HIGH-RESOLUTION (e,e′p) STUDY OF THE $1/2^+$ STATE AT 6.79 MeV IN ^{11}B

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The spectral function for the reaction ^{12}C(e,e′p) ^{11}B leading to the $1/2^+$ state at 6.79 MeV in ^{11}B has been measured. The excitation of this non-normal parity state indicates the presence of wave function components beyond the 1p shell A shell-model calculation, performed in a large configuration space, yields a fair description of the shape of the momentum distribution.

Perhaps one of the most venerable applications of the shell model is to be found in the 1p shell nuclei. Level schemes and electromagnetic properties have been successfully described in the framework of this model [1,2]. A well known deficiency, however, pertinent to most of the shell-model calculations performed thus far, is that effective operators have to be used, e.g. in the calculation of electromagnetic observables. The need for effective operators is a signature of the truncation of the configuration space employed in the calculation. Information on wave function components beyond the standard $0\hbar\omega$ configuration is of importance, e.g., to assess the role of delta–hole states in the observed reduction of the spin–isospin response function [3], since the deduced amount of the delta–hole mixing depends crucially on the assumed wave function in the nucleonic sector [4]. It would therefore be interesting to have experimental information on the importance of wave function components beyond the 1p configuration space.

Recently it has been shown [5,6] to be possible to perform shell-model calculations in the mass region A = 4–16 in a large configuration space with complete elimination of spurious states. The space is spanned by the single-particle states 1s, 1p, 1d2s and 1f2p, albeit with restrictions on the total number of oscillator quanta involved.

Experimentally, transfer and knock-out reactions can be used to investigate nuclear states that involve the break-up of the ^{4}He core and/or promotion of particles into the sd shell and beyond. Hadronic reactions, like (p, 2p) and (d, ^{3}He), are subject to distortion effects and two-step processes especially for weakly excited final states [7,8]. The electron-induced proton knock-out reaction is less hampered by complications due to the reaction mechanism. Since the (e, e′p) reaction essentially samples the single-nucleon wave function in momentum space, it is in principle possible to distinguish between core break-up and excitations beyond the 1p shell. Hitherto the (e, e′p) reaction has not been used to study weak transitions, mainly because of insufficient energy resolution [9].

In this letter we report the results of a high-reso-

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lution study of the ^{12}C(e, e′p)^{11}B reaction leading to the 1/2$^+$ state at 6.79 MeV in ^{11}B. The experiment has been performed at the NIKHEF-K electron accelerator MEA at incident energies of 352 and 411 MeV. By using the two-spectrometer set-up [10] and a novel dispersion-matching technique [11] a missing energy (E_m) resolution of 150 keV has been achieved with a 15.9 mg/cm^2 carbon target. The coincidence time resolution was about 1.0 ns. Data have been acquired in parallel kinematics, i.e. the outgoing proton is detected in the direction of the transferred momentum (q). The missing momentum (p_m) range of −20 to 110 MeV/c was covered in four partially overlapping intervals with a constant proton kinetic energy of 70 MeV. The results are presented as a momentum distribution $\rho(p_m)$ of the knocked-out proton, which has been derived from the data as described in ref. [12]. The systematic error in the analysis, which is mainly due to uncertainties in target thickness, solid angles and detection efficiency has been estimated at 10%.

A typical missing-energy spectrum (fig. 1) shows several states of ^{11}B. The well-known states at 0(3/2$^-$), 2.12(1/2$^-$) and 5.02(3/2$^-$) MeV correspond to 1p-proton knock-out and their momentum distributions show the expected $l = 1$ behaviour [13]. The 1/2$^+$ state at 6.79 MeV was clearly observed in all four spectra. Its momentum distribution, shown in fig. 2, exhibits a typical $l = 0$ behaviour, indicating the knock-out of a proton from an s$_{1/2}$ orbit.

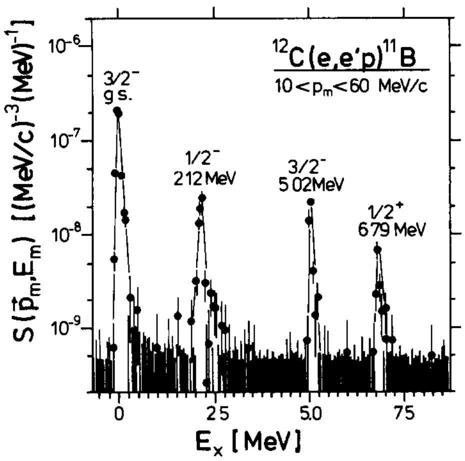

Fig. 1. Missing energy spectrum of the reaction ^{12}C(e, e′p)^{11}B taken at E = 352 MeV, averaged in the $|p_m|$ interval 10–60 MeV/c.

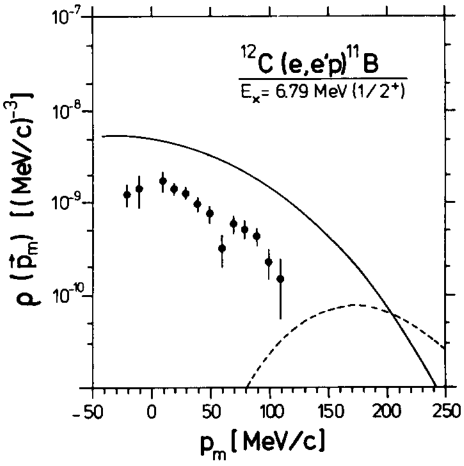

Fig. 2. Missing momentum distribution of the 1/2$^+$ state at 6.79 MeV in ^{11}B. The drawn curve represents the shell-model calculation and the dashed curve represents the calculated strength of the 1f$_{7/2}$ state at 6.74 MeV under extreme assumptions. Note: p_m is defined as $p - q$.

The absence of strength in all spectra at 4.45 MeV, where a 5/2$^-$ state is located, has two important consequences. Firstly, the two-step process – 1p knock-out plus inelastic excitation – appears to be negligible for this state. Since in the ^{11}B(p, p′) reaction the 4.45 MeV state is more strongly excited than the one at 6.79 MeV [14], two-step contributions leading to the 6.79 MeV peak may also be assumed to be negligible. Secondly, if the excitation mechanism of the 7/2$^-$ state at 6.74 MeV is the same as that of the 5/2$^-$ state at 4.45 MeV [15], the lack of excitation of the latter implies a negligible contribution of the former to the 1/2$^+$ state at 6.79 MeV. As a confirmation of this observation possible contributions from the unresolved 7/2$^-$ state at 6.74 MeV have been estimated as follows. With the extreme assumption of 100% overlap between this state and the 1f$_{7/2}$ component of the ^{12}C ground-state wave function and using a calculated 1f$_{7/2}$ amplitude of 0.10 [5], the momentum distribution for the 7/2$^-$ state can be calculated. As shown in fig. 2 (dashed curve) the largest contribution to the cross section of the 1/2$^+$ state occurs at $|p_m|$ = 110 MeV/c and amounts to 20%.

In the plane-wave impulse approximation (PWIA) the cross section for the (e, e′p) reaction can be written in the factorized form [16]

$$d^6\sigma/de'\,d\boldsymbol{p} = |\boldsymbol{p}|^2\sigma_{ep}S(p_m, E_m), \qquad (1)$$

where $\boldsymbol{p}$ is the momentum of the outgoing proton, σ_{ep} the (off-shell) electron–nucleon cross section [17] and $S(p_m, E_m)$ the spectral function. The spectral function, which contains the nuclear-structure information, can be expressed as [18]

$$S(p_m, E_m) = \frac{1}{2J_i + 1}\sum_{i,f}\Phi_{if}(p_m)^2\delta(E_m - E_f + E_i), \qquad (2)$$

where i (f) labels a complete set of eigenstates of the initial (final) system. The Fourier transformed overlap integral is defined by [18,19]

$$\Phi_{if}(p_m) = (2\pi)^{-3/2} \times \int \exp(-i p_m \cdot r)\langle\psi_f(1 \ldots A-1)|\psi_i(1 \ldots A)\rangle\,dr. \qquad (3)$$

No centre-of-mass corrections have been applied, but they are expected to be small [20].

The data have been interpreted in the framework of the distorted-wave impulse approximation (DWIA). In parallel kinematics the factorization can be retained in DWIA [21]. Therefore the data can be represented in the form of a distorted spectral function. The DWIA calculations have been performed with a version of the computer code PEEP [22]. The optical-model parameters of ref. [23] have been scaled from 87 to 70 MeV proton energy following the prescription of Schwandt [24].

In the framework of the shell model the overlap integral of the ^{12}C ground state and the ^{11}B $1/2^+$ wave function can be written as a coherent sum [18] of $1s_{1/2}$ and $2s_{1/2}$ single-particle wave functions,

$$\langle\psi(^{11}B_{1/2^+})|\psi(^{12}C_{gs})\rangle = A_{1s}\phi(1s) + A_{2s}\phi(2s). \qquad (4)$$

The squares of the amplitudes A_{1s} and A_{2s} are the spectroscopic factors C^2S for the orbitals involved.

The amplitudes in eq. (4) have been deduced from shell-model calculations [5] performed in a large model space, which in particular does not require an inert ^{4}He core. A Reid soft-core potential describes the translationally invariant two-particle interaction. This realistic interaction has to be renormalized due to the still limited model space. The renormalization is parametrized by empirically found Talmi integrals.

For ^{12}C a $2\hbar\omega$ model space has been used, which resulted in the following major components of the ground state wave function: $0.80(1s)^4(1p)^8 + 0.33(1s)^3(1p)^8(2s1d)^1 + 0.24(1s)^4(1p)^6(2s1d)^2$, where the third component mainly consists of configurations with two particles in the 1d shell (amplitude = 0.22). The most notable feature of this calculation is the large depletion of the 1p shell, which is indicated by the relatively small probability (64%) of the standard $(1s)^4(1p)^8$ component. Furthermore, the ^{4}He core has an $1s_{1/2}$ hole content of 10% and the $2s_{1/2}$ orbit has an occupancy of 2.2%. The wave function of the $1/2^+$ state in ^{11}B, calculated in a more restricted $1\hbar\omega$ model space, has an eigenvalue at the excitation energy of 8.15 MeV, fairly close to the experimental value. The calculated wave function is given by $0.96(1s)^4(1p)^6(2s1d)^1 + 0.29(1s)^3(1p)^8$ with a $1s_{1/2}$ hole content of 8.4%. The calculated overlap integral [eq. (4)] is dominated by the $1s_{1/2}$ amplitude, $A_{1s} = 0.297$. The $2s_{1/2}$ amplitude is small due to severe cancelations between the various configurations, leading to an amplitude $A_{2s} = 0.032$.

The momentum distribution $[\rho(p_m) = \int_{\Delta E_m} S(p_m, E_m)\,dE_m]$ has been calculated with harmonic oscillator (HO) radial wave functions with a length parameter $b = 1.781$ fm, derived from the ^{12}C charge radius. The effect of using a Woods–Saxon (WS) radial wave function has also been considered. The main difference between HO and WS radial wave functions is located in the asymptotic tail. Since the (e, e'p) reaction samples the entire wave function and the main part of an $l = 0$ wave function is located in the nuclear interior, we find changes of less than 5% for the spectral function in the p_m-range considered here.

As shown in fig. 2 the shape of the calculated momentum distribution is in fair agreement with the data. This agreement represents a major improvement relative to a calculation with Cohen/Kurath wave functions, that would yield a vanishing momentum distribution for this transition. The observation that the calculated magnitude is too large is presumably due to the restricted $1\hbar\omega$ model space used for the wave function of the $1/2^+$ state. It will be interesting to investigate whether an extension of the configuration space will yield an improved agreement with the data.

In the present calculation the values of the amplitudes A_{1s}, A_{2s} are mainly determined by the magnitude of the $(1s)^3(1p)^8$ component of the $^{11}B_{1/2^+}$

wave function. Assuming that the observed reduction of strength as compared to the shell model prediction, is exclusively due to a smaller $(1s)^3(1p)^8$ component one arrives at a value of 2.1 ± 0.8% for the $1s_{1/2}$ hole content. The quoted error is mainly due to the freedom in the optical-model parameters and HO parameter.

In conclusion it can be stated that developments in the experimental technique of (e, e′p) reactions have made it possible to investigate the weak $1/2^+$ state at 6.79 MeV in ^{11}B. The excitation of this non-normal parity state indicates the presence of wave function components beyond the 1p shell. It is shown that a novel shell-model calculation with a large configuration space succeeds in describing the global features of the transition. Additional (e, e′p) experiments, especially on lighter nuclei, will be needed to obtain a more detailed understanding of the importance of wave function components beyond the 1p shell.

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References

[1] S. Cohen and D. Kurath, Nucl. Phys. A73 (1965) 1.
[2] S. Cohen and D. Kurath, Nucl. Phys. A101 (1967) 1.
[3] W. Weise, Nucl. Phys. A396 (1983) 373c.
[4] R.S. Hicks et al., Phys. Rev. C26 (1982) 337.
[5] D. Zwarts, Thesis, State University Utrecht (1984).
[6] A.G.M. van Hees and P.W.M. Glaudemans, Z. Phys. A314 (1983) 323; A315 (1985) 223.
[7] P.G. Roos et al., Phys. Rev. Lett. 40 (1978) 1439.
[8] F. Hinterberger et al., Nucl. Phys. A106 (1968) 161.
[9] J. Mougey et al., Nucl. Phys. A262 (1976) 461.
[10] C. de Vries et al., Nucl. Instrum. Methods 223 (1984) 1.
[11] L. Lapikás and P.K.A. de Witt Huberts, Proc. Symp. on Perspectives in electro- and photonuclear physics (Saclay, 1980).
[12] L. Lapikás and P.K.A. de Witt Huberts, J. de Phys. 45 (1984) C4-57.
[13] M. Bernheim et al., Nucl. Phys. A375 (1982) 381.
[14] J.F. Cavaignac et al., Nucl. Phys. A243 (1975) 349.
[15] D. Newton et al., Nucl. Phys. 53 (1964) 433.
[16] G. Jacob and Th.A.J. Maris, Rev. Mod. Phys. 38 (1966) 121.
[17] T. de Forest Jr., Nucl. Phys. A392 (1983) 232.
[18] S. Frullani and J. Mougey, Adv. Nucl. Phys. 14 (1984) 1.
[19] A.E.L. Dieperink and T. de Forest Jr., Ann. Rev. Nucl. Sci. 25 (1975) 1.
[20] A.E.L. Dieperink and T. de Forest Jr., Phys. Rev. C10 (1974) 543.
[21] S. Boffi et al., Nucl. Phys. A319 (1979) 461.
[22] J. Knoll, Thesis, University of Freiburg (1971).
[23] A.E. Glassgold and P.J. Kellog, Phys. Rev. C1 (1970) 1633.
[24] P. Schwandt et al., Phys. Rev. C26 (1982) 55.