The Energy-Dependence of Polarization Observables in the $^2H(d,\gamma)^4He$ reaction

H. R. Weller

R. M. Whitton

J. Langenbrunner

Evans Hayward

W. R. Dodge

See next page for additional authors

Original Publication Citation

Weller, H. R., Whitton, R. M., Langenbrunner, J., Hayward, E., Dodge, W. R., Kuhn, S., & Tilley, D. R. (1988). The energy-dependence of polarization observables in the $^2H(d,\gamma)^4He$ reaction. *Physics Letters B, 213*(4), 413-418. https://doi.org/10.1016/0370-2693(88)91283-x

THE ENERGY DEPENDENCE OF POLARIZATION OBSERVABLES IN THE $^2H(d, \gamma)^4He$ REACTION

H.R. WELLER [a,b], R.M. WHITTON [a,b], J. LANGENBRUNNER [a,b], Evans HAYWARD [c,1], W.R. DODGE [c], S. KUHN [d] and D.R. TILLEY [e,b]

[a] Duke University, Durham, NC 27706, USA
[b] Triangle Universities Nuclear Laboratory, Durham, NC 27706, USA
[c] National Bureau of Standards, Gaithersburg, MD 20899, USA
[d] Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA
[e] North Carolina State University, Raleigh, NC 27607, USA

Received 16 June 1988

Measurements of the tensor and vector analyzing powers, $A_{yy}(130°)$ and $A_y(130°)$, have been obtained for the $^2H(d, \gamma)^4He$ reaction for energies ranging from $E_d(\text{lab})=0.3$ MeV to $E_d(\text{lab})=50$ MeV. The $A_{yy}(130°)$ data are sensitive to the D-state present in the ground state of ^4He and are observed to have their maximum value near $E_d=30$ MeV. The vector analyzing power data show a maximum near $E_d=3$ MeV. The data are compared to the results of a microscopic multi-channel resonating group model calculation.

1. Introduction

The observation of a large tensor analyzing power, $T_{20}(\theta)$, in the reaction $^2H(d, \gamma)^4He$ for 9.7 MeV incident deuterons has generated a great deal of interest because it provided independent evidence for a D-state component in the ground state of ^4He [1–3]. In this reaction the deuteron captures an identical deuteron having spin 1, permitting channel spins of 0, 1, and 2. The excited or scattering state then has total angular momentum $\boldsymbol{J}=\boldsymbol{l}+\boldsymbol{S}$, where $\boldsymbol{l}$ is the relative orbital angular momentum in the incoming channel. The fact that we are dealing with identical bosons requires that $l+S$ be even. From the dominant $l=2$ capture state, electric quadrupole photons populate the 0^+, $L=S=0$ ground state of ^4He. The D-state admixture in ^4He manifests itself in the three $S=2$ transitions involving $l=0, 2, 4$. It is the interference of the dominant $S=0$ E2 capture amplitude with these three $S=2$ E2 capture terms leading to the D-state of ^4He which is expected to give rise to non-vanishing tensor analyzing powers [e.g. $A_{yy}(\theta)$].

[1] On leave of absence at Duke University, Durham, NC 27706, USA.

There are two outstanding questions in this problem. First, there is the problem of extracting a quantitative estimate of the D-state component in ^4He from these measurements (which must be done with the use of a model). Second, and not independent of the first, is the question of understanding the non-E2 radiation whose presence is apparent in the vector analyzing power. In this connection it is important to realize that the tensor analyzing powers are finite only if S, S' and 2 triangulate, while the vector analyzing powers require S, S' and 1 to triangulate (S and S' are the channel spins of two interfering amplitudes). This means that it is possible to have an $S=1$ capture amplitude interfere with the dominant $S=0$ E2 term to produce a sizeable vector analyzing power while having only second order effects in the tensor analyzing powers [there it would have to interfere with itself or one of the (small) $S=2$ E2 terms]. This statement indicates that the physics driving the vector analyzing power can be quite different from that driving the tensor analyzing powers. Data on the vector analyzing power $iT_{11}(\theta)$ (or A_y, where $A_y=2\sqrt{3}iT_{11}$) have been obtained at $E_d=9.7$ MeV and showed significant non-zero values [4]. This ob-

0370-2693/88/$ 03.50 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

servable indicates the presence of radiation having a parity opposite to that of E2, as first pointed out by Mellema et al. [5], whose additional measurements at $E_d=9.7$ MeV verify that at least three multipoles are contributing: the dominant E2, along with E1 and M2. It is also worth noting that while the spherical tensor analyzing powers, $T_{20}(\theta)$ and $T_{22}(\theta)$, depend on the interference of the dominant $S=0$ $(L=2)$ E2 amplitude with each and all of the $S=2(L=0, 2, 4)$ E2 amplitudes, the cartesian tensor analyzing power $A_{yy}(\theta)$ does not contain the interference term which contains the $S=2(L=0)$ E2 amplitude [neglecting second order $(S=2)^2$ type terms [6,7]. This result is significant because it is the $S=2(L=0)$ E2 amplitude which will be the most strongly affected [8] by the D-state of the deuteron; the latter is expected to have a relatively small effect on $A_{yy}(\theta)$ [9].

There have been a number of theoretical attempts to explain and interpret the results of this reaction study. Following the methods of Santos et al. [7], Tostevin [10] was able to account for the A_y and A_{yy} data at $E_d=9.7$ MeV with a point deuteron model. His calculations used wave functions [11] which corresponded to a value of the D_2 parameter of -0.16 and -0.24 fm^2, and included E2, E1 and M2 radiations. (D_2 is closely related to the asymptotic D-to-S state ratio.) The E1 strength in his calculation arose from the isoscalar spin-dependent part of the E1 operator.

Very recent work has been critical of such potential model calculations [12], especially at very low energies. In another effort [13], a microscopic model calculation using S-state only deuterons was compared to the low energy behavior of the cross section of the ^{2}H(d, γ)^{4}He reaction and it was concluded that the D-state admixture in ^{4}He is $\sim$5–7%. However, Picarewicz and Koonin [8] have pointed out that the $^2S_2(E2)\to{}^0S_0$ amplitude (using the notation ^SL_J) becomes important when the deuteron D-state is considered and, since S-wave capture dominates the very low energy cross section [14,15], the deuteron D-state is important in analyzing this observable. This effect was not considered in ref. [13]. New results [16] now suggest that the coupling to other channels (n+^{3}He and the p+^{3}H channels) also has large effects on these calculated cross sections. And, as will be illustrated below, significant amounts of non-E2 radiation may be present at the low ($E_d\leqslant 3$ MeV) energies [17]. These results indicate the need for further experimental data to help define and isolate these complicating effects.

In this paper we present our experimental results for $A_y(130°)$ and $A_{yy}(130°)$ which cover the deuteron energy range from $\sim$0.3 MeV up to 50 MeV. These results provide new information which should be critical to future theoretical treatments of this reaction, especially to attempts to extract information on the D-state of ^{4}He. We also present the results of a recent microscopic calculation of the ^{2}H(d, γ)^{4}He reaction which includes E1, M1, E2 and M2 radiation as well as coupling to the n–^{3}He and p–^{3}He channels [16]. This model provides a good description of $A_{yy}(E)$ below 35 MeV and displays the qualitative trend of $A_y(E)$.

2. Experimental details

Here we describe three separate experiments in which $A_y(130°)$ and $A_{yy}(130°)$ have been measured using tensor polarized incident deuterons.

The experiment below $E_d=20$ MeV used the deuteron beam accelerated in the TUNL FN tandem Van de Graaff, the polarized ions being generated by a Lamb-shift source equipped with a spin filter [18]. The lowest energy experiment was performed using 3.4 MeV deuterons degraded in energy to $\sim$0.6 MeV before they entered the gas region of the gas-filled target operated at 827.4 kPa and having Havar windows with a total thickness of 2.54×10^{-3} cm. The deuterons actually stopped in the gas target so that they should be viewed as having energies extending from zero to 0.6 MeV with an average energy near 0.3 MeV. The second low energy experiment was performed with the thin-walled, tantalum-lined gas cell described in ref. [19], where the beam entered the target having 1.6 MeV and emerged at 0.6 MeV with a center-of-target energy of 1.2 MeV. The effect of the degrading foils on the beam polarization was studied in a separate experiment. A tritiated titanium target was placed at the rear end of the gas cell and the analyzing power of the ^{3}H(d, n)^{4}He reaction was measured. The known analyzing powers [20] were used to deduce the beam polarization for various values of gas pressure ranging from zero to the value needed to stop producing neutrons. The deuteron beam polarization measured this way was found to be about 10% less than the value obtained from the quench-ratio method, and was independent of gas pressure. The experiments using polarized deuteron energies of from 3 to 15 MeV were performed using the 1.9 cm diameter liquid nitrogen-cooled gas cell having tantalum windows, as described in ref. [3]. The captured γ-rays were detected in a pair of NaI(Tl) spectrometers having plastic anticoincidence shields as well as massive lead and paraffin shielding. The high Q-value of this reaction (23.8 MeV) places the γ-rays of interest in a background-free region of the spectrum. The quality of the spectra produced using this technique is illustrated in ref. [19].

The analyzing powers, $A_y(\theta)$ and $A_{yy}(\theta)$, have been measured with these targets. These measurable quantities are defined as

$$A_y(\theta)=\frac{1}{P}\frac{Y_1-Y_3}{Y_1+Y_2+Y_3}, \quad A_{yy}(\theta)=\frac{1}{P}\frac{Y_1+Y_3-2Y_2}{Y_1+Y_2+Y_3},$$

where P is the polarized fraction of the beam current and Y_1, Y_2, and Y_3 are the yields obtained with the deuteron in states $m=1$, $m=0$, and $m=-1$, respectively, with the spin symmetry axis of the deuteron parallel to $\boldsymbol{k}_{\text{in}}\times\boldsymbol{k}_{\text{out}}$.

The high energy (20–50 MeV deuterons) measurements made use of the polarized deuteron beam generated at the 88 inch cyclotron at Lawrence Berkeley Laboratory. The physical layout of the experiment is shown in fig. 1. The target was contained in a 10 cm diameter gas cell having 2.54×10^{-3} cm Kapton windows and cooled to liquid nitrogen temperature. The resulting target thickness was 15 mg/cm^2. The target was viewed by two NaI(Tl) spectrometers having anticoincidence shields as well as massive, passive neutron and γ-ray shielding.

Pulses registered in the NaI(Tl) detectors were timed relative to the cyclotron RF pulse and a time-of-flight condition was used to select the γ-rays. In order to eliminate all background, plastic scintillation counters were installed in a vacuum chamber two meters from the target to detect the recoil α-particles in coincidence with the capture γ-rays. The kinematics of this reaction demand that the α-particles associated with the detected γ-rays lie within 3°–8° of either side of the incident beam. The α-recoil detectors were carefully designed and positioned to accept

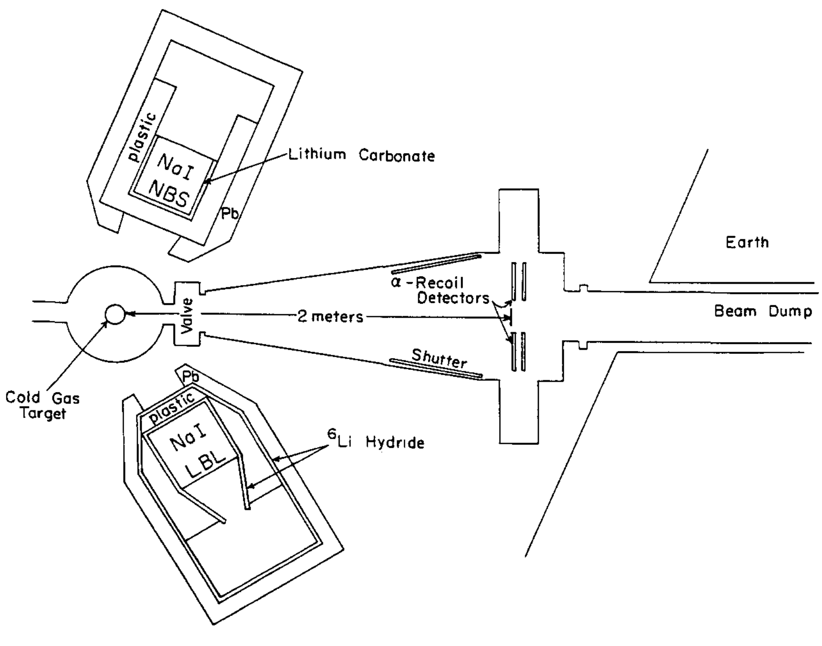

Fig. 1. The experimental arrangement used at the 88 inch cyclotron in Berkeley. Both the γ ray detectors and the scintillators used to observe the ^{4}He recoils are indicated.

all appropriate α-particles. Each of these detectors consisted of two fast plastic BC418 scintillators (4.5″×2.75″×0.030″) viewed by 2 inch diameter photomultiplier tubes through Lucite light pipes. These detectors were, of course, subjected to an intense background of elastically scattered deuterons that arrived 20 ns before the alpha particles. The scintillator thickness was chosen so that the alpha particles of interest stopped in the first. The second provided a veto to reduce the rate in some of the slower electronic components. When a deuteron was detected in the rear plane, the pulse was vetoed in a very early stage of the electronics while the time-to-amplitude converters and slow amplifiers remained ready to process the signal from an alpha particle that might arrive 20 ns later. The combined requirements of proper γ-ray energy, recoil particle time-of-flight, and γ-ray time-of-flight along with the use of the veto requirement between the two scintillators, produced background-free events. These results are illustrated in fig. 2, which shows that the α-coincidence requirement produces background free spectra.

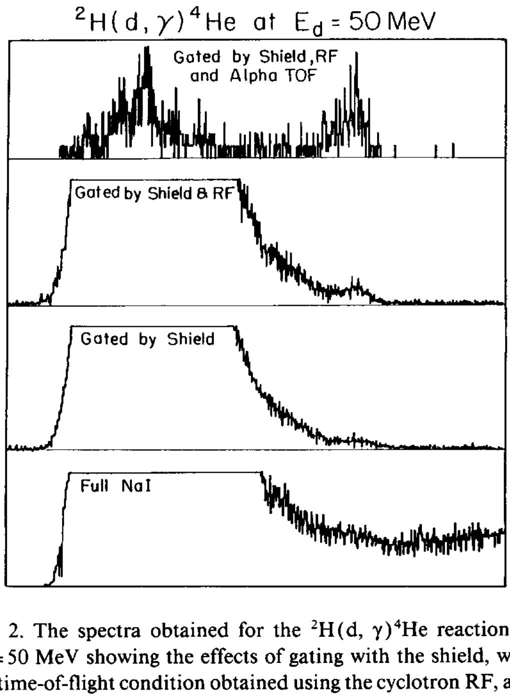

Fig. 2. The spectra obtained for the $^2H(d, \gamma)^4He$ reaction at $E_d = 50$ MeV showing the effects of gating with the shield, with the time-of-flight condition obtained using the cyclotron RF, and the recoil α-coincidence condition. The peak on the right side of the top spectrum corresponds to the γ-rays of interest; the peak on the left was produced by a discriminator threshold and accidentals.

The LBL data were taken in two different modes. In mode 1 three different polarization states of the beam were used with $P_y \approx \frac{1}{3}$, $P_{yy} \approx \pm 1$ and $P_y = 0$, $P_{yy} = 0$ (utilizing two intermediate field RF transitions). In mode 2 we cycled through all four possible combinations of $P_y \approx \pm\frac{1}{3}$ and $P_{yy} \approx \pm 1$ (utilizing the weak field RF transition together with th IF transitions) [21]. The actual polarization values were between 60% and 80% of the maximum possible values. In both modes the source was switched between all states approximately once per second to minimize systematic errors due to long term drifts in the beam quality and in the detectors.

The analyzing powers, A_y and A_{yy}, as well as the unpolarized count rate, N^0, were obtained by solving the set of equations

$$N^s = N^0 (1 \pm \tfrac{3}{2} A_y P_y^s + \tfrac{1}{2} A_{yy} P_{yy}^s) ,$$

$+$: left detector, $-$: right detector ,

where AN^s are the count rates for polarization state s, and s runs through all states used in a given mode. The polarizations, P_y^s and P_{yy}^s, were determined utilizing elastic d–^{4}He scattering. A ^{4}He polarimeter was installed in the beam line which was moved into the beam at ~20 h intervals. All polarizations were determined to ~10% accuracy and interpolated between two measurements to give the actual polarizations during data taking runs. Error bars on the actual values were taken to be large enough to

Table 1
The measured values of A_y and A_{yy}.

E_d (MeV) center-of-target	Lab angle (°)	$A_y \pm \Delta A_y$	$A_{yy} \pm \Delta A_{yy}$
0.3	130	−0.115±0.064	0.015±0.086
1.2	125	−0.131±0.032	0.122±0.040
2.84	130	−0.199±0.019	0.081±0.04
4.03	130	−0.181±0.017	0.104±0.036
6.25	130	−0.127±0.014	0.093±0.029
8.38	130	−0.108±0.012	0.056±0.025
9.55	130	−0.089±0.019	0.053±0.030
12.02	130	−0.016±0.015	0.057±0.027
14.7	130	−0.066±0.029	0.147±0.049
19.90	135	−0.014±0.11	0.18 ±0.06
29.73	132	−0.04 ±0.05	0.30 ±0.05
49.76	134	−0.07 ±0.037	0.210±0.028

cover both measured values. The measured values for $A_y(130°)$ and $A_{yy}(130°)$ for the experiments as a function of incident deuteron energy are given in table 1. The actual angle was not always 130° (see table 1), but the angle subtended by the detector was large enough ($\sim 20°$) so that these differences are unimportant. The errors given here (and in the figures) are statistical, but include the effect of the uncertainty in beam polarization. The states of polarization were changed rapidly in order to cancel most systematic errors. This, plus the high quality (background-free) spectra indicates that the systematic uncertainties associated with these results are small in comparison to the statistical errors given here.

3. Results and discussion

3.1. The tensor analyzing power

The data for the tensor analyzing power A_{yy} at $\theta_{lab} = 130°$ are presented in fig. 3. The three highest energy points shown here were obtained with the LBL set-up. The lower energy data were obtained at TUNL, as described earlier. The calculated curve for $A_{yy}(E)$ at 130° shown in fig. 3 was obtained using the microscopic multi-channel resonating group model (MRGM), as described in ref. [16]. A semi-realistic nucleon–nucleon force [22], consisting of Coulomb, central, spin–orbit and tensor components, was used to determine the scattering and bound-state wavefunctions. The fragments were treated as finite, but as pure S-states, and were allowed to have orbital angular momenta up to $L=2$. The bound state wavefunction of ^4He was determined [16] to have a D-state probability of 2.2%. As noted in ref. [16], proper antisymmetrization of the nucleons destroys the identity of the deuterons so that components besides d–d ones (i.e. n–^3He and p–T) must be included in the scattering wavefunction. The results for $A_{yy}(E)$ at $\theta = 130°$, shown in fig. 3 for E_d(lab) of from 600 keV to 35 MeV, are in excellent agreement with the data. This calculation indicates that E2 radiation is responsible for 95–96% of the capture cross section between $E_d = 10$ and 35 MeV. The gradual rise in A_{yy} in the calculation is the result of the increasing importance of $l=0$ and $l=2$ E2 capture to the D-state of ^4He: from 10% of the total cross section at 10 MeV to 17% at 35 MeV. The remarkably good agreement shown here was obtained using the same parameters as those used previously in describing the $E_d = 10$ MeV data [16]; no parameter adjustments were performed. The calculation has not yet been extended beyond 35 MeV, both because the potential used in the present calculations does not contain enough hard core repulsion to describe properly the phase shifts at these higher energies and because the need for higher partial waves ($l > 2$) increases as E_d does.

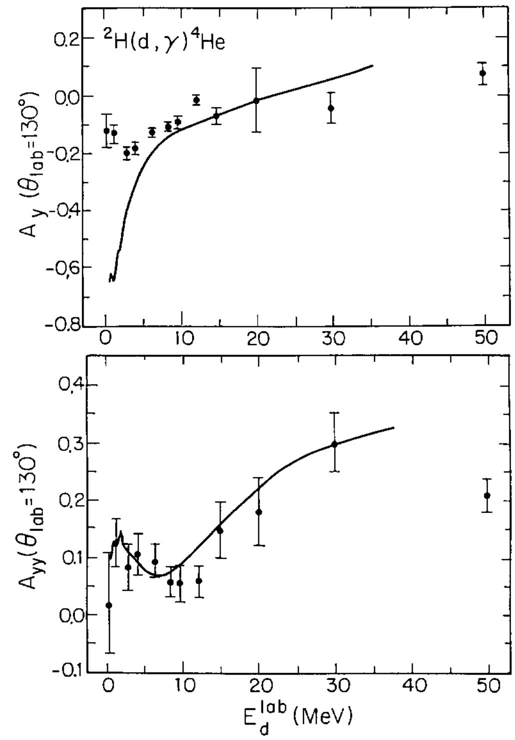

Fig. 3. The measured tensor (A_{yy}) and vector (A_y) analyzing powers as a function of incident deuteron energy at "130°". The curves, as discussed in the text, are the result of the microscopic resonating group model calculation [16].

3.2. The vector analyzing power

The $A_y(130°)$ data as a function of laboratory deuteron bombarding energy are also shown in fig. 3. These data are characterized by rather large negative values below 15 MeV, with values consistent with zero at higher energies. A pure E2 model can only give A_y from interference of two $S=2$ capture amplitudes [10] and produces values which are essentially zero

(< 0.01) on the scale shown. In addition, the angular dependence of $A_y(\theta)$ at 9.7 MeV requires the presence of two multipoles of opposite parity. Therefore, these data imply that non-E2 radiation is present in this reaction, especially at the lower energies.

The results of the MRGM calculation for the vector analyzing power, $A_y(E)$, at 130° are shown in fig. 3. This calculation, which includes the full form of the operators for E1, M1, E2 and M2 radiations in the long-wavelength approximation, overestimates the enhancement of A_y seen in the data at low energies. The large A_y values predicted by this calculation arise from large E1 and M2 contributions at these lower energies [17]. In fact the E1-plus-M2 strength in this calculation varies from about 3% of the total cross section at 10 MeV up to almost 55% at 1.2 MeV. The E1-plus-M2 contribution remains near the 3% level between the energies of 10 and 35 MeV.

The results of the measurements of the energy dependence of A_{yy} and A_y for the ^{2}H(d, γ)^{4}He reaction provide a new signal which can be used to test theoretical models of this reaction. The most sophisticated calculation presently available gives a remarkably good description of the A_{yy} data. In this model calculation the D-state probability in the ground state of ^{4}He was found to be 2.2%, although the sensitivity of the calculated observables to this number was found to be small at $E_d = 9.7$ MeV [16]. The large value of $A_{yy}(130°)$ measured at $E_d = 30$ MeV (0.30) is accounted for by this calculation and arises from the large E2 capture strength going to the D-state of ^{4}He, which comprises 17% of the total capture cross section at this energy in this calculation. While the A_y data are qualitatively described, this model overpredicts the low energy values of A_y by a factor of three or more. Further improvements in the theoretical description of this reaction (e.g. including the D-state of all fragments and using more realistic nucleon–nucleon forces) are needed.

Acknowledgement

We wish to acknowledge the support and encouragement of Dr. R. Stokstad and Dr. E.G. Bilpuch, especially regarding the LBL project. We also wish to thank R.M. Larimer, K. Lesko, E. Norman, and J. Riley for their help. This work was partially supported by the US Department of Energy, Office of High Energy and Nuclear Physics, under Contract No. DE-AC05-76ER01067. S.K. was supported through a fellowship of the NATO science committee administered by the German Academic Exchange Service.

References

[1] G.R. Plattner, R.D. Viollier and K. Adler, Phys. Rev. Lett. 34 (1975) 830.
[2] F.D. Santos et al., Phys. Rev. C 25 (1982) 3243.
[3] H.R. Weller, P. Colby, N.R. Roberson and D.R. Tilley, Phys. Rev. Lett. 53 (1984) 1325.
[4] H.R. Weller, J. Phys. Soc. Jpn. Suppl. 55 (1986) 113–122.
[5] S. Mellema, T.R. Wang and W. Haeberli, Phys. Lett. B 166 (1986) 282; Phys. Rev. C 34 (1986) 204.
[6] H.R. Weiler, in: Proc. European Workshop on Few-body physics, eds. C. Ciofi degli Atti, O. Benhar, E. Pace and G. Salmé, Suppl. 1 (Springer, Berlin, 1986) p. 238.
[7] F.D. Santos, A. Arriaga, A.M. Eiró and J.A. Tostevin, Phys. Rev. C 31 (1985) 707.
[8] J. Piekarewicz and S.E. Koonin, Phys. Rev. C 36 (1987) 875.
[9] A. Arriaga, A.M. Eiró, F.D. Santos and J.E. Ribeiro, Phys. Rev. C 37 (1988) 2312.
[10] J.A. Tostevin, Phys. Rev. C 34 (1986) 1497.
[11] R.Schiavilla, V.R. Pandharipande and R.B. Wiringa, Nucl. Phys. A 449 (1986) 219.
[12] G. Blüge, H.J. Assenbaum and K. Langanke, Phys. Rev. C 36 (1987) 21.
[13] H.J. Assenbaum and K. Langanke, Phys. Rev. C 36 (1987) 17.
[14] F.J. Wilkinson III and F.E. Cecil, Phys. Rev. C 31 (1985) 2036.
[15] C.A. Barnes, K.H. Chang, T.R. Donoghue, C. Rolfs and J. Kammeraad, Phys. Lett. B 197 (1987) 315.
[16] B. Wachter, T. Mertelmeier and H.M. Hofmann, Phys. Lett. B 200 (1988) 246;
H.M. Hofmann, private communication.
[17] J.L. Langenbrunner, G. Feldman, H.R. Weller, D.R. Tilley, B. Wachter, T. Mertelmeier and H.M. Hofmann, Phys. Rev. C 38 (1988) 565.
[18] T.B. Clegg et al., Nucl. Instrum. Methods 120 (1974) 445.
[19] H.R. Weller, P. Colby, J. Langenbrunner, Z.D. Huang, D.R. Tilley, F.D. Santos, A. Arriaga and A.M. Eiró, Phys. Rev. C 34 (1986) 32.
[20] G.G. Ohlsen, J.L. McKibben and G.P. Lawrence, in: Polarization phenomena in nuclear reactions, eds. H.H. Barshall and W. Haeberli (The University of Wisconsin Press, Madison, WI, 1970) p. 503.
[21] D.J. Clark, A.U. Luccio, F. Resminin and H. Heiner, in: Proc. Fifth Intern. Cyclotron Conf., ed. R.W. McIlroy (Butterworths, London, 1971) p. 610.
[21] T. Mertelmeier and H.M. Hoffmann, Nucl. Phys. A 459 (1986) 387.