第 30 卷 增刊 II 高 能 物 理 与 核 物 理 Vol. 30, Supp. II
2006 年 12 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Dec., 2006

Does Pseudo-Spin Symmetry Exist in the Continuum?*

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Abstract With the relativistic boundary condition, single proton resonant states in spherical nuclei are studied by an analytic continuation in the coupling constant (ACCC) method within the framework of the self-consistent relativistic mean field (RMF) theory. In this scheme, the energies, widths and the wave functions for proton resonant states in ^{120}Sn are analyzed to discuss the probability of the existence of pseudospin symmetry in the resonant states, which is consistent with that in the bound states, where the splittings of energies and widths, as well as the behavior of the wave function between pseudospin doublets are found in correlation with the quantum numbers of single particle states.

Key words RMF-ACCC, pseudo-spin symmetry, relativistic boundary condition, proton resonant states

Pseudo-spin doublets were introduced more than three decades into nuclear physics to accommodate an observed near degeneracy of certain normal parity shell model orbitals with non-relativistic quantum numbers $(n_{\rm r}, l, j=l+1/2)$ and $(n_{\rm r}-1, l+2, j=l+3/2)$ where n, l, and j are the single-nucleon radial, the orbital, and the total angular momentum quantum numbers, respectively[1, 2]. The doublet structure is expressed in terms of a "pseudo" orbital angular momentum, which is an average of the orbital angular momentum of the two orbits in the doublet, $\tilde{l}=l+1$, coupled to a "pseudo" spin, $\tilde{s}=1/2$. For example, the shell model orbitals $(n_{\rm r}s_{1/2}, (n_{\rm r}-1)d_{3/2})$ will have $\tilde{l}=1$, $(n_{\rm r}p_{3/2}, (n_{\rm r}-1)f_{5/2})$ will have $\tilde{l}=2$, for the two states in the doublet. Then the single-particle energy is approximately independent of the orientation of the pseudo-spin leading to an approximate pseudo-spin symmetry. The quasi-degenerative states are suggested as the pseudo-spin doublets $j=\tilde{l}\pm\tilde{s}$ with the pseudo orbital angular momentum $\tilde{l}$, and the pseudo-spin angular momentum $\tilde{s}$, and have explained a number of phenomena in nuclear structure. Because of these successes, comprehensive efforts[3, 4] have been given to understand its origin since pseudo-spin symmetry discovered. All these indicate the pseudo-spin symmetry is a good approximate for the single-particle bound states of atomic nuclei. However for the resonant states, which are thought to play an important role in formation of the exotic phenomena such as halo and skin[5, 6], the symmetry has not been analyzed from the information of the energies and wave functions for real nuclei before. Here, we aim at studying the resonant states by RMF-ACCC method and discussing their pseudo-

* Supported by National Natural Science Foundation of China (10447102, 10605004, 50302001), Scientific Research Innovation Foundation of BUAA and Program for New Century Excellent Talents in University (NCET) of China

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spin through the energies and wave functions for proton resonant states.

The theoretical framework of RMF-ACCC method can be found in Ref. [7]. For protons, the outer wave functions, i.e. the upper and lower components, can be expressed exactly as the relativistic solutions[8],

$$G^R_\kappa(kr)=\frac{\sqrt{\varepsilon_i+M}(2kr)^\gamma \mathrm{e}^{-\pi y/2}|\Gamma(\gamma-\mathrm{i}y)|}{2\sqrt{k\pi}\,\Gamma(2\gamma+1)}$$
$$\{\mathrm{e}^{-\mathrm{i}kr+\mathrm{i}\eta}(\gamma-\mathrm{i}y)F(\gamma+1-\mathrm{i}y,2\gamma+1;2\mathrm{i}kr)+c.c.\},\quad (1)$$

$$F^R_\kappa(kr)=\mathrm{i}\frac{\sqrt{\varepsilon_i-M}(2kr)^\gamma \mathrm{e}^{-\pi y/2}|\Gamma(\gamma-\mathrm{i}y)|}{2\sqrt{k\pi}\,\Gamma(2\gamma+1)}$$
$$\{\mathrm{e}^{-\mathrm{i}kr+\mathrm{i}\eta}(\gamma-\mathrm{i}y)F(\gamma+1-\mathrm{i}y,2\gamma+1;2\mathrm{i}kr)-c.c.\}.\quad (2)$$

in which γ satisfied with $\gamma^2=\kappa^2-(Z\alpha)^2$, $y=\dfrac{Z\alpha\varepsilon_i}{k}$, $\mathrm{e}^{2\mathrm{i}\eta}=-\dfrac{\kappa+\mathrm{i}yM/\varepsilon_i}{\gamma-\mathrm{i}y}$, and the superscript R refers to the regular solutions of the wave function. Similarly, if γ is substituted by $-\gamma$, the irregular solutions of the wave function, $G^{\mathrm{IR}}_\kappa(kr)$ and $F^{\mathrm{IR}}_\kappa(kr)$ can be obtained (IR refers to the irregular solutions).

Table 1. Given the energies and widths (MeV) for proton resonant states $\pi 2f_{7/2}$, $\pi 1h_{9/2}$, $\pi 3p_{3/2}$, $\pi 3p_{1/2}$ and $\pi 2f_{5/2}$ in ^{120}Sn by RMF-ACCC method, compared with corresponding results by RMF-rS method in parameter set NL3.

πnl_j	RMF-ACCC		RMF-rS	
	E	Γ	E	Γ
$2f_{7/2}$	6.22	0.073	6.210	0.043
$1h_{9/2}$	7.13	0.017	7.132	0.003
$3p_{3/2}$	7.32	0.82	7.513	0.924
$3p_{1/2}$	7.69	1.13	8.085	1.344
$2f_{5/2}$	7.97	0.30	7.934	0.307

The wave functions obtained from the analytic continuation is connected continuously to the relativistic Coulomb functions from the expressions Eqs. (1) and (2) at the matching point r_{m}. Similarly, the matching point r_{m} should be large enough to make sure that the nuclear potential $V_{\mathrm{nucl}}(r)$ vanishes (at least in the order of 10^{-3}MeV) at r_{m}, and $V_{\mathrm{coul}}(r)$ dominates instead. For ^{120}Sn, r_{m} should be close to 13fm. Because of the boundary condition in the RMF calculation, the matching point should be far from 20fm at the same time. In practice, we found that when r_{m} chosen in the vicinity of 13fm, the whole behavior of the wave functions for proton resonant states is reasonable. The wave functions for proton resonant states are the results of $L'=N'=3$ PAs at resonance k_{R} extracted from $L=N=5$ PAs.

We calculate the energies and widths for these proton resonant states $\pi 2f_{7/2}$, $\pi 1h_{9/2}$, $\pi 3p_{3/2}$, $\pi 3p_{1/2}$ and $\pi 2f_{5/2}$ in ^{120}Sn by RMF-ACCC method, The results are presented in Table 1 and compared with those by RMF-rS method (r stands for relativistic and S stands for scattering) in parameter set NL3. As we can see that the energy level for the proton resonant state $\pi 2f_{7/2}$ approaches to that for $\pi 1h_{9/2}$, and the corresponding widths are in the same order. Same thing happens to the proton resonant states $\pi 3p_{3/2}$ and $\pi 2f_{5/2}$. We also notice the quantum numbers of these two pair of proton resonant states: $\pi 2f_{7/2}$ and $\pi 1h_{9/2}$ satisfying $(n_{\mathrm{r}}f_{7/2}$, $(n_{\mathrm{r}}-1)h_{9/2})$ with $\tilde{l}=4$, as well as $\pi 3p_{3/2}$ and $\pi 2f_{5/2}$ satisfying $(n_{\mathrm{r}}p_{3/2}$, $(n_{\mathrm{r}}-1)f_{5/2})$ with $\tilde{l}=2$. Does the energy-splitting appear in pseudo-spin partners of resonant states? Could we say those resonant states have the doublet structure of pseudo-spin symmetry, just as the bound states?

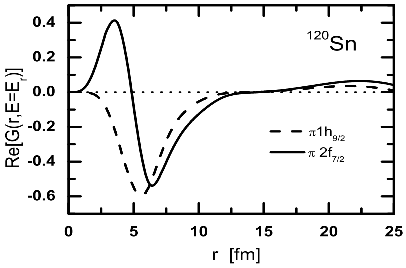

Fig. 1. The real part of the upper components $G(r)$ for the proton resonant state $\pi 1h_{9/2}$ (dashed line) compared to the proton resonant state $\pi 2f_{7/2}$ (solid line) in ^{120}Sn with parameter set NL3.

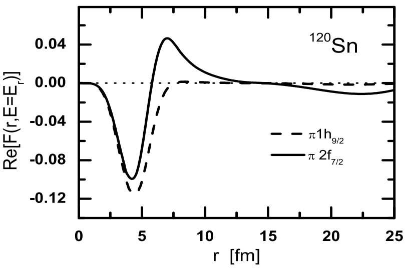

Fig. 2. Similar as Fig. 1, but for the real part of the lower components $F(r)$.

Once the resonance parameters, energies and widths, are determined exactly, we can obtain the inner part of the wave functions by ACCC method and then match the inner part to the outer part, i.e. relativistic Coulomb wave functions. Obviously, Coulomb force dominates the behavior of the wave function for proton resonant states, both the inner and outer part. In Fig. 1 we compare the real part of the upper components $G(r)$ of the spatial wave functions for the partner, the proton resonant states $\pi 1h_{9/2}$ (dashed line where $\tilde{l}=4,\ j=9/2$) and $\pi 2f_{7/2}$ (solid line) in ^{120}Sn with parameter set NL3. Similar as Fig. 1, but for the real part of the lower components $F(r)$ of the spatial wave functions for the proton resonant states $\pi 1h_{9/2}$ and $\pi 2f_{7/2}$ are displayed in Fig. 2. As we can see from these two figures that the lower components agree very well in the region where nuclear potential dominates, except for some disagreement on the surface. For the upper components, the magnitude agree well on the surface where nuclear and Coulomb potential dominate, but with different nodes. This is also the case for the partner $\pi 3p_{3/2}$ and $\pi 2f_{5/2}$. Could we say that the proton wave functions for the partner $\pi 2f_{7/2}$ and $\pi 1h_{9/2}$, $\pi 3p_{3/2}$ and $\pi 2f_{5/2}$ probably have pseudo-spin symmetry discussed in Ref. [9]?

In this paper, RMF-ACCC method is adopted to determine the energies, widths and the wave functions for single proton resonant states in ^{120}Sn and discuss the probability of the existence of pseudospin symmetry in the resonant states.

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赝自旋对称性在连续谱中是否存在？*

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摘要　在相对论边界条件下, 用基于相对论平均场的耦合常数解析延拓方法研究球形核单质子共振态. 此法计算的^{120}Sn质子共振态能量、宽度和波函数首次用于分析共振态中赝自旋对称性存在的可能性, 包括相应量子数的单粒子态的能级劈裂, 以及宽度和波函数的行为.

关键词　RMF-ACCC　赝自旋对称性　相对论边界条件　质子共振态

∗ 国家自然科学基金(10447102, 10605004, 50302001), 北京航空航天大学理学院科研创新基金和中国高校新世纪人才项目资助

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