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ISOVECTOR PROPERTIES OF COLLECTIVE STATES AND THE IBA-2 MODEL [☆]

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The IBA-2 model of nuclear structure makes explicit predictions of isovector properties of collective states which have never before been tested. We have made the first measurements of separate neutron (M_n) and proton (M_p) matrix elements for the first 2^+ and 3^- states in $^{104,106,108,110}\text{Pd}$ by means of inelastic scattering of 180 MeV π^+ and π^- . It is found that the IBA-2 model with core polarization can explain the trend of the data for M_p , and M_n/M_p , but only if its parameters are empirically adjusted.

Isovector (or equivalently proton–neutron) properties of nuclear states provide extremely sensitive tests of nuclear structure models [1,2]. For heavy nuclei one model, which has gained increasing attention in recent years is the Interacting Boson Approximation (IBA) model [3]. In the latest version of this model, called the IBA-2 model [4] the active part of the nucleus (outside a supposedly inert core) is described in terms of a small number of mutually interacting proton and neutron bosons which can be either in s-state or d-state. This model is able to make explicit predictions regarding the isovector properties of nuclear transitions. Here we report on the first successful experiment specifically designed to test these predictions.

In the pioneering work of Iversen et al. [2] on ^{18}O it was clearly shown that comparison of inelastic scattering of positive and negative pions of energies near the (3, 3) resonance is a unique and powerful tool in the study of isovector characteristics. The unique advantage of pion scattering is that both the experimental method and the method of data analysis

are completely symmetric with respect to π^+ and π^- , and minimum uncertainty can be expected in the extraction of relative quantities such as M_n/M_p , the ratio of neutron and proton matrix elements for inelastic excitations. Pion inelastic scattering is therefore ideally suited for the study of isovector properties of IBA-2 [5]. However, pion beam intensity and energy resolution introduce severe practical limitations and no such studies have been reported so far. In the present experiment we report on the first such measurement of M_n and M_p for a series of palladium isotopes for which detailed IBA-2 calculations are available [6].

We have measured differential cross sections for elastic and inelastic scattering of 180 MeV π^+ and π^- from enriched targets ($\geq 95\%$) of $^{104,106,108,110}\text{Pd}$ at the EPICS spectrometer facility at LAMPF. As illustrated in fig. 1, the energy resolution obtained was ≈ 165 MeV. The absolute cross section normalization was determined both by normalizing elastic scattering to optical model predictions which are described later, and by measuring π^+p scattering at several angles from a CH_2 target and comparing it with phase shift predictions. The two methods were found to lead to consistent absolute normalization to within $\pm 5\%$, for

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Fig. 1. Excitation energy spectra for the reaction $\text{Pd}(\pi, \pi')$ at $\theta_{\text{lab}} = 42.5^\circ$.

all the four isotopes. The relative errors in the final cross-sections between the isotopes are estimated to be $\leq 3\%$. In fig. 2, where we show the elastic and inelastic 2_1^+ and 3_1^- angular distributions only the statistical errors are indicated. In order to extract M_n and M_p from our data we have made distorted wave impulse approximation (DWIA) calculations with the coordinate space computer code DWPI [7] using Kisslinger type optical potential and collective form factors. In order to obtain simultaneous good fits for π^+ and π^- elastic and inelastic angular distributions it was found necessary to evaluate the π -nucleon t -matrix at an energy 30 keV less than the incident energy [8]. We find

Fig. 2. Angular distributions for elastic and inelastic scattering for the reaction $\text{Pd}(\pi, \pi')$. The solid lines are DWPI predictions.

that if the measured cross sections are renormalized by optical model fits to the elastic scattering, and the inelastic scattering is analyzed in terms of DWIA using the same optical model, the resulting deformation parameters β are quite stable with respect to minor changes in the optical model parameters. This procedure also minimizes the effect of systematic errors and

we have adopted it for the analysis of the present data. The neutron and proton deformation parameters β_n and β_p for a given transition were varied till a simultaneous, best χ^2 fit to both π^+ and π^- inelastic angular distributions was obtained. As is well known the proton transition matrix element M_p is related to β_p as: $B(E1^+) \equiv M_p^2 \equiv (3ZR^1/4\pi)^2 \beta_p^2$. M_n is defined in an exactly similar manner in terms of N and β_n . The radius parameter R is sometimes related to the half density radius of the potential well used in the DWIA analysis. However, for strongly surface absorbed pions, the effective value of R is known to occur farther out in the surface, and we have set $R = 1.20 A^{1/3}$ fm. In the present case ($c = 1.06 A^{1/3}$ fm and $a = 0.55$ fm) this R corresponds to the point where the density has fallen to 23% of its central value. With this choice of R we obtain the results shown in table 1. We note that our values of M_p for the 2_1^+ states agree well within errors ($\leq 5\%$) with those from lifetime measurements [9]. For the 3_1^- states no other direct results for M_p are available for comparison.

In the IBA-2 model the neutron and proton quadrupole transition matrix elements are defined as [6]:

$$Q_p = \alpha_p A_p + \beta_p B_p, \quad Q_n = \alpha_n A_n + \beta_n B_n.$$

The nuclear structure information is contained in the reduced boson proton-neutron-transition matrix elements $A_{p,n}$ and $B_{p,n}$; for the d-boson non-conserving and d-boson conserving parts, respectively. $\alpha_{p,n}$ and $\beta_{p,n}$ are the corresponding values of the quadrupole operators.

We relate our experimental results to the IBA-2 model at two different levels. We can consider the IBA-2 model with or without core polarization. Further, we can treat $\alpha_{n,p}$ and $\beta_{n,p}$ as adjustable parameters, as was done in ref. [6], or we can use the values calculated in a generalized seniority scheme using a surface delta interaction [10]. These calculations give (all in fm^2) $\alpha_n = 18.5, 16.6, 15.6, 14.8$; $\beta_n = -8.2, -8.2, -3.7, 2.4$ and $\alpha_p = 14.7, 15.1, 15.3, 15.6$, $\beta_p = -4.3, -3.9, -2.6, -3.3$ for palladium 104, 106, 108 and 110 respectively. In all these comparisons we take A_i and B_i from ref. [6].

We first consider the IBA-2 model with core polarization. If we follow the phenomenological procedure, use $\chi_p \equiv \alpha_p/\beta_p$, and $\chi_n \equiv \alpha_n/\beta_n$ as optimized in ref. [6], and set $M_n = eQ_n$, $M_p = eQ_p$ for the 2_1^+ states, we obtain the average values $\langle \alpha_n \rangle = 21.2 \text{ fm}^2$, and $\langle \alpha_p \rangle = 38.8 \text{ fm}^2$. These lead to a constant $M_p \approx 86 e \text{ fm}^2$ and to rapidly changing M_n/M_p shown by the thin

Table 1
Summary of results for excitation of 2^+ states in Pd isotopes a).

J^π	A	Experimental results				Model predictions				
		ref. [8]	(π, π')		M_n/M_p	N/Z	IBA-2			
		M_p	M_p	M_n			M_n^b	M_p^b	M_n^c	M_p^c
2_1^+	104	74(2)	77(2)	106(3)	1.38(5)	1.26	108	79	119	83
	106	83(3)	83(2)	118(3)	1.43(5)	1.30	125	85	126	86
	108	88(3)	89(2)	136(3)	1.52(5)	1.35	135	89	129	87
	110	94(3)	98(2)	156(4)	1.59(6)	1.39	150	95	136	90
2_2^+	104	16(1)					6	17	13	17
	106	13(1)					10	18	19	19
	108	13(1)					9	15	21	18
	110	11(1)					14	16	30	21
3_1^-	104		365(9)	542(14)	1.49(5)	1.26				
	106		360(9)	533(13)	1.48(5)	1.30				
	108		334(8)	539(13)	1.61(6)	1.35				
	110		315(8)	523(13)	1.66(6)	1.39				

a) $M_{p,n}$ are in units of $e \text{ fm}^2$ for 2^+ , and $e \text{ fm}^3$ for 3^- .

b) Average $\langle e_p \rangle = 1.13 e$, $\langle e_n \rangle = 0.49 e$, and empirical α 's and β 's.

c) Average $\langle e_p \rangle = 1.17 e$, $\langle e_n \rangle = 0.48 e$, calculated α 's and β 's.

Fig. 3. $(M_n/M_p)/(N/Z)$ for the 2^+ states in Pd isotopes. The curves refer to IBA-2 calculations described in the text. *Without core-polarization*: thin solid line for empirically adjusted $\langle\alpha\rangle$, $\langle\beta\rangle$, thin dashed line for microscopically calculated α , β . *With core-polarization*: thick solid for empirically adjusted $\langle\alpha\rangle$ and $\langle\beta\rangle$ and $\langle e_p\rangle = 1.12 e$, $\langle e_n\rangle = 0.49 e$, thick dashed line for microscopically calculated α , β and $\langle e_p\rangle = 1.17 e$, $\langle e_n\rangle = 0.48 e$.

solid curve in fig. 3. Neither of these results are in agreement with the data. Further, M_p for the 2_2^+ states are predicted to be ≈ 2.5 larger than the experimental ones. If we use the calculated values of α and β , we obtain even poorer agreement with the data. We obtain M_n which are $\approx 75(\pm 8)\%$ of the experimental ones, M_p which are $\approx 41(\pm 4)\%$ the experimental ones, and M_n/M_p which are uniform factor ~ 2 larger than the experimental results (thin dashed curve in fig. 3). M_p for the 2_1^+ states fare better, being only $\approx 21(\pm 5)\%$ smaller than the experimental values.

From the above results we conclude that irrespective of what approach one adopts towards α 's and β 's, we must compensate for the truncation of the valence boson space by including core polarization. As in the shell model one can do this by introducing "effective" charges e_p and e_n for proton and neutron bosons and note that for a self-conjugate core (here $N = Z = 50$):

$$M_p = e_p Q_p + e_n Q_n, \quad M_n = e_n Q_p + e_p Q_n.$$

For a given nucleus once Q_p and Q_n are known, e_p and e_n are determined uniquely by fitting the measured values of M_n and M_p . We first use χ 's as empirically optimized in ref. [6] and $\langle\alpha_n\rangle = 16.4 \text{ fm}^2$, $\langle\alpha_p\rangle = 15.2 \text{ fm}^2$ (which are averages of the calculated results), to obtain Q_p and Q_n for each isotope. Comparison with M_p and M_n then leads to a set of e_p and e_n which are found to be essentially the same (within $\approx \pm 5\%$) for

all isotopes: $\langle e_p\rangle = 1.13 e$, $\langle e_n\rangle = 0.49 e$. The results for M_p and M_n/M_p obtained by using these effective charges are shown in table 1 and by the thick solid curve in fig. 3. The fit to the data is quite good. As shown in table 1 the same effective charges predict M_p for the 2_2^+ states which are in fair agreement with the data. In addition they lead to very distinctive predictions for M_n/M_p which should be tested in future experiments.

Unfortunately, if we use α 's and β 's as obtained from the microscopic calculations referred to earlier, the results are much poorer. Individual e_n are found to be fairly constant ($e_n = 0.46 e \rightarrow 0.50 e$) but e_p shows an unacceptable amount of variation ($e_p = 1.02 e \rightarrow 1.35 e$) in going from ^{104}Pd to ^{110}Pd . Equivalently, we note that if we use the average values: $\langle e_n\rangle = 0.48 e$, $\langle e_p\rangle = 1.17 e$, we fail to reproduce the trend of M_p and M_n individually, although M_n/M_p agrees with the data (thick dashed curve in fig. 3). For the 2_2^+ states the predicted M_p differ from the experimental ones by $43(\pm 23)\%$ and the predicted M_n/M_p differ by a factor two from those with empirically adjusted α 's and β 's.

Because of the limited success obtained above with the IBA-2 model without empirically adjusted parameters, it is instructive to examine what other simple phenomenological models predict. In the hydrodynamical model, nuclei in the Pd region are well described as vibrational nuclei, with

$$E(\lambda) = \hbar \langle C_\lambda/B_\lambda \rangle^{1/2},$$

$$M_p^2 = \hbar(\lambda + 1/2) [(3/4\pi) ZeR_p^\lambda]^2 / (B_\lambda C_\lambda)^{1/2}.$$

By analogy, M_n is defined in terms of N , R_n and $(B_\lambda, C_\lambda)_n$. The parameters B_λ (related to the mass transport associated with the vibration) C_λ (related to the effective surface tension or restoring force) and R can, in principle, vary from nucleus to nucleus and between neutron and proton fluids, but are generally considered constant in a small region of N and Z . Thus this model predicts $M_p = \text{constant}$ for a series of isotopes and $M_n/M_p = N/Z$. As seen in table 1, the experimental M_p increases by $\sim 25\%$ from ^{104}Pd to ^{110}Pd . Also the experimentally observed ratios of M_n/M_p for the 2_1^+ and 3_1^- states are respectively $\sim 12\%$ and $\sim 18\%$ higher than N/Z (see table 1). Better agreement with the experimental results can be obtained by treating B_λ , C_λ , and R as adjustable parameters. For example, we can

obtain excellent fits to the measured M_p by simply varying C_2 with neutron number. Similarly, the experimental M_n/M_p for both 2_1^+ and 3_1^- can be fitted perfectly by assuming either that the effective radius parameters R_n and R_p are different, or that $(B_\lambda, C_\lambda)_p$ and $(B_\lambda, C_\lambda)_n$ are different.

We can summarize our results as follows. The IBA-2 model without core-polarization is clearly unsuccessful in explaining the experimental results. With the inclusion of core polarization effects, via effective charges, the IBA-2 model can provide a good description of the data as long one allows empirical adjustment of its parameters. However, at this level, it is worthwhile to remember that other, even simpler models, can also explain the experimental results provided their parameters are also adjusted from isotope to isotope. Our first attempts to calculate some of the IBA-2 parameters on a microscopic basis have so far been unsuccessful. Clearly more theoretical work is required. At the experimental front measurement of M_n/M_p for other quadrupole transitions, particularly 0_1^+ to 2_2^+ would help narrow the range of alternative explanations.

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