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ABSTRACT

The effects of the Coulomb force, charge independence breaking (CIB) and charge symmetry breaking (CSB) nuclear forces, and $\pi\pi$, $\pi\rho$, and $\rho\rho$ exchange three-nucleon forces on the binding energies of ^{3}H and ^{3}He are studied in detail by solving Coulomb-modified Faddeev equations for various realistic NN potentials. 52-channel calculations are performed for the first time in order to get convergent and reliable results. Our calculation results may be summarized as follows.

[1] First, we calculated the binding energies of the trinuclei. After 32 case studies, we found a very good linear relationship between ^{3}H and ^{3}He binding energies (see Fig. 1), from which we deduce a model independent value for the Coulomb-energy difference, 648 ± 4 keV with finite-size proton. As for the effects of CIB and CSB nuclear forces, we found that the effect of CIB contributes about 0.1-0.2 MeV to the binding energies of trinuclei. On the other hand, the effect of CSB contributes 75 ± 7 keV to the binding energy difference (see Fig. 1). With other small effects, these reasonably account for the ^{3}H-^{3}He binding energy difference (see TABLE 1).

[2] In addition to 2π exchange three-uncleon forces, we considered also three-nucleon forces with $\pi\rho$, $\rho\rho$ exchange and K.R. term. We found that the binding energies of ^{3}H and ^{3}He can be reproduced with some reasonable sets of values of $\Lambda\pi$, and $\Lambda\hat{\rho}$. Among them, the set $\Lambda\pi=0.81$ GeV and $\Lambda\hat{\rho}=1.13$ GeV yields the triton binding energy of 8.485 MeV (experimentally, 8,482 MeV) and the Gamow-Teller matrix element of $0.955\sqrt{3}$ (experimentally, $(0.962\pm0.002)\sqrt{3}$) in the triton β-decay.

[3] Using the wave functions obtained from Faddeev partial-wave calculations, we investigated the bound state properties of trinuclei. For the percentage of the partial waves, we obtained about 90% of the space symmetric S-state. The D-state caused by the tensor forces in the NN interactions is about 10%. The small but nevertheless important S′-state arised from the spin-and isospin-dependence of the NN interactions is about 1%. We found that the Coulomb force makes decrease the percentage both for the S-state and the D-state but does increase the S′-state percentage in ^{3}He compared with ^{3}H. Because of the Coulomb force CIB and CSB nuclear forces, the isospin $T=3/2$ component is mixed in the wave functions of trinuclei. However, its percentage is only about 10^{-3}%, so we can omit it in most of the calculations.

[4] For asymptotic normalization constants, we got the relation $C_0{}^c \approx C_0$ for the S-wave. However, for the D-wave the Coulomb effect makes decrese the asymptotic

normalization constants of ^{3}He compared with that of ^{3}H by about 5%. We also obtained a good linear relationship between the ratio $\eta = C_2/C_0$ and the binding energies of trinuclei (see Fig. 2). We see that the experimental ratio η are reproduced well at the binding energies of trinuclei.

[5] We investigated the charge from factors of ^{3}H and ^{3}He. By including meson exchange currents : the π^-,ρ^- and ω-pair currents, the $\rho\pi\gamma$ and the $\omega\pi\gamma$ mixing currents, the π^-, ρ-and ω-retardation currents, we reproduced the experimental date very well, especially for triton (see Fig. 3). We also calculated the charge radius of ^{3}H and ^{3}He from the charge from factors and found $r_c(^3H) = 1.725 \pm 0.007$ fm (experimentally, 1.68 ± 0.03 fm) and $r_c(^3He) = 1.958 \pm 0.006$ fm (experimentally, 1.978 ± 0.015 fm).

[6] As an extended calculation, we generalized the Faddeev eqautoin approach to a system with distinguishable particles. It was applied to the three-nucleon systems by taking neutron and proton as distinguishable particles because of their mass difference. We obtained 13 keV difference in the binding energy of ^{3}H and ^{3}He due to the n-p mass difference. By the success of solving the three-nucleon systems of this kind, we hope to apply the same formalism to other physical systems, such as hypertriton $^3_\Lambda$H, in a near future.

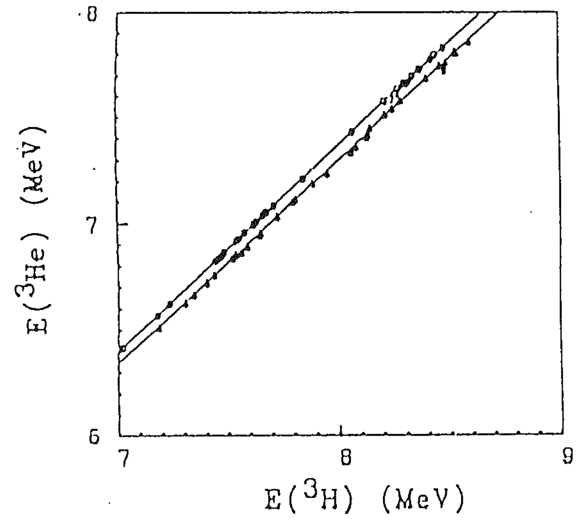

FIG. I. The 32 circles are the binding energies of ^{3}He with Coulomb forces plotted vs the binding energies of ^{3}H for the following casces (2NP means the two-nucleon potential) : RSC6, 28 ; (RSC+TM) 6,28 ; 2NP 6, 28, 38, 52 for 2NP = AV, PARIS, TRS, and BONN ; [2NP+TM] 6, 28, 38, 52 for 2NP = AV, PARIS, and TRS. The 32 triangles are the results with CIB and CSB forces. The experimental point is shown as a square.

TABLE I. The contribution of charge-asymmetric effects to the ^{3}H-^{3}He binding enery difference in keV

Charge asymmetry effects	δE
Static Coulomb ($E\hat{c}$, $_{\mathrm{MI}}$)	648± 4
Magnetic interaction	10± 1
Vacuum polarization	4
Orbit-Orbit interactions	9± 1
K.E. due to n-p mass diff.	11
$\delta E_{\mathrm{other}}$	34± 2
CIB and CSB forces ($^1S_0$)	75± 7
CSB other than $^1S_0$	2
Uncertainty from V_{phe}.	1± 1
δE_{CSB}	78± 8
Total (theory)	760±14
Experiment	764

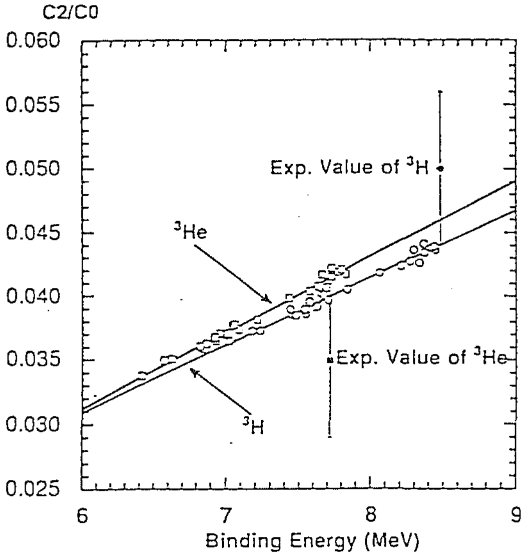

FIG. 2 The D/S ratio of the asymptotic normalization constants of trinuclei plotted versus the corresponding binding energies.

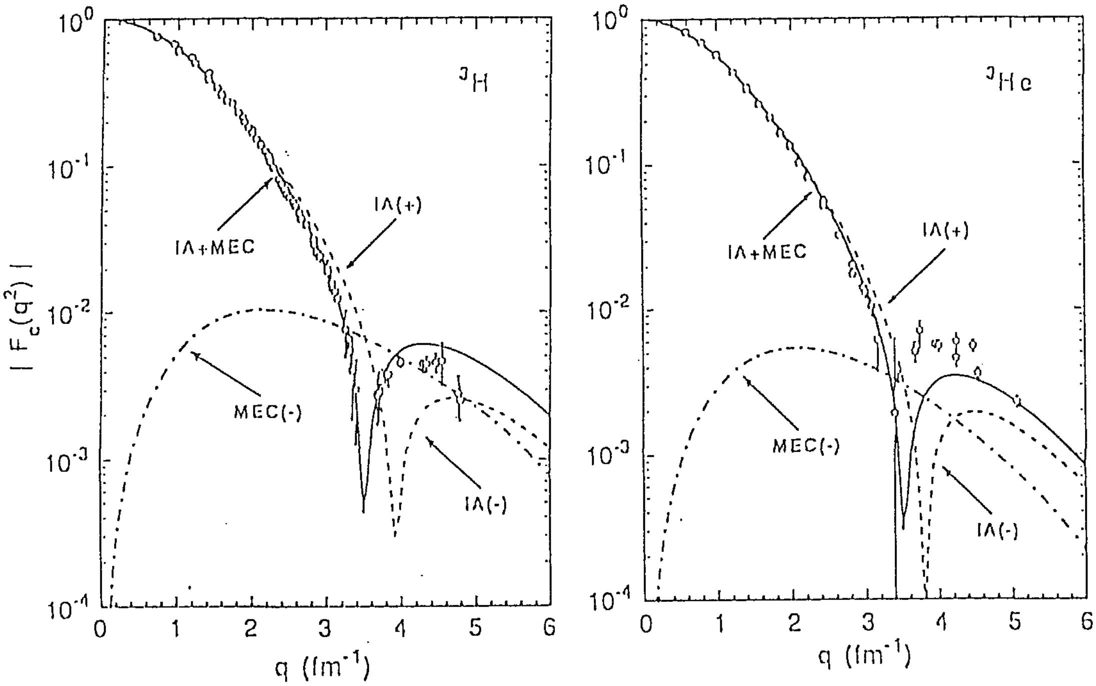

FIG. 3 The charge from factors of ^{3}H and ^{3}He. The impulse approximation (IA) and the effects of MEC are calculated and shown as dashed line and dot-dashed line, respectively. The solid line represents the result of IA+MEC. The wave function is obtained for the 52-channelcalculation for AV14 [II] potential. The open circles are the experimental data.

論文審査の結果の要旨

陽子と中性子を総称する核子から成る三体系は，量子力学的な精密計算によって核子間に働く力を正確に決定できる貴重な少数粒子系である。

本研究は，三体問題の基礎方程式であるファデェーエフ方程式に基づき，クーロン力を考慮した修正を加え，トリトン^{3}H と^{3}He の詳細な波動関数を精密に数値計算することによって，実験データを再現できる現実的な核力ポテンシャルを明らかにしたものである。数値計算は，52 チャンネルを含む連分数法に基づく近似である。

先ず，^{3}H と^{3}He の束縛エネルギー差の実験値とクーロン力の寄与の評価から，二体力の成分にアイソピン対称性を破る力が大きさで約 100 KeV 必要であることが明らかにされた。これは電磁質量差などに起因する既知の対称性の破れ以外にある種の現象論的な力で説明できた。一方，二核子の散乱データを説明できる現実的な二体の核力模型として既存のどれをとっても^{3}H と^{3}He の束縛エネルギーの絶対値を説明できない。このことから三体力の必要性が結論される。三体力としてパイオン２つの交換力以外に，$\pi\rho$, $\rho\rho$ の交換力も必要であるが，本研究によりパイオンと ρ 中間子の核子との結合に現れる形状因子のカットオフパラメータがそれぞれ 0.8 GeV（π），1.13 GeV（ρ）と決定された。

本研究により束縛エネルギーの大きさのみならずトリトンの β 崩壊のガモフ・テラー行列要素と^{3}H と^{3}He の荷電形状因子が計算できる。実験値との一致は^{3}He の高運動量移行部分を除いて良好である。また新しい試みとして陽子と中性子を質量の異なる識別可能な粒子として取扱う方法でファデェーエフ方程式を拡張した。これは将来${}^3_\Lambda$H などの系に応用できる新しい結果である。

以上のように本論文は博士論文として十分に独自の結果を含み，また本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。よって呉勇提出の論文は博士（理学）の学位論文として合格と認める。