Excitation of the 21+ and 22+ states in the 88Sr(p, p′) reaction at 25 and 31 MeV

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EXCITATION OF THE 2_1^+ AND 2_2^+ STATES
IN THE ^{88}Sr(p, p') REACTION AT 25 AND 31 MeV·
A LOOK BEHIND THE NUCLEAR SURFACE ☆

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Data for the excitation of the 2_1^+ and 2_2^+ states in the ^{88}Sr(p, p') reaction at 25 and 31 MeV indicate substantial contributions from the interior of the nucleus, Microscopic DWBA calculations reproduce this and yield a fair description of the data A detailed description, especially of the 2_2^+ state, is sensitive to the effective nucleon–nucleon interaction used and the non-locality of the optical potential, which are insufficiently known at present

It is generally believed that low-energy nucleon–nucleus scattering is sensitive only to the transition density in the vicinity of the nuclear surface, because contributions from the nuclear interior are suppressed as a result of absorption processes, reduction of the effective nucleon–nucleon interaction and non-locality effects

In order to test the actual sensitivity to the nuclear interior a transition with a transition density that has a main peak in the interior is needed The 2_2^+ state in ^{88}Sr at $E_x = 3\ 218$ MeV provides a good test case

The transition charge density as measured by (e, e') scattering shows a dominant peak well inside the nucleus, which qualitatively can be explained from simple shell-model considerations [1] Nuclear-structure calculations in a large model space [2] reproduce the (e, e') data for this state as well as those for the 2_1^+ state at 1 836 MeV and indicate that for the 2_2^+ state also the neutron transition density peaks inside the nucleus In this letter we present an analysis of the excitation of these states in inelastic proton scattering at 25 1 and 30 7 MeV We have chosen two different proton energies to ensure that characteristics of the data are not due to the choice of a specific projectile energy

Data at 25 1 MeV had been obtained at the AVF cyclotron of the Free University in a study of the
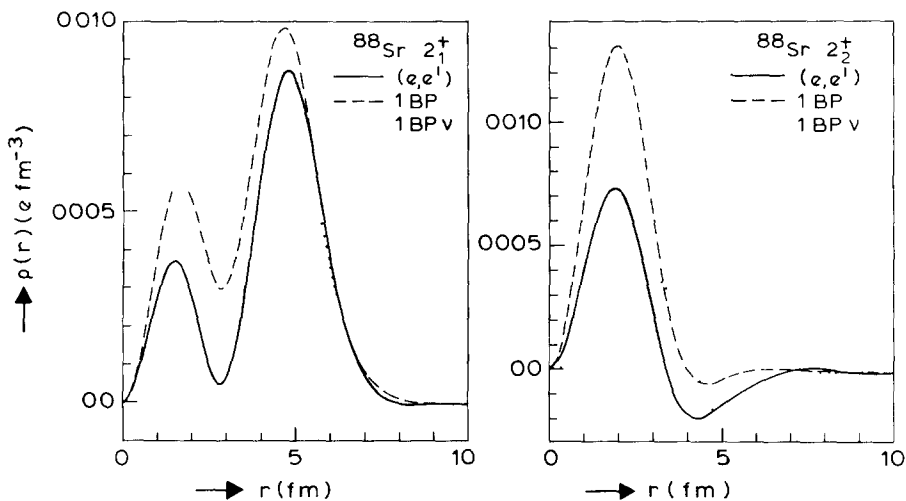
Fig 1 Transition charge densities for the 2_1^+ and 2_2^+ states as measured in electron scattering [1] (full curve) compared with the 1BP predictions for the transition charge densities (dashed curves) and for the neutron transition densities (dotted curves)

excited states of ^{88}Sr [3] The 30 7 MeV data were obtained at the KVI in Groningen The scattered protons were detected in the QMG/2 magnetic spectrograph [4,5], with an overall energy resolution of 18 keV Data were taken from 8° to 136° in steps of 4° with a horizontal resolution of 1 6° Targets of about 350 μg/cm^2 ^{88}Sr, enriched to 99 84%, deposited on carbon foils of ~18 μg/cm^2 thickness were used The absolute normalisation of the data was obtained from an optical-model fit to the elastic-scattering data

The transition charge densities for the 2_1^+ and 2_2^+ states as measured in (e, e') scattering [1] are shown in fig 1 The most prominent feature is the large value of the transition density in the nuclear interior for the 2_1^+ state A one-broken-pair (1BP) model calculation [2] with a number-projected ground state for both neutrons and protons gives a fair description of the measured transition charge densities (fig 1) Because of this and the fact that the transition current densities, which are sensitive also to the neutrons, are also rather well described we assume that the neutron transition densities, which play the most important role in (p, p') scattering at low energies, but which can not so easily be determined experimentally, are fairly well described by these model calculations The important point is then that also the neutron

transition density for the 2_2^+ state (see fig 1) has a large peak inside the nucleus

The (p, p') data for both states are shown in fig 2 It is clear that the angular distributions for both 2^+ states are rather different This is an indication for the sensitivity of the probing proton to the nuclear interior

We performed microscopic DWBA calculations for the transitions to these states with a density dependent interaction and using the density-matrix elements as given by the 1BP model calculations [2] (It was checked that two-step excitation of the 2_2^+ state via the 2_1^+ or 3_1^- state plays a negligible role) The single-particle wave functions were calculated in a Woods–Saxon potential with $r_0 = 1$ 29 fm, $a = 0$ 65 fm, $V_{so} = 6$ 2 MeV with the depth adjusted to reproduce the single-particle energies A Perey non-locality correction [6] was applied with $\beta = 0$ 85 fm With these parameters the transition densities of various transitions were well described [7] For the 2^+ states they are shown in fig 1

For the microscopic interaction we used the density and energy dependent complex effective interaction $v(E, \rho)$ derived in a BHF calculation [8] from the Hamada–Johnson (HJ) potential [9] The local energy was calculated as $E = E_p - V_C$ where E_p is the projectile energy and V_C the Coulomb potential
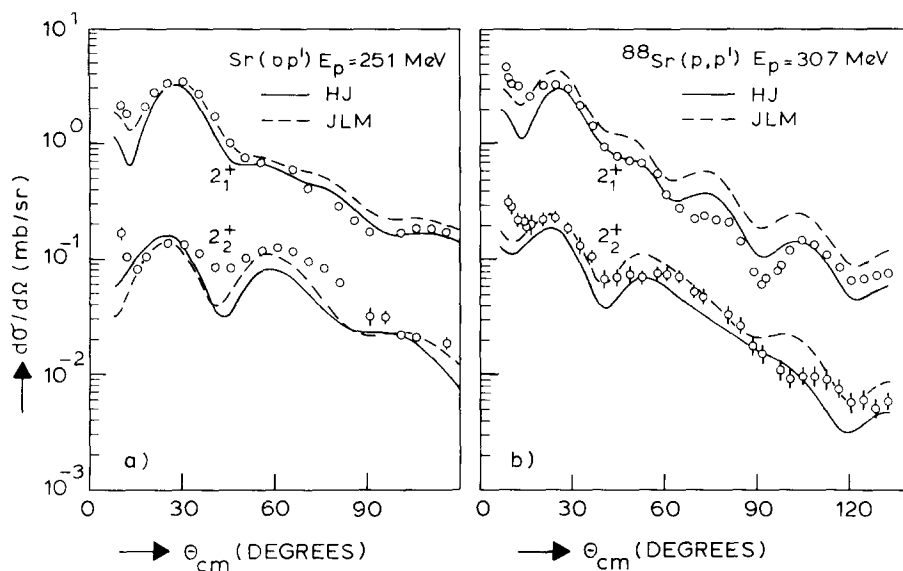
Fig 2 Measured angular distributions for the 2_1^+ and 2_2^+ states at E_p = 25 1 MeV (a) and E_p = 30 7 MeV (b) compared with DWBA calculations with the HJ interaction (full curves) and the JLM interaction (dashed curves)

Furthermore a local-density approximation of the form

$$V(r) = \{v(r, E(r_1), \rho(r_1))v(r, E(r_2), \rho(r_2))\}^{1/2} ,$$

with

$$r = |r_1 - r_2| ,$$

was used The target matter density ρ was obtained from the charge density determined in electron scattering [10] (see also ref [11]) by unfolding the proton charge distribution and assuming the neutron density to be proportional We used a phenomenological optical potential that was determined in a $^{88}Sr(p, p')$ experiment at 24 6 MeV [12], applying the Becchetti–Greenlees energy correction [13] to obtain the parameters at the actual energies in the entrance and exit channels A Perey non-locality correction with β = 0 85 fm was also included for the distorted waves The calculations were performes with exact treatment of exchange using the code DWBA82 [14]

The cross sections calculated in this way for both energies are shown in fig 2 as the full curves The difference in strength and the large difference in shape of the angular distributions for the two 2^+ states are described very well in the calculations (we want to point out that there are no free parameters in our

calculations) The large second maximum of the angular distribution for the 2_2^+ state, which is not present for the 2_1^+ state, is reproduced in the calculations and indicates that there is indeed a sensitivity to the nuclear interior even at these low energies of the incoming proton Also the decrease of the ratio of the second to the first maximum in the cross section data for the 2_2^+ state in going from 25 to 31 MeV is reproduced by the calculation This decrease is mainly due to kinematical effects and to the energy dependence of the optical potential The cross sections at forward angles are underpredicted although Coulomb excitation was included

The sensitivity to the nuclear interior depends on several ingredients in the calculations, explicitly through the density dependence of the effective interaction and through the non-locality correction and implicitly through the exchange contributions To study these points several other calculations were performed The first is one in which we employed the JLM interaction [15] which has been quite successful in predicting elastic-scattering data This interaction contains the exchange terms implicitly, hence the (now local) transition potential can be obtained by folding the interaction with the neutron and proton transition densities as given by the 1BP model For the local energy

we used the same prescription as before We corrected the interaction to fulfill the dispersion relation along the lines of ref [16] For the spin–orbit interaction we used a short range interaction with a strength that reproduced the strength of the spin–orbit potential of the Becchetti–Greenlees global potential The optical potential was treated in a consistent manner by using also the JLM interaction, changing the overall strength of the real and imaginary terms by a few percent to fit the elastic scattering data The nonlocality correction for the distorted waves was also taken from the JLM interaction, i e we used a damping factor of the form $F(r) = (m_k/m)^{1/2}$, where m_k is the k-mass [15] These calculations were performed with the code ECIS79 [14] The resulting cross sections are given by the dashed curves in fig 2 The results are similar to the ones obtained in the calculations with the HJ interaction, although the cross sections are on the average somewhat larger The JLM results were essentially the same when we used the phenomenological distorted waves instead of the "consistent" ones

In order to test the approximate treatment of exchange, which is implicit in the use of the JLM interaction, we performed the following calculations We treated the exchange terms in the HJ interaction in a similar way as in JLM by using the Slater approximation [17] The results for the 2_1^+ state are within 20% the same as in the "exact" calculations For the 2_2^+ state they differ, however This is shown for the case of 25 MeV in fig 3 The second maximum is reduced relatively to the first, contrary to the experimental data and the JLM description as shown in fig 2a Turning off the spin-dependent terms in the interaction hardly affects the 2_1^+ state and gives an overall reduction of the cross section for the 2_2^+ state of about 20% Finally changing the r-dependence of the HJ interaction (a sum of Yukawa's and a delta function for exchange) to the (one) gaussian r-dependence of JLM, keeping the volume integrals of the interaction the same, leads to the dotted curve in fig 3, which resembles very much the JLM result shown in fig 2a Hence it turns out that the form factor of the used effective interaction plays a quite important role and the good description of the 2_2^+ state with the JLM interaction seems to be at least partly due to the use of a gaussian form factor One has to be careful in drawing quantitative conclusions for a non-collective transition from
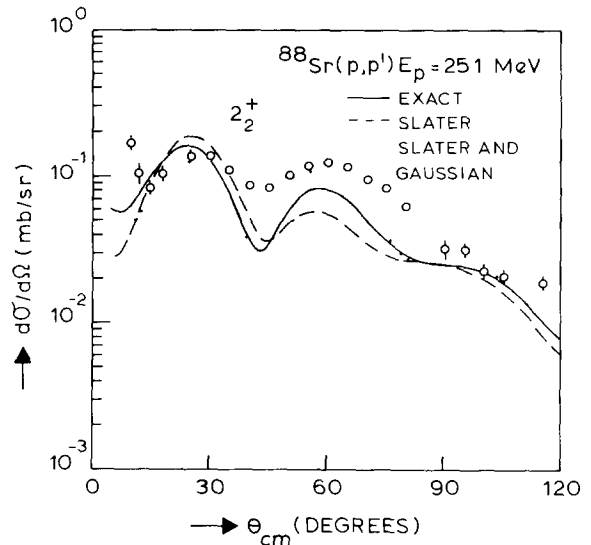

Fig 3 Measured angular distribution for the 2_2^+ state for E_p = 25 1 MeV compared with DWBA calculations with the HJ interaction, exact exchange (full curve), Slater approximation (dashed curve), Slater approximation with gaussian form factor (dotted curve)

a JLM description, as we have seen that the neglect of spin-dependent terms in the interaction has a considerable effect on the magnitude of the calculated cross section

The influence of the non-locality correction on the distorted waves, which is a direct weighting of the nuclear interior in the direct part of the T-matrix element, but more complicated in the exchange part, was studied by replacing the Perey prescription by the one given by JLM or turning it off completely We used the HJ interaction with exact exchange and found only for the 2_2^+ state an enhancement of about 25% in the cross section in case of a vanishing non-locality correction This is smaller than expected because the damping of the distorted waves is about 15% in the interior so that, if we neglect exchange effects, and assuming all cross section to come from inside of the nucleus, an increase by a factor of $(1/0 85)^4$ = 2 is expected We also performed a calculation with a M3Y interaction [18] replacing the HJ interaction With this interaction the cross section is enhanced by a factor of two when the Perey damping factor is turned off So it seems that with the HJ interaction the interior already contributes less and the

exchange terms almost compensate the non-locality correction

Finally the importance of the density dependence of the nucleon–nucleon interaction was studied by turning off In case of the HJ interaction this hardly effected the calculated cross sections This suggests that exchange effects are dominant in this case For the JLM interaction this resulted in a strong enhancement of the second maximum for the 2_2^+ state while the 2_1^+ state was almost not effected This demonstrates again that this second maximum is largely due to contributions from the nuclear interior

In conclusion, we can say that nucleon–nucleus scattering at a projectile energy as low as 25 MeV shows definitely a sensitivity to the nuclear interior This confirms and extends the observation by Kelly [19] from a simulation study of $E_p > 60$ MeV proton scattering that at the lower energies one still feels the nuclear interior although some detailed sensitivity is lost

Microscopic DWBA calculations reproduce the measured (p, p') data both at $E_p = 25$ and $E_p = 31$ MeV with a quality approaching the description of the (e, e') data, taking into account that we did not optimise the neutron density in order to get a better description of the data We feel that the latter would be premature as our analysis indicates that the detailed results of the calculations for a state with a large transition density in the nuclear interior, sensitively depend on the type of interaction used, especially its form factor and density dependence, and on the use of a non-locality correction It seems that due to exchange the HJ interaction suppresses the nuclear interior slightly to much Unfortunately, the HJ interaction is the only realistic density-dependent and complex interaction, parametrised in terms of Yukawa's (as needed in DWA82), for these energies at this moment that can be used in microscopic calculations including exchange The JLM interaction gives quite acceptable

results, although the approximate treatment of exchange and the neglect of the spin-dependent part leads to errors for non-collective transitions Certainly, data like the ones described here for transitions, which originate mainly from the interior, will help to determine the effective nucleon–nucleon interaction at low energies

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