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NEUTRON PARTICLE-HOLE STATES OBSERVED BY INELASTIC PROTON SCATTERING FROM ^{136}Xe†

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Neutron particle-hole states have been observed in the decay of isobaric analog resonances formed in the reaction ^{136}Xe plus proton. Analysis of the on-resonance inelastic data has given inelastic proton partial widths, spectroscopic factors, spins, and parities of several of the observed particle-hole states.

We have recently completed an extensive series of measurements of elastic and inelastic proton scattering from ^{136}Xe in the bombarding energy region 9.77 to 12.98 MeV. Analysis of the elastic-scattering data[1] shows that well-defined isobaric analog resonances occur at bombarding energies of 10.270 ($f_{7/2}$), 10.874 ($p_{3/2}$), 11.255 ($p_{1/2}$), 11.583 ($f_{5/2}$), and 11.810 MeV ($f_{5/2}$) and that the corresponding compound states in ^{137}Cs are analogs of states in ^{137}Xe formed by addition of a neutron to the closed $N=82$ neutron shell in the configurations indicated above.

Virtually all the inelastic excitation functions show resonant structure. Many have an even more distinctive behavior in that they exhibit sharp peaks at some, but not all, of the analog resonances described above. These peaks in the excitation functions are symmetric and typically have a height which at angles greater than 90° is 10 to 20 times higher than the nearby off-resonance background. In common with other workers who have studied similar nuclei,[2] we identify these inelastic transitions as being due to the excitation of neutron particle-hole states in ^{136}Xe. The motivation for this Letter is to show that it is possible not only to make an identification as to the nature of these states but also to use the observed data in conjunction with a simple theory to extract information about their spins and parities and to some extent about their configurations.

The neutron particle-hole states which we wish to discuss are expected to have configurations in which the particle is in a level above $N=82$ ($2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$), and the hole is in a level below $N=82$ ($2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$, $2d_{5/2}$). The possibility of $h_{11/2}$ or $d_{5/2}$ hole states will be ignored in the present analysis because of the high angular momentum involved in a $h_{11/2}$ transition and because these two levels lie further from the Fermi surface in ^{136}Xe. Particle-hole states will therefore be considered to be populated by the inelastic emission of a $d_{3/2}$ or $s_{1/2}$ proton from the analog state formed in the reaction.

The theoretical expression used in our analysis[3] is derived from the R-matrix theory as developed by Lane and Thomas.[4] We assume that the single-level approximation is valid and further that the background matrix R_0L_0 is zero. This second assumption is equivalent to the assumption that on resonance, the direct contribution to the inelastic cross section may be neglected in comparison to the compound contribution. This assumption is only partially justified since there is a small but clearly present off-resonance yield in the inelastic excitation functions. We justify this assumption on the basis that our fits at backward angles are reasonably good and that, to our knowledge, no theory which properly takes account of the direct contribution is available. In order to facilitate computation, we have used the J-J coupling scheme[5] instead of the usual L-S coupling scheme. We have also replaced the hard-sphere phase usually found in R-matrix formulas with a corresponding phase calculated with an optical potential.

For the case of inelastic scattering of protons from spin-zero targets at angle θ and bombarding energy E, our expression is

$$\sigma(\theta)=\frac{\bar{\lambda}^2\Gamma_p}{2}\,\frac{(2J+1)(-)^{2J-I}}{4(E-E_\gamma)^2+\Gamma^2}\sum_{\lambda=0}^{2J-1}P_\lambda(\cos\theta)\bar{Z}(LJLJ;\tfrac{1}{2}\lambda)\sum_{j_1J_2}\cos(\xi_{j_1}-\xi_{j_2})$$
$$\times(\pm\Gamma_{Ij_1J}{}^{1/2})(\pm\Gamma_{Ij_2J}{}^{1/2})\bar{Z}(l_1j_1l_2j_2;\tfrac{1}{2}\lambda)W(j_1Jj_2J;I\lambda),$$

where E_γ, Γ_p, Γ, J, and L are, respectively, the resonant energy, proton elastic partial width, total width, spin, and orbital angular momentum of the analog state as obtained from fits to the elastic scattering data.[1] The spin and orbital angular momentum of a given hole state are j_1 and l_1, respectively, while I is the spin of the residual nucleus. The phases ξ_j are given by

$$\xi_j=\delta_{lj}+\sigma_{lj},$$

where δ_{lj} and σ_{lj} are the nuclear and Coulomb phase shifts, respectively, for proton elastic scattering from the appropriate particle-hole excited state of the core at the emission energy of the inelastic protons. These phase shifts were calculated by code GPMAIN[6] using the optical potential deduced from our previous study of elastic scattering from the ground state of the core.[1] Γ_{IjJ} are the inelastic partial proton widths, and were the only free parameters in the data analysis.

In order to calculate spectroscopic factors, it was necessary to estimate single-particle widths $\Gamma_{IjJ}{}^{(sp)}$ corresponding to the observed transitions. These were approximately determined by evaluating the elastic proton partial width of the isobaric analog of a single neutron state of spin j and orbital angular momentum l lying below the observed analog state by an energy equal to the excitation energy of the final state. This width is given by the equation[7]

$$\Gamma_{IjJ}{}^{(sp)}=\Gamma_{lj}{}^{(sp)}$$
$$=(k'T_0/E_p')|\langle\varphi_{nA}|V_1|\chi_{pC}{}^{(+)}\rangle|^2,$$

and was evaluated using code GPMAIN. E_p' is the emission energy of the inelastic protons. The proton inelastic spectroscopic factors were evaluated from

$$S_{pp'}(j)=\frac{\Gamma_{IjJ}(2J+1)}{\Gamma_{IjJ}{}^{(sp)}(2I+1)}.$$

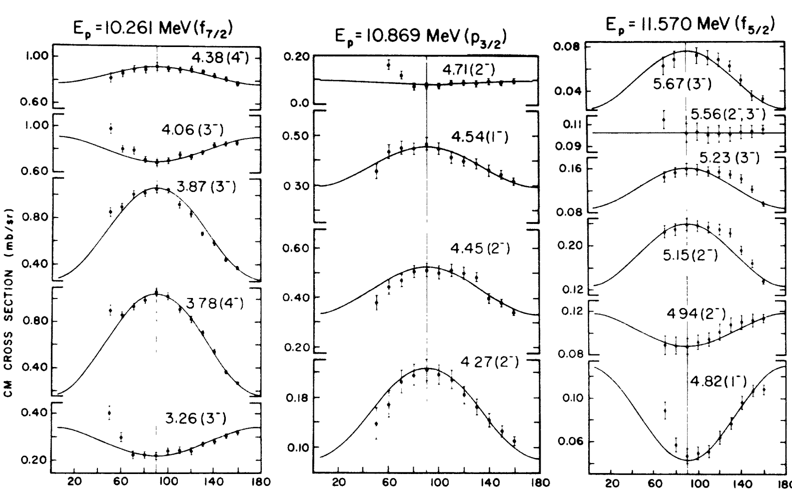

FIG. 1. Fits, indicated by the solid lines, to ^{136}Xe(p,p') angular distributions. The indicated proton bombarding energies are those at which the data were measured. The fit shown for the 5.56-MeV resonance is the same for both of the spin values indicated.

The data and fits obtained at the $f_{7/2}$, $p_{3/2}$, and the first $f_{5/2}$ resonances are shown in Fig. 1. The excitation energy of the state, and the assumed spin value used in obtaining the fit shown, are indicated. In most cases reasonable fits to the data were possible with two assumed spin values. Spin assignments were consequently made both on the basis of the angular distribution fits and on the basis of the resonance behavior of the states at the different analog resonances. For experimental reasons, we were unable to measure angular distributions for some of the inelastic groups. The inelastic transitions chosen for comparison to the theory were those which exhibited the characteristic "particle-hole" behavior described above and for which we were able to measure angular distributions. Since the direct background was observed to peak at forward angles, only data measured for angles greater than 90° were used for the fits.

Inferred final spin values, spectroscopic factors, and particle-hole configurations are shown in Table I. In this table, E^* is the excitation of the excited state in ^{136}Xe. The notation j^{-1} for a hole configuration indicates that resonant behavior was observed but that an assignment of relative hole strength was not made. Parentheses indicate small hole-configuration admixtures. Entries under I^π are spins of the residual excited state compatible with fits to the angular distributions and excitation-function behavior. The spin values used in the calculations are underlined. Parentheses indicate that a spin assignment has low probability. Where two spins are given without parentheses, either assignment is considered probable. The deduced partial widths are relatively insensitive to the choice of final spin value. L_J is the particle configuration used for the fits in the figure. $S_{pp'}(\frac{1}{2})$ and $S_{pp'}(\frac{3}{2})$ are the spectroscopic factors defined above. The entry of a particle-hole configuration in this table indicates the presence of resonant behavior. Thus, for example, the 4.27-MeV transition resonated at both the $f_{7/2}$ and $p_{3/2}$ compound resonances indicating the presence of both fd^{-1} and (ps^{-1} and pd^{-1}) components in the wave function of the residual state. In these cases, where more than one particle component is present, we have analyzed only the angular distribution at the most pronounced resonance. The deduced spectroscopic factors in these cases will represent not the total strength but that part of the strength corresponding to a particular particle configuration.

The relative values of $S_{pp'}(\frac{1}{2})$ and $S_{pp'}(\frac{3}{2})$ are a measure of the extent of the admixture of the $s_{1/2}$ and $d_{3/2}$ holes for a given state. The upper limit

Table I. Particle-hole configurations, spins, and spectroscopic factors of excited states of ^{136}Xe.

E^* (MeV)	Compound analog resonance $f_{7/2}$	$p_{3/2}$	$p_{1/2}$	$f_{5/2}$	I^π	L_J	$S_{pp'}(1/2)$	$S_{pp'}(3/2)$
3.26	$fs^{-1}+(fd^{-1})$				$\underline{3}^-$, (5^-)	$f_{7/2}$	0.07	0.03
3.78	$(fs^{-1})+fd^{-1}$				3^-, $\underline{4}^-$	$f_{7/2}$	0.08	0.87
3.87	$(fs^{-1})+fd^{-1}$				$\underline{3}^-$, 4^-	$f_{7/2}$	0.24	0.81
4.06	$fs^{-1}+(fd^{-1})$	(pd^{-1})			$\underline{3}^-$	$f_{7/2}$	0.48	0.07
4.15	fd^{-1}	pj^{-1}			2^-, (3^-)			
4.27	fd^{-1}	$(ps^{-1})+pd^{-1}$			$\underline{2}^-$	$p_{3/2}$	0.06	0.21
4.38	$fs^{-1}+(fd^{-1})$				(3^-), $\underline{4}^-$	$f_{7/2}$	0.64	0.05
4.45		$ps^{-1}+pd^{-1}$			1^-, $\underline{2}^-$	$p_{3/2}$	0.29	0.21
4.54		$ps^{-1}+pd^{-1}$			$\underline{1}^-$, 2^-	$p_{3/2}$	0.51	0.13
4.71		$ps^{-1}+pd^{-1}$	pd^{-1}	(fj^{-1})	$\underline{2}^-$	$p_{3/2}$	0.07	0.06
4.82		pj^{-1}	pj^{-1}	fd^{-1}	$\underline{1}^-$, (2^-)	$f_{5/2}$		0.66
4.94		pj^{-1}	pd^{-1}	$fs^{-1}+fd^{-1}$	$\underline{2}^-$	$f_{5/2}$	0.14	0.22
5.10	(fd^{-1})	pj^{-1}		fj^{-1}	2^-			
5.15				$(fs^{-1})+fd^{-1}$	$\underline{2}^-$, 3^-	$f_{5/2}$	0.20	1.60
5.23				$(fs^{-1})+fd^{-1}$	2^-, $\underline{3}^-$	$f_{5/2}$	0.21	0.81
5.56				fs^{-1}	2^-, $\underline{3}^-$	$f_{5/2}$	0.22	
5.67				$(fs^{-1})+fd^{-1}$	2^-, $\underline{3}^-$	$f_{5/2}$	0.09	0.27

of unity on the spectroscopic factors is exceeded only for the state at 5.15 MeV. The sums of the $d_{3/2}$ and $s_{1/2}$ spectroscopic factors at the $f_{7/2}$ resonance are 1.83 and 1.51, respectively. The sum rule,

$$\sum_i S_{pp'}^{(i)}(Jj) = 2j + 1,$$

where j is the spin of the hole state, indicates that the sum of the $d_{3/2}$ spectroscopic factors should be 4.00, and that of the $s_{1/2}$ spectroscopic factors, 2.00. Only about one-half of the total $d_{3/2}$ hole strength is accounted for, as is expected, since only 3^- and 4^- spins have been analyzed at this resonance, and $d_{3/2}$ strength will be present in 2^- and 5^- states. The $s_{1/2}$ sum rule is, as expected, nearly satisfied. The situation is more complicated at the $p_{3/2}$ and $f_{5/2}$ resonances since at the $p_{3/2}$ resonance the data allowed analysis of only four out of nine particle-hole states, and at the $f_{5/2}$ resonance, only six out of ten particle-hole states.

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MEASUREMENT OF THE STATIC QUADRUPOLE MOMENT OF THE FIRST EXCITED STATE IN ^{24}Mg

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The static quadrupole moment of the first excited $J^\pi = 2^+$ state in ^{24}Mg was measured to be $Q = -0.243 \pm 0.035$ b. The experimental technique developed for this measurement uses the reorientation effect in heavy ion Coulomb excitation and allows accurate determinations of static quadrupole moments to be made, particularly in light nuclei.

The low cross sections encountered in the Coulomb excitation of nuclei with $A < 40$ have until recently prevented measurements of the quadrupole moments of excited states in this mass region using the reorientation effect. However, ion beams provided by tandem accelerators with terminal voltages of about 10 MV have now made these experiments feasible. The interpretation of the data on the first excited 2^+ states in light even-even nuclei in terms of the reorientation effect is straightforward in principle, because the contribution of other low-lying excited states and of the giant-dipole states[1] to the population of the first excited state is altogether less than 1%.