THE PUZZLE OF THE $\sigma(\gamma, p)/\sigma(\gamma, n)$ RATIO IN ^4He

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الخلاصة :

نلخص الوضع الحالي للنظريات التي تعلل القياسات الحديثة لنسبة المقاطع العرضية لتفاعل (فوتون ، بروتون) إلى تفاعل (فوتون ، نيوترون) على نواة الهيليوم٤ .

ABSTRACT

The current theoretical situation explaining the results of recent measurements of the $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio in ^4He is summarized.

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Isospin symmetry (charge independence) of the strong nuclear interaction is, in principle, broken at the fundamental (QCD) level only by the electromagnetic (primarily Coulomb) interaction and differences in up-and-down quark masses. Estimates of the 'current' quark masses [1] yield $m_d/m_u = 1.8$ with $m_u \simeq 2$ MeV; despite this large difference the *net* effect expected is nonetheless *small*, since the relevant parameter is $(m_d - m_u)/m_{\mathrm{const}} \lesssim 1\%$, where m_{const} is the 'constituent' quark mass $\approx m_{\mathrm{proton}}/3 \approx 300$ MeV. Although it is difficult to predict reliably the implied effects on nuclear structure and reaction observables, a wide variety of experimental data agree with the estimate that charge independence is a valid symmetry, broken only at the 1% level.

It is in this context that the observed large difference, recently confirmed, between the photoneutron and photoproton reaction cross sections in ^{4}He, becomes so striking. Of particular interest is the ratio $R(E_x) \equiv \sigma(\gamma, \mathrm{p})/\sigma(\gamma, \mathrm{n})$, in the excitation energy region $24 \leq E_x \leq 30$ MeV. After about ten years of estimates of $R(E_x)$ oscillating between 1 and 2, depending on the method used for the measurements and their interpretation, it seems to be finally agreed [2–4] that $R(E_x)$ has a nearly constant value of 1.7 ± 0.2 between 24 and 30 MeV, followed by a slow decrease to 1.0 ± 0.2 about 10 MeV later.

The TUNL capture experiments were performed using the detector set-up shown in Figure 1. The arrangement shown here was used in the case of the ^{3}He(n,γ)^{4}He reaction [3,5]. (A scattering chamber replaced the deuterium gas cell for the ^{3}H(p,γ)^{4}He

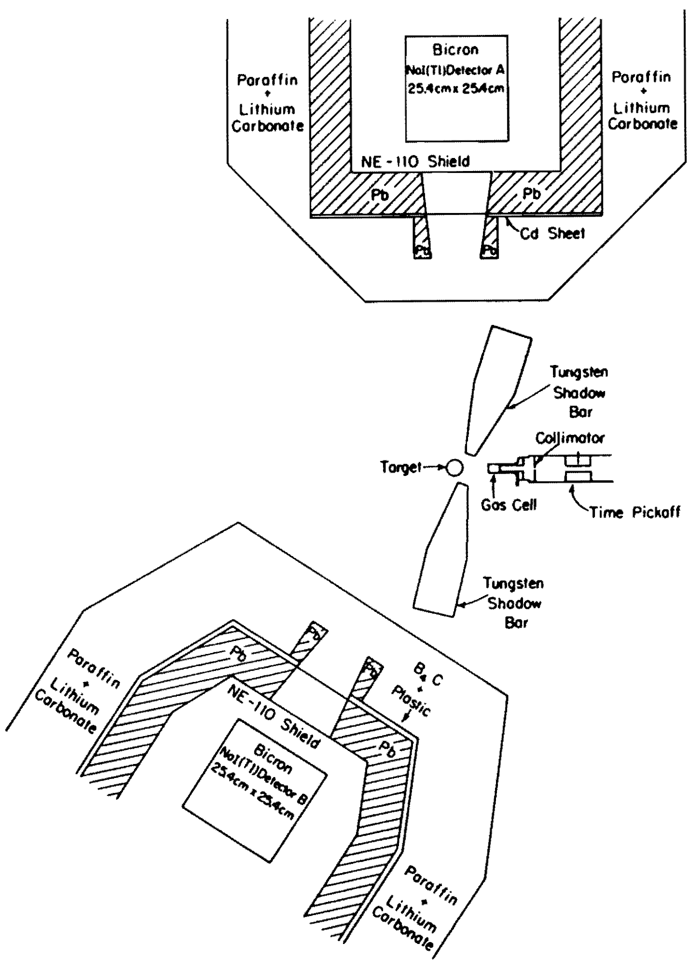

Figure 1. The TUNL Experimental Set-up used for the ^{3}He(n,γ) Measurements. The Pulsed (Polarized) Deuteron Beam Produced Neutrons by Striking Deuterium Gas Contained in the Gas Cell. The ^{3}He Target was a Stainless Steel Cylinder Containing about 140 atm of ^{3}He

measurements which employed a tritiated titanium foil target [4].) The $^2H(d,n)^3He$ reaction was used as shown in Figure 1 to produce the neutron flux. A beam of polarized deuterons was used to produce the polarized neutrons [5].

The results of these capture experiments are shown in Figure 2. Details are given in references [3–5]. The ratio of the (γ,p)-to-(γ,n) cross sections (obtained by angle integrating and detail balancing the observed capture cross sections) are in excellent agreement with the most recent photonuclear (γ,p)-to-(γ,n) results [6].

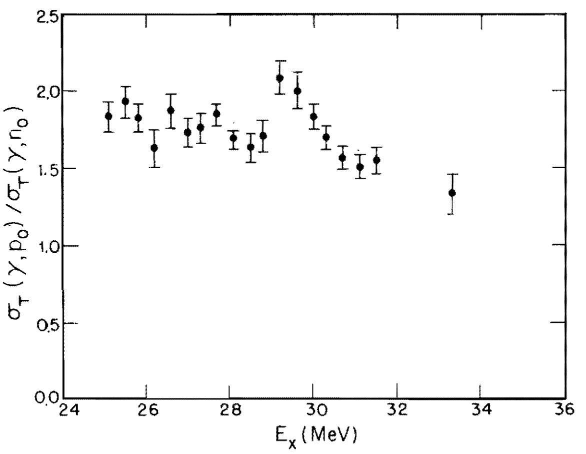

Figure 2. The $^4He(\gamma,p)^3H$-to-$^4He(\gamma,n_0)^3He$ Ratio Obtained by Detail Balancing the Neutron and Proton Capture Measurements. The Angle Integration was Performed by Multiplying $\sigma(90°)$ by 8π/–a 3 Procedure which was Experimentally Verified

Further experimental studies of these two capture reactions have consisted of measurements of the analyzing powers for the case of polarized neutron and proton beams [5]. These measurements have indicated that the cross section is only 1–2% E2 and 2–3% $S=1$ E1 in both the neutron and the proton channels. This result is important since it proves that the ratio effect is neither due to E2 nor to spin-flip ($S=1$ to $S=0$) E1 interference effects [7].

The electrostatic potential between the two protons can account for about 10% of the observed difference between proton and neutron cross sections. Since the difference $\Delta Q = Q_n - Q_p$ between the neutron and proton thresholds is small ($\Delta Q = 0.754$ MeV), 'threshold effects', which are of the order of $\Delta Q/(E_x - Q_n)$, become small a few MeV above $Q_n = 20.578$ MeV. All other direct Coulomb effects (n–p mass difference, finite charge and magnetic moment distributions in the nucleons, and vacuum polarization) are relatively unimportant and cannot contribute appreciably to $R(E_x)$.

It is important to note that a reliable theoretical evaluation of $R(E_x)$ requires a continuum calculation, which can be performed with one of the many different methods available [11, 12]. In fact, in the so-called bound state calculations, one obtains, instead of continuum cross sections, a discrete set of strength lines, to which, with some degree of arbitrariness, widths can be assigned. However, any interference, arising from the overlapping of the resonances, is absent. This can be very misleading, especially when resonances are broad, as in the case of ^4He in the energy region of interest. Although 1p–1h continuum calculations have often failed (by a factor of 2 or more) to reproduce the height and width of the individual peaks in the observed cross section, the predicted ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ is expected to be more reliable, since the same approximations are used for proton and neutron channels.

Several different continuum calculations have been performed in the past for ^4He in the framework of the 1p–1h approximation [8–10], and they all agree with:

$$R(E_x) = 1.08 \pm 0.05 \text{ for } 25 \leq E_x \leq 35 \text{ MeV}.$$

The question then arises as to which modifications of the basic model are required in order to reproduce the experimental ratio of 1.7 ± 0.2. After an extensive search of the parameters of both the central (shell model) potentials and the residual interaction, Delsanto, Biedenharn, Danos, and Tuan [13] have recently found (Figure 3) that:

(a) no 'reasonable' choice of parameters for the central potentials could reproduce the observed $R(E_x)$;
(b) a reduction of about 30 to 50% in the proton–proton residual matrix elements could reproduce the observed $R(E_x)$ if the following prescriptions were adopted:
  (1) that the Coulomb potential be removed from the central potentials,
  (2) that the residual interaction parameters be chosen in such a way as to minimize the contribution of the E1 spin-flip ($S=1$) term, in agreement with the previously mentioned observation that the $S=0$ E1 term is predominant.

The calculation of reference [13] does not, however, answer the basic question of the physical origin of the phenomenon, i.e. whether the observed asymmetry is due to some anomalous charge dependence of the nuclear force.

To investigate this question, Halderson and Philpott [14] have also performed a continuum calculation, in

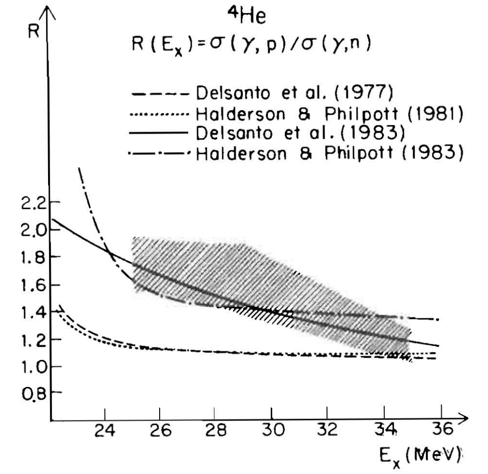

Figure 3. Ratio $R(E_x)$ from the Continuum Calculations of Reference [9] (Dashed Line), Reference [10] (Dotted Line), Reference [13] (Solid Line), and Reference [14], 3CSB (Dashed-Dotted Line). For Comparison, the Band of Recommended Experimental Values of $R(E_x)$ *from Reference 2 is also Shown (Shaded Area).*

which a charge symmetry breaking (CSB) interaction has been added to the usual nuclear interaction. They have found (Figure 3) that, in order to reproduce the observed $R(E_x)$, one needs to add a CSB term more than three times as large as a phenomenological CSB potential used to remove discrepancies in the Coulomb energy shifts in mirror nuclei [15]. However, with this correction (which they call '3CSB'), a few serious 'side effects' result:

(1) The difference between the calculated proton and neutron reaction thresholds moves from 0.69 MeV (no CSB) to 2.05 MeV (3CSB) (the measured threshold energy difference is 0.76 MeV).
(2) The agreement of the polarization and analyzing power in the reaction $^3H(p,n)^3He$, which is very good when no CSB term is included, is completely destroyed by the presence of the 3CSB term.

Although their calculation is restricted to a particular choice of CSB interaction, they conclude that, within the standard assumptions of nuclear theory, it is highly unlikely that a charge symmetry breaking term in the nuclear forces can explain the observed $R(E_x)$.

It then becomes plausible to ask whether some, as yet unaccounted for, indirect Coulomb mechanism can be responsible for the discrepancy.

It has been noted [16] that, in the energy region between $Q_d = 23.75$ MeV and $Q_{2n2p} = 28.3$ MeV, deuterons have a high probability of being formed, but not of escaping (due to the 1^- selection rule). Loosely bound 'quasideuteron' configurations may therefore be very important at these low energies, and they can be easily charge polarized [17], with the protons being on the average further apart from each other than the neutrons. Beyond Q_{2n2p}, the competing process of complete nuclear breakup makes this mechanism progressively less important.

Recent TUNL measurements [18] of $^2H(p,\gamma)^3He$ and $^2H(n,\gamma)^3H$ cross sections for incident protons and neutrons between 6 and 15 MeV have found the $R(E_x)$ to be approximately unity for mass-3 nuclei. This agrees with the proposed mechanism, in that for mass-3 nuclei no such quasideuteron configuration occurs.

In ^4He the observed asymmetry would then result as a consequence of the interaction between the continuum of quasideuteron channels, which can be considered as closed, although they are energetically open, and the one-particle continuum of open channels of the usual doorway states. This interaction can be treated by extending the Dirac–Fano formalism [19] for the interaction of one discrete state and one continuum to the case of two continua (one open channel continuum interacting with one closed channel continuum). For the quasideuteron configurations we assume wave-functions of the form:

$$\psi_{l_1 l_2 l_3}(\bar{r}_1,\bar{r}_2,\bar{r}_3,\bar{r}_4)= N\mathcal{A}\{r_{12}^{l_1} e^{-\alpha r_{12}} r_{34}^{l_2} e^{-\beta r_{34}} \rho^{l_3} e^{-\gamma\rho} e^{-\tau R^2_{\mathrm{C.M.}}} \times [Y^{[l_1]}(\hat{r}_{12}) \times Y^{[l_2]}(\hat{r}_{34}) \times Y^{[l_3]}(\hat{\rho})]^{[0]}\},$$

where r_{12} and r_{34} are the neutron–proton distances in each quasideuteron, ρ is the distance between the centers of mass of the two deuterons, N is a normalization factor, $\mathcal{A}$ is an antisymmetrization operator and α, β, γ, τ are suitable constants.

Calculations are presently being performed, using the natural boundary conditions method of Barrett and Delsanto [20], to ascertain the validity of our proposed explanation of the observed asymmetry.

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