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Proton and deuteron inelastic excitation of the 1^+ state at $E_x = 5.846$ MeV in ^{208}Pb: Isoscalar character and importance of tensor correlations

J. L. Tain,* G. P. A. Berg, I. Katayama,† S. A. Martin, J. Meissburger, J. G. M. Römer,‡ and J. Wambach§
Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, Federal Republic of Germany
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Differential cross sections for ^{208}Pb(p,p′) and ^{208}Pb(d,d′) excitation of the 1^+ state at $E_x = 5.846$ MeV were measured at $E_{inc} = 45$ MeV. The fact that the measured strengths of both reactions are very similar supports the isoscalar nature of the 1^+ state. The comparison of the experimental proton angular distribution to microscopic distorted-wave calculations using random phase approximation wave functions with and without tensor correlations suggests that the isoscalar tensor part of the $(\pi+\rho)$-exchange potential is too strong.

The identification of the 1^+ state discovered[1] in ^{208}Pb at $E_x = 5.846$ MeV with the isoscalar state of several theoretical predictions[2,3] opens the possibility to study the rather unknown spin-dependent and isospin-independent part of the residual interaction in nuclei. In this connection, it is highly desirable to obtain as detailed as possible knowledge of the structure of this state. Several experimental studies[4–7] were already performed with this aim. We were particularly interested in two different aspects: (a) whether the state has really isoscalar nature, and (b) what is the importance of tensor correlations in the description of this state.

It has been pointed out[8] that in order to produce an isoscalar 1^+ state near the unperturbed energy of the two spin-flip $(0\hbar\omega)$ contributions $\pi(1h_{9/2}1h^{-1}_{11/2})$ ($\epsilon_{ph} = 5.573$ MeV) and $\nu(1i_{11/2}1i^{-1}_{13/2})$ ($\epsilon_{ph} = 5.845$ MeV) the isoscalar spin-dependent part v_σ of the nuclear residual interaction has to be small. This can be achieved in two ways, either with a small central term and no tensor interaction[2] or with a larger central term compensated by a large tensor term.[3] The effect of the tensor interaction is to increase in the wave function of the 1^+ state the weight of the higher lying $(2\hbar\omega)$ particle-hole (p-h) contributions. This increase depends on the strength of the tensor force. For reasonable interaction strengths the dominant part of the wave function is still the in-phase combination of the spin-flip contributions. The interesting question is whether one could experimentally distinguish between these two types of descriptions. Experiments[1] with real photons test essentially the momentum transfer $q = 0$ region, while the $2\hbar\omega$ contributions peak at large q values. Electron scattering, which can go to larger q values, does not show[5,6] sensitivity to the tensor correlations. As pointed out in Ref. 3, the tensor mixing is an exchange effect imposed by the antisymmetry of the interaction. Thus the $2\hbar\omega$ component in the wave function is strongly excited only by nucleon-nucleus scattering via the exchange amplitude. We choose inelastic proton scattering to investigate the importance of tensor correlation in the low lying 1^+ state in ^{208}Pb.

To investigate the isoscalar nature of this state one could make use of the property that deuteron inelastic scattering strongly excites only isoscalar states.

According to these considerations we carried out measurements of the ^{208}Pb(p,p′) and ^{208}Pb(d,d′) reactions using the 45 MeV proton and deuteron beams of the energy variable isochronous cyclotron JULIC. The necessary high resolution in the beam energy was achieved with the double analyzing magnet system in the beam line operated in the dispersive mode. The targets consisted of 480 and 200 μg/cm^2 thick ^{208}Pb layers evaporated on a 20 μg/cm^2 thick carbon backing for the (p,p′) and (d,d′) experiments, respectively. The reaction products were momentum analyzed in the quadrupole-quadrupole-dipole-dipole-quadrupole (QQDDQ) magnet spectrometer BIG KARL,[9] which was operated at a dispersion of $D = 15$ cm/%. The beam line dispersion was matched to this dispersion. The reaction products were detected with a 30 cm long and 3 cm high two-dimensional multiwire proportional chamber[10] and were identified with a ΔE gas counter followed by a 1 cm thick plastic scintillator. First- and second-order aberrations of the spectrometer were corrected by means of the first two quadrupoles and the H_t correction coils using a ray tracing procedure. In this way the acceptance solid angle could be opened to $\Delta\Omega = 3.0$ msr in the case of (p,p′) and $\Delta\Omega = 2.4$ msr in the case of (d,d′) without loss of resolution, which was 12 to 18 keV full width at half maximum (FWHM) for protons, and 15 to 20 keV (FWHM) for deuterons. The resolution worsened with increasing angle as a consequence of the kinematical mismatch. Proton spectra for the region around 5.5 MeV of excitation energy were measured at 13 laboratory angles ranging from 12.5° to 44.0°, while deuteron spectra were recorded at ten laboratory angles from 10.0° to 50.0°. Sample spectra are shown in the upper part of Fig. 1. The identification of the peaks in the proton spectra was accomplished as follows: Lines from known states in ^{27}Al (calibration target) were used to identify the strongest peaks in ^{208}Pb known from another experiment.[11] With these lines the final $B\rho$ vs channel calibration curve was produced, which is free from uncertainties on the angle and energy of the incoming beam. This procedure gave an excitation energy $E_x = 5.844 \pm 0.003$ MeV for a peak which was identified with the 1^+ state seen at 5.846 ± 0.001 MeV in the $(\vec{\gamma},\gamma')$ study.[1] The similarity of the proton and deuteron spectra allowed a direct

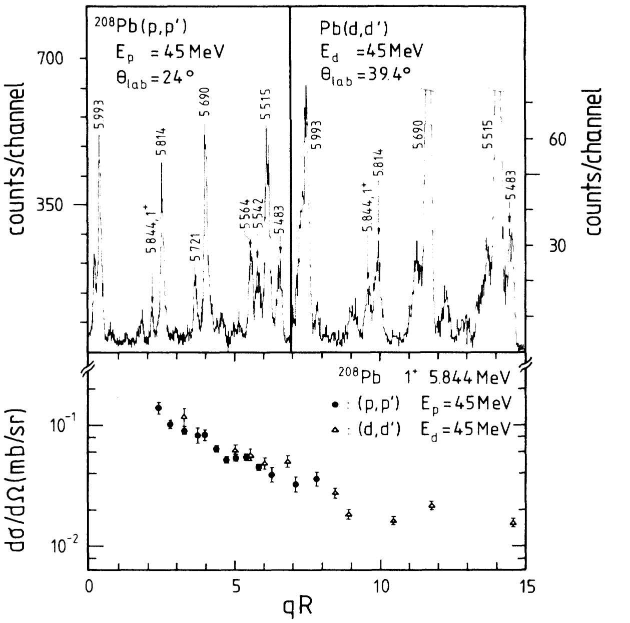

FIG. 1. Upper part: Detail of the measured proton and deuteron spectra showing the 1^+ state. Lower part: Measured proton and deuteron cross sections as a function of momentum transfer (q) times absorption radius (R).

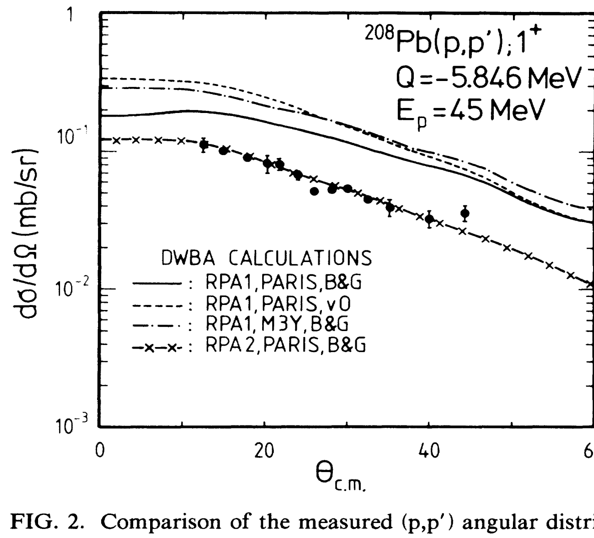

FIG. 2. Comparison of the measured (p,p′) angular distribution of the 1^+ state with several theoretical calculations. For the meaning of RPA1 and RPA2, see the text. The following parameters were used: PARIS (Ref. 19), M3Y (Ref. 21), B&G (Ref. 13), and vO (Ref. 20).

identification of this state in the later one.

Absolute cross sections were determined by comparison of the measured elastic scattering cross section to the results of an optical model calculation[12] using the parameters from the global fits of Ref. 13 for protons and of Ref. 14 for deuterons. The estimated uncertainty of this method is of the order of 10%. The cross section angular distributions for both reactions are depicted in the lower part of Fig. 1. Instead of the scattering angles the quantity qR = momentum transfer × absorption radius is used in Fig. 1 in order to make the plot independent of kinematics and nature of the projectile. The measured proton data are shown again in Fig. 2 as a function of angle together with theoretical calculations.

As already mentioned, deuterons, which have isospin $t=0$, can be used to distinguish isoscalar ($\tau=0$) from isovector ($\tau=1$) excitations. In inelastic scattering on $N=Z$ nuclei with ground state isospin $T_0=0$ deuterons cannot excite isovector states ($T=1$) due to the conservation of the isospin quantum number. For $N \gg Z$ nuclei ($T_0 \gg 0$) this argument cannot be applied because here isovector excitation is not equivalent to isospin transfer $\Delta T=1$, and actually most of the strength of isovector excitation concentrates on $T=T_0$ states.[15] However, one can arrive at the same conclusion if one considers the dynamical aspects of isospin, which in turn allows one to define more precisely isoscalar and isovector excitations: *Isoscalar excitations* are those in which protons (π) and neutrons (ν) move in phase with comparable strength, or using more formal language, which have a large isoscalar transition density $\rho_+=\rho_\pi+\rho_\nu$. *Isovector excitations* are those in which protons and neutrons move out of phase, that is, those which have large isovector transition density $\rho_-=\rho_\pi-\rho_\nu$. In a folding model description of deuteron scattering[16] the interaction terms dependent on the isospin (of the form $\vec{\tau}\cdot\vec{\tau}$) will be absent due to the $t=0$ isospin value of the deuteron, and the remaining terms will couple only the isoscalar part ρ_+ of the transition density. One expects then a strong suppression of isovector excitations which have small ρ^+, in deuteron inelastic scattering. In order to set the scale for the cross section strength in the case of the inelastic scattering of 45 MeV deuterons we decided to compare it with the inelastic scattering of 45 MeV protons, which is not an isospin selecting probe. This is done for the 1^+ state at $E_x=5.846$ MeV in the lower part of Fig. 1. We do not give any deep meaning to the striking similarity found, since the reaction mechanism for (d,d′) is probably more complex than for (p,p′). Important for our argument is that the strength is not suppressed in (d,d′). From this we can rule out the suggestion of Ref. 5 that the state could be a piece of the higher lying isovector strength, shifted down in energy by 2p-2h admixing. This conclusion agrees with the results of Refs. 6 and 17, and supports the assumption that this state has predominantly isoscalar character.

To investigate the importance of tensor-induced correlations in the wave function of the 1^+ state, we compared the measured (p,p′) angular distributions with microscopic DWBA calculations performed with the computer code DWBA70,[18] which includes the knockon exchange terms. The results are shown in Fig. 2. We used random phase approximation (RPA) wave functions similar to those from Ref. 3, but with a larger configuration space which included 202 p-h contributions. Calculations were carried out with two different nuclear residual interactions. The first included the one-pion—one-rho ($\pi+\rho$) exchange model potential (responsible for the large tensor term) plus zero-range Landau-Migdal terms with $g_0=g_0'=0.6$ ($C_0=302.1$ MeV fm^3) and produced an isoscalar 1^+ state at 5.49 MeV. In the reaction calculation only the 72 configurations with amplitudes X (or Y) ≥ 0.01 were included (RPA1 in Fig. 2). The second included only the zero-range part with $g_0 = 0.05$ and $g'_0 = 0.6$ in order to produce an isoscalar state at 5.92 MeV. In this case only the two $0\hbar\omega$ contributions had amplitudes X (or Y) ≥ 0.01 and were included in the calculations (RPA2 in Fig. 2).

Calculations with the Tamm-Dancoff approximation (TDA) wave function of Vergados[2] were also performed, but the results did not differ essentially from those with RPA2, and are not shown. The remaining parameters employed in the calculation were the effective interaction derived in Ref. 19 (PARIS) and the optical model potential from the global fit of Ref. 13 (B&G). While the result obtained with RPA2 (cross-dashed line) reproduces the data quite well, the one from RPA1 (continuous line) overestimates the data by a factor of about 2. In order to check if the change of some of the other parameters would reduce the RPA1 cross sections, we also performed calculations using the optical parameters (vO) from Ref. 20 (dashed line) and two other sets of effective interaction parameters: the older M3Y interaction[21] (dashed-dotted line) and the one recently reported in Ref. 22, which gave a result indistinguishable from the one using the PARIS interaction. It can be seen from Fig. 2 that although the results are sensitive to the optical potentials and effective interactions employed, no improvement is obtained when available sets of parameters are used. We conclude that the discrepancy is produced at least in part because the isoscalar tensor part of the $(\pi+\rho)$-exchange potential used in Ref. 3 is too strong. We also performed calculations[23] at $E_p = 201$ MeV and compared these with the data of Ref. 7. It is interesting to note that again RPA2 describes the data much better, which supports our conclusion. In part triggered by these results, a mechanism for the reduction of the strong isoscalar $(\pi+\rho)$-exchange tensor term has been proposed:[23,24] a screening effect induced by 2p-2h excitations, which reduces its strength and range.

In conclusion, it is found that the 1^+ state in ^{208}Pb at $E_x = 5.846$ MeV has a predominantly isoscalar character from the relatively strong excitation in deuteron inelastic scattering. It was found to be necessary to reduce the isoscalar tensor part obtained in the $(\pi+\rho)$-exchange model in order to reproduce the proton inelastic scattering data with microscopic DWBA calculations using available optical potentials and effective interactions.

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*Permanent address: Instituto de Fisica Corpuscular (CSIC), Universidad de Valencia, Burjassot, Valencia, Spain.

†Permanent address: Research Center for Nuclear Physics, Osaka University, Osaka 567, Japan.

‡Permanent address: Leybold-Heraues, Köln, Federal Republic of Germany.

§Permanent address: Department of Physics, University of Illinois, Urbana, IL 61801.

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