现实核力Gamow壳模型计算丰中子碳同位素

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摘要 远离 β 稳定线的弱束缚原子核存在很多奇特的现象, 已成为当前核物理研究的热点. 在通过理论描述这些非稳定区域时, 束缚态、共振态与连续态的耦合效应变得尤为突出. 与此同时, 很多工作也表明了三体力在计算原子核结构时的重要性. 本文以丰中子碳同位素为研究对象, 采用现实核力Gamow壳模型, 从手征有效场论的 $N^3\text{LO}$ 两体与 $N^2\text{LO}$ 三体核力出发, 同时考虑束缚态、共振态与连续态, 计算了碳同位素基态与第一个 2^+ 激发态的位置. 我们的计算给出了正确的滴线位置, 验证了氧同位素中子数 $N=14$ 的壳结构在碳同位素中消失的现象, 同时预言了 $N=16$ 的壳结构. 我们将包含与不包含三体力的计算结果进行了比较, 显示出三体力对于描述滴线区原子核的重要性. 此外, 三体力的引入还可以升高第一个 2^+ 激发态的位置, 得到与实验更加符合的激发态能量.

关键词 壳模型, 三体力, 连续态, 弱束缚核, 碳同位素

随着原子核物理实验研究向滴线区域推进, 弱束缚原子核的特性被逐步了解. 碳同位素可以达到极高的中子质子比 N/Z , 实验中相继在 ^{17}C , ^{19}C 的低激发态能谱中测量到共振态宽度^[1-3], 并证实 ^{19}C , ^{22}C 中存在中子的晕结构^[4-9]. 其中, 滴线核 ^{22}C 是目前发现的最重的Borromean核^[10], 对应着中子数 $N=16$ 可能是一个幻数^[11,12], 同样的幻数在邻近的 N , O 等核素中也有被观测到^[12,13]. 以上这些特性使得丰中子碳同位素成为了核物理研究的热点与代表之一.

由于丰中子碳同位素中存在很多共振态、晕结构等弱束缚核的特性, 使得在理论计算中需要引入共振态和连续态, 才能对它们的描述更加完善. 传统的壳模型是在谐振子基矢下计算的, 谐振子基矢对应的是无限深势阱, 得到的是定域的波函数与束缚的本征态, 难以描述弱束缚系统. Gamow壳模型使用有限深势阱生成的Berggren基矢^[14], 将传统壳模型从实空间拓展到

复动量空间, 它同时包含了束缚态、共振态和连续态的信息并考虑了它们之间的耦合. 文献^[15]通过基于唯象相互作用的Gamow壳模型计算了碳同位素偶 A 核能谱, 并讨论了核子对关联在其中的影响. 除此之外, 使用resonating-group方法包含连续态的无核芯壳模型(no-core shell model with continuum, NCSMC)也被应用于 ^{17}C 的计算^[16], 发现 ^{17}C 的 $1/2^+$ 态位置会因为连续态效应变得更低.

除了考虑共振态与连续态之外, 三体力在丰中子碳同位素的计算中也扮演了重要的角色. 已有计算表明, 三体力对锂、铍、硼和碳同位素的低激发态能谱有较大影响, 解决了 ^{10}B 基态反转的问题, 给出了与实验相符的能谱顺序^[17,18]. 在比碳同位素多两个质子的氧同位素中, 三体力的引入还可以改善对基态结合能的描述并给出与实验相符的滴线位置^[19]. 包含三体相互作用的无核芯壳模型已被应用于碳同位素的计

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算^[16,20,21]. 在这些工作中, 三体力的引入可以得到与实验更接近的计算结果. 此外, 包含三体力的耦合簇有效相互作用(coupled-cluster effective interaction, CCEI)也被应用于计算碳同位素^[22], 但得到的奇 A 核能谱基态与实验不符; 文章指出连续态的耦合效应将会降低 $1/2^+$ 态的位置, 得到与实验相符的基态.

连续态效应和基于手征有效场论的三体力都是国际上核理论的前沿与热点, 并且当研究区域向滴线靠近时, 它们的效应变得尤为明显. 本文将基于现实核力的有核芯Gamow壳模型(realistic Gamow shell model, RGSM)应用于丰中子碳同位素的计算, 同时包含了连续态效应和基于手征有效场论的三体力, 讨论了碳同位素的壳演化, 并给出了与实验相符的滴线位置.

1 模型

通过引入单体势 U , 哈密顿量 H 可写为如下形式, 以方便进行微扰计算:

$$\begin{aligned} H &= \sum_{i < j} \frac{(p_i - p_j)^2}{2Am} + \bar{V}_{NN} + \bar{V}_{3N} \\ &= \sum_{i=1}^A \left(\frac{p_i^2}{2m} + U \right) + \sum_{i < j} \left(V_{NN} - U - \frac{p_i^2}{2Am} - \frac{p_i \cdot p_j}{Am} \right) \\ &\quad + \sum_{i < j < k} V_{3N} \\ &= H_0 + H_1, \end{aligned} \quad (1)$$

其中, $H_0 = \sum_{i=1}^A \left(\frac{p_i^2}{2m} + U \right)$ 描述单个核子的独立运动, 核子的两体、三体相互作用包含在 H_1 中. 选取有限深的Woods-Saxon(WS)势^[23]作为单体势 U , 通过在复动量空间求解径向薛定谔方程

$$\frac{d^2 u(k, r)}{dr^2} = \left[\frac{l(l+1)}{r^2} + \frac{2m}{\hbar^2} U(r) - k^2 \right] u(k, r), \quad (2)$$

得到Gamow壳模型所需要的Berggren基^[14], 统一描述束缚态、共振态和连续态. 对应的复本征值表示为 $E = E_0 - i\Gamma/2$, 其中 E_0 表示观测到的能量位置, Γ 为共振态的宽度. Berggren基的完备性关系表示为

$$\begin{aligned} &\sum_n u_n(r, k_n) u_n(r', k_n) + \int_{L^+} dk v(r, k) v(r', k) \\ &= \delta(r - r'), \end{aligned} \quad (3)$$

其中, 求和和部分包含束缚态和共振态, 连续态位于复平

面的积分围道 L^+ 上面, 并在计算时使用Gauss-Legendre求积公式对其进行离散化处理^[24~26]. 关于Gamow壳模型的细节可进一步参考基于唯像相互作用的计算^[24,27~29].

表1列出了所使用的WS参数, 这些参数是通过将WS势生成的单粒子能量拟合实验数值得到的. 单粒子能量的计算值与实验值列于表2, 其中 $1s_{1/2}$, $0d_{5/2}$ 与 $0d_{3/2}$ 轨道拟合 ^{15}C 的单中子激发能量, $0d_{3/2}$ 轨道的虚部能很好地给出 ^{15}C 的共振态宽度^[30]. 表1中不同宇称的分波使用不同的参数 V_0 , 使 $0p_{1/2}$ 轨道拟合 ^{14}C 的单中子分离能^[31]. 为 $d_{3/2}$ 与 $s_{1/2}$ 连续态分波选取同样的积分围道 $L^+ = \{0 \rightarrow (4-2i) \rightarrow 8 \rightarrow 100\}$ (单位: MeV, $1 \text{ eV} = 1.602176565(35) \times 10^{-19} \text{ J}$), 并为每条围道选取34个离散点以取得收敛的结果.

手征有效核力以核子和 π 介子为自由度, 同时考虑手征对称性, 两体部分拟合高精度的核子-核子散射相移, 三体部分拟合核子数 $A \geq 3$ 的可观测量, 它可以为原子核计算提供精确可靠的哈密顿量. 本次计算中, 我们采用 N^3LO 的手征两体力(NN)^[32]和 N^2LO 的手征三体力(3N)^[18], 其中三体力的低能常数取值为 $c_D = -1$, $c_E = -0.34$, 与引文中保持一致. 目前在核结构计算中直接处理三体力仍然是一个巨大的困难, 本文中采用正规序(normal-ordering)的方法将三体力的贡献考虑进

表1 WS势参数^{a)}

Table 1 Parameters for WS potential

宇称	V_0 (MeV)	R_0 (fm)	a (fm)	V_{so} (MeV)
+	60.00	1.13	0.60	10.60
-	53.12	1.13	0.60	10.60

a) 以 ^{14}C 为核芯, V_0 代表势阱深度, 不同宇称下取不同数值, R_0 代表半径, a 代表弥散深度, V_{so} 代表自旋轨道耦合强度

表2 中子单粒子能量的WS势计算值和实验值^[30,31] (单位: MeV)^{a)}

Table 2 The calculated neutron single-particle energies (in MeV) compared with experimental values^[30,31]

单粒子轨道nj	计算值	实验值
$0p_{1/2}$	-8.17	-8.18
$1s_{1/2}$	-1.21	-1.22
$0d_{5/2}$	-0.47	-0.48
$0d_{3/2}$	$3.59 - i0.90$	$3.56 - i0.87$

a) $0d_{3/2}$ 是一条共振态轨道, 表示为 $E = E_0 - i\Gamma/2$, Γ 为共振态的宽度

来^[33]. 现实核力直接拟合自核子-核子散射相移, 具有较硬的排斥芯, 微扰性较差. 为了加快多体计算中的收敛速度, 使用 $V_{\text{low-k}}$ 方法对两体核力进行软化, 取截断参数 $\Lambda=2.6 \text{ fm}^{-1}$ ^[34]. 初始核力基于谐振子基, 谐振子频率取经验值 $\hbar\omega = 14 \text{ MeV}$, 相互作用截断取 $n \leq 9$, $l \leq 4$. 通过基转换的方法, 将基于谐振子基的相互作用转换到Berggren基, 并使用 $\bar{Q}$ -box折叠图方法^[35,36]在模型空间内构建有效相互作用. 选取 ^{14}C 为核芯, $1s_{1/2}$, $0d_{5/2}$ 束缚态, $0d_{3/2}$ 共振态, $d_{3/2}$, $s_{1/2}$ 连续态分波为模型空间.

Gamow壳模型需要在复空间中进行对角化. 由于连续态的引入使模型空间剧烈增加, 因此限制最多两个核子可以占据连续态, 多于两个核子占据连续态的情形已被证明贡献很小可以忽略^[37].

2 计算结果与讨论

首先, 分别使用纯两体与包含三体的相互作用计算丰中子碳同位素偶 A 核结合能的变化趋势, 并与实验做对比, 如图1(a)所示. 其中, 所使用能量是以 ^{14}C 为基准的相对值, NN只包含两体相互作用, NN+3N同时包含两体与三体相互作用. 可以看出, 当仅采用两体相互作用时, 结合能明显低于实验值, 说明核子之间过于束缚; 而三体力的引入可以使 $^{22,24}\text{C}$ 的结合能明显抬高, 得到更接近实验值的计算值. 这表明三体力的引入增加了核子之间的排斥相互作用, 相似的效应也在Otsuka等人^[19]的工作中被发现. 同时, 计算结果表明, ^{22}C 是最后一个束缚的碳同位素偶 A 核, 与目前大部分的理论 and 实验观点一致^[8,38-40].

Gamow壳模型能够自洽地给出共振态的能量宽度. 图1(a)中 ^{24}C 基态结合能位置高于 ^{22}C , 表明 ^{24}C 的基态非束缚. 在仅包含两体相互作用时, ^{24}C 基态存在 0.064 MeV 的共振宽度; 当引入三体力后, 排斥效应使得 ^{24}C 变得更加不束缚, 共振宽度增加为 0.581 MeV .

此外, 还计算了碳同位素第一个 2^+ 激发态能量的变化趋势, 如图1(b)所示. 其中, 能量数值是以基态为基准的激发能, 数据点旁边的阴影与数字代表共振态宽度(单位: MeV), 阴影高度只做示意. 实验上已经在氧同位素中观测到中子数 $N=14$ 和 $N=16$ 的壳效应^[12,43], 并得到了理论的支持^[19,44-46]. 对于基态同样由中子 s , d 轨道占主要成分, 仅比氧同位素少两个质子的碳同位素, 目前已有的大部分实验^[47,48]和理论^[22,38]证明 $N=14$ 的壳效应消失了. 在Stanoiu等人^[47]的实验中, $^{17-20}\text{C}$ 的 2^+ 态被测量, 与氧同位素的 2^+ 态变化趋势相比较, 碳同

图1 (网络版彩色)碳同位素基态(a)与第一个 2^+ 激发态(b)能量的实验值^[31,41,42]与计算值

Figure 1 (Color online) Ground (a) and the first 2^+ (b) states energies for carbon isotopes from experiment^[31,41,42] and calculation

位素在 $N=14$ 时的 2^+ 态能量比氧同位素低一倍. 而在我们的计算中, $N=10$ 至 $N=14$ (图1(b)中 $A=16$ 至 $A=20$)的第一个 2^+ 激发态能量变化趋势与实验相符, 并没有出现壳效应导致的激发态能级变高的现象, 表明碳同位素在 $N=14$ 处的壳效应减弱或消失. 此外, 计算结果表明, 第一个 2^+ 激发态能量在 $N=16$ (图1(b)中 $A=22$)处明显增大, 说明 $N=16$ 处的壳结构在碳同位素中依然存在.

在计算 2^+ 激发态时, 依旧采用包含与不包含三体力的两种不同的相互作用, 并给出相似的变化趋势; 当中子数取 $N=10$ 至 $N=14$ (图1(b)中 $A=16$ 至 $A=20$)时, 仅包含两体相互作用计算得到的第一个 2^+ 态位置比实验偏低; 而三体相互作用的引入, 能够有效改善这种压缩状况, 得到与实验更相符的计算结果. 此外, 由于引入三体力后原子核更加弱束缚, $^{22,24}\text{C}$ 的第一个 2^+ 激发态的

共振宽度显著增大,但目前还没有实验数据,我们的计算值可以作为一个参考.

3 结论

使用现实核力Gamow壳模型计算了丰中子碳同位素基态与第一个 2^+ 激发态能量的变化趋势,并给出了共振宽度.计算结果表明, ^{22}C 是碳同位素中最后一个束

缚的偶 A 核,并且实验上中子数 $N=14$ 时壳效应的消失也被计算结果所支持.同时还预言了氧同位素中出现的 $N=16$ 的壳效应在碳同位素中依然存在.通过对比发现,仅包含两体相互作用会出现基态过于束缚的问题,而引入三体力可以有效抬高结合能曲线并改善对滴线位置的描述.此外,三体力还可以抬高第一个 2^+ 激发态的位置,使理论计算结果与实验符合得更好.

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Summary for “现实核力Gamow壳模型计算丰中子碳同位素”

Realistic Gamow shell-model calculations for neutron-rich carbon isotopes

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The weakly bound nuclei near the drip-line have many interesting properties which have been the hot spot for current nuclear physics research. Carbon isotopes can reach a high neutron to proton ratio and could be a good example to investigate the weakly bound and unbound nuclei. The drip-line nucleus ^{22}C is the heaviest Borromean nucleus that people have observed and corresponds to a sub-shell at neutron number $N=16$ which is also observed in nitrogen and oxygen isotopes.

For nuclei close to drip-line, the coupling of bound-, resonant- and continuum states becomes particularly important. But the traditional shell models with harmonic-oscillator basis are difficult to describe the resonant- and continuum states because the harmonic-oscillator potential always has a localized wave function and bound-eigenstates. One of the ways to include the continuum effects is employing the Berggren basis which is generated by finite potential like Woods-Saxon potential. With Berggren basis, the Schrodinger equation is expanded to complex-momentum space and the bound-, resonant- and continuum states could be taken into account on an equal footing. In addition, the necessity of chiral three-body forces has been shown in many *ab-initio* calculations like the reproducing of oxygen drip-line and low-lying spectrum of beryllium and boron isotopes. So it is meaningful to have a theoretical research of the carbon isotopes with considering both continuum effects and three-body forces.

In this paper, we calculate the neutron-rich carbon isotopes with realistic Gamow shell model which starts from chiral N^3LO two-body and chiral N^2LO three-body forces. The three-body forces are included by normal-ordering approach. We use Woods-Saxon potential with ^{14}C as a core to generate the Berggren basis. The parameters of Woods-Saxon potential are chosen to reproduce the single-particle energies close to experimental data. In Berggren basis, the continuum states are lying on the integral contour within the fourth quarter of complex-momentum space and discretized by Gauss-Legendre quadrature method for the further calculations. The effective interactions are built by $\bar{Q}$ -box folded-diagram method within the model space of $\{1s_{1/2}\text{-bound}, 0d_{5/2}\text{-bound}, 0d_{3/2}\text{-resonance}, d_{3/2}\text{-continuum}, s_{1/2}\text{-continuum}\}$. In order to deal with the large dimensions caused by the introducing of continuum states, we take an approximation that only two or less particles are allowed to occupy the continuum states.

The ground states energies and the first 2^+ excitation energies are calculated for even-mass carbon isotopes from $A=16$ to $A=24$ and achieve a good agreement with the experimental data. With our calculations, the ^{22}C is shown to be the last bound even- A carbon isotope. In addition, by investigating the evolution of the first 2^+ states, our results agree with the experiment that the sub-shell at $N=14$ in oxygen isotopes is observed to disappear in carbon isotopes, meanwhile the sub-shell at $N=16$ is reproduced by our calculations. Furthermore, we compare the ground states energies calculated with and without three-body forces and find out that the three-body forces will make the results more weakly bound and more consistent with experimental values especially for ^{22}C and ^{24}C . Meanwhile, the resonance widths which are calculated self-consistently by realistic Gamow shell model become broader. So our calculations give a support that the three-body forces will introduce a repulsive effect in neutron rich carbon isotopes and play a key role when describing the nuclear drip-line.

shell-model, three-body force, continuum states, weakly bound nuclei, carbon isotopesdoi: [10.1360/N972019-00267](https://doi.org/10.1360/N972019-00267)