Instead, one tries to use the reaction $dt \to ^4\mathrm{He}\, n$ driven by the strong interaction when overcoming the Coulomb repulsion.

2. Double pionic fusion

If the relative energy between the colliding nucleons/nuclei is high enough, then the exchange particle — primarily the pion — of the nucleon–nucleon interaction may come on mass shell and be released. Particularly interesting is the double-pionic fusion process, where a pair of pions is released. In this case, the so-called ABC effect has been observed — for the first time in the year 1960 by Abashian, Booth and Crowe [1]. The initials of those were used later on for giving this effect a name. The effect denotes the fact that in the double pionic fusion process a huge low-mass enhancement is observed in the $\pi\pi$-invariant mass spectrum, as soon as the produced pion pair is scalar–isoscalar. Hence, for some time it was believed to see here an evidence for the σ meson, which has been searched for since long.

The huge enhancement right at the $\pi\pi$ threshold means that the two produced pions dominantly fly in parallel away from the fused nucleus — a really peculiar behavior.

To unveil the origin of the ABC effect, exclusive and kinematically complete measurements on this topic and on double-pion production have been carried out with the WASA 4π detector [2, 3], first on the CELSIUS ring at Uppsala [4–14], and later on on the COSY ring at the Research Center Jülich [15–21]. For a review, see Ref. [22].

From the wealth of high-quality experimental results, the following picture emerges:

- The ABC effect observed in the double-pionic fusion is strictly correlated with a resonance-like energy dependence in the total cross section.

- Accounting for the Fermi motion in fusing and fused nuclei this resonance-like behavior can be traced back to an isoscalar resonance in the pn system with mass of 2.37 GeV, *i.e.* 500 MeV above the deuteron groundstate, and with a width of only 70 MeV.

- From the angular distributions in the basic reaction, the fusion to deuterium, the spin-parity of the resonance is determined to be 3^+.
- From the Dalitz plots, we see that the resonance dominantly decays via a $\Delta\Delta$ excitation in the intermediate state.

3. Conclusions

From these observations, we conclude that for the first time a profound and solid evidence has been found for a non-trivial narrow resonance in the system of two baryons. Also from the *experimentum crucis*, the polarized np scattering, evidence for the observation of this resonance in the pn system has been reported [23].

Due to its quantum numbers this resonance state is fully symmetric in spin, color and angular momentum as well as fully antisymmetric in isospin. Due to this particular feature Ref. [24] claims that any model based on confinement and effective one-gluon exchange leads to the prediction of the existence of a nonstrange dibaryon with $I(J^{\mathrm{P}}) = 0(3^+)$, the "inevitable nonstrange dibaryon". In fact, many groups [24–29] predicted such a state at similar mass. It is remarkable that the first such prediction, which was published by Dyson and Nguyen-Hu Xuong [29] just half a year after the Gell-Mann's publication of the quark model [30], appears now to be quite precise in the prediction of the mass of this resonance. But it took now nearly 50 years to establish such a resonance experimentally — and more than 50 years to connect the peculiar ABC effect in double-pionic fusion to this dibaryonic resonance, which obviously is strong enough to survive even in nuclei — as the measurements of the double-pionic fusion to ^{3}He and ^{4}He demonstrate.

REFERENCES

[1] N.E. Booth, A. Abashian, K.M. Crowe, *Phys. Rev. Lett.* **7**, 35 (1961); **5**, 258 (1960); *Phys. Rev.* **132**, 2296 (1963).

[2] Ch. Bargholtz *et al.*, *Nucl. Instrum. Methods* **A547**, 294 (2005).

[3] H.H. Adam *et al.*, `arXiv:nucl-ex/0411038`.

[4] M. Bashkanov *et al.*, *Phys. Lett.* **B637**, 223 (2006).

[5] M. Bashkanov *et al.*, *Phys. Rev. Lett.* **102**, 052301 (2009).

[6] S. Keleta *et al.*, *Nucl. Phys.* **A825**, 71 (2009).

[7] F. Kren *et al.*, *Phys. Lett.* **B684**, 110 (2010); [*Erratum ibid.*, **B702**, 312 (2011)] [`arXiv:0910.0995v2 [nucl-ex]`].

[8] J. Johanson *et al.*, *Nucl. Phys.* **A712**, 75 (2002).

[9] W. Brodowski *et al.*, *Phys. Rev. Lett.* **88**, 192301 (2002).

[10] J. Pätzold *et al.*, *Phys. Rev.* **C67**, 052202(R) (2003).
[11] T. Skorodko, *et al.*, *Eur. Phys. J.* **A35**, 317 (2008).
[12] T. Skorodko, *et al.*, *Phys. Lett.* **B679**, 30 (2009).
[13] T. Skorodko *et al.*, *Phys. Lett.* **B695**, 115 (2011).
[14] T. Skorodko *et al.*, *Eur. Phys. J.* **A47**, 108 (2011).
[15] P. Adlarson *et al.*, *Phys. Rev. Lett.* **106**, 242302 (2011).
[16] P. Adlarson *et al.*, *Phys. Lett.* **B721**, 229 (2013).
[17] S. Abd El-Bary *et al.*, *Eur. Phys. J.* **A37**, 267 (2008).
[18] S. Abd El-Samad *et al.*, *Eur. Phys. J.* **A42**, 159 (2009).
[19] P. Adlarson *et al.*, *Phys. Lett.* **B706**, 256 (2011) [`arXiv:1107.0879 [hep-ex]`].
[20] P. Adlarson *et al.*, *Phys. Rev.* **C87**, 035204 (2013).
[21] P. Adlarson *et al.*, `arXiv:1306.5130[nucl-ex]`, submitted for publication.
[22] H. Clement, *Prog. Part. Nucl. Phys.* **67**, 486 (2012).
[23] M. Bashkanov, talk at Baryon 2013, Glasgow.
[24] T. Goldman *et al.*, *Phys. Rev.* **C39**, 1889 (1989).
[25] J. Ping *et al.*, *Phys. Rev.* **C79**, 024001 (2009) and references therein.
[26] P.J.G. Mulders, A.W. Thomas, *J. Phys. G* **9**, 1159 (1983).
[27] A.Th.M. Aerts, P.J.G. Mulders, J.J. de Swart, *Phys. Rev.* **D17**, 260 (1978).
[28] K. Maltman, *Nucl. Phys.* **A438**, 669 (1985).
[29] J.F. Dyson, Nguyen-Huu Xuong, *Phys. Rev. Lett.* **13**, 815 (1964).
[30] M. Gell-Mann, *Phys. Lett.* **8**, 214 (1964).