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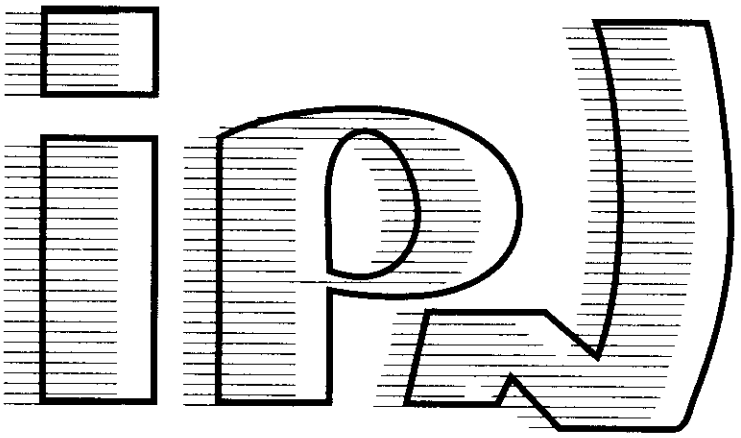

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Core excitation in $^{11}Be_{gs}$ via the p(^{11}Be,^{10}Be)d reaction

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Abstract

The p(^{11}Be,^{10}Be)d reaction has been studied using a radioactive ^{11}Be beam of 35.3 MeV/nucleon. Differential cross sections have been compared with Distorted Wave Born Approximation calculations, using bound state form factors determined by solving the particle-vibration coupling equations. Calculated cross sections corresponding to a 16% core excitation admixture in the $^{11}Be_{gs}$ wave function are in good agreement with the present data.

Key words: Transfer reactions with radioactive nuclear beams, DWBA analysis, vibrational coupling form factors, $^{11}Be_{gs}$ structure.
PACS: 25.60.+v, 25.40.Hs, 21.60.Ev, 21.10.Jx

1 Introduction

Much effort has been devoted to the understanding of the light neutron-rich ^{11}Be nucleus, since the observation of a parity inversion between its ground state ($J^\pi=1/2^+$) and its first excited state at 0.32 MeV($J^\pi=1/2^-$) several decades ago. This interest in ^{11}Be was further enhanced following experimental evidence for a neutron "halo" around the ^{10}Be core [1,2]. Various theoretical calculations [3–12] have attempted to reproduce the level sequence in this benchmark halo nucleus. Most models emphasize the role of coupling between the valence neutron and the first excited 2^+ state at 3.34 MeV in ^{10}Be core in generating the parity inversion, but they predict very different core excitation admixtures in the ^{11}Be$_{gs}$ wave function, varying from 7% [6,10] to 75% [3]. In this context, it is important to get experimental information on the relative weights of its $[0^+\otimes 2s]$ and $[2^+\otimes 1d]$ components, which may be provided by measuring the cross sections of one-neutron pick-up reactions feeding the 0^+_{gs} and 2^+_1 states in ^{10}Be.

This letter reports a study of the structure of ^{11}Be$_{gs}$ by means of the (p,d) reaction in inverse kinematics. This experiment may be considered as a testing ground for future investigations of exotic nuclei via transfer reactions induced by radioactive beams. Preliminary data have been reported in refs. [13,14], together with the first results of a standard DWBA analysis, which used single-particle form factors evaluated according to the usual Separation Energy (SE) prescription. Spectroscopic factors deduced from this preliminary analysis indicate a very large $[2^+\otimes 1d]$ admixture in the ^{11}Be$_{gs}$ wave function, exceeding most theoretical predictions [14]. However, such a comparison between experiment and structure calculation via spectroscopic factors assumes that the radial wave function $u_{\ell j}(r)$ may be approximated by the product of the single-particle form factor times a spectroscopic amplitude. This assumption is in fact questionable, considering the large deformation parameter of the final nucleus ^{10}Be (β_2=0.74 [15]), which could induce important coupling effects. Under such conditions, correct form factors should be taken as solutions of coupled equations [16]. The present (p,d) transfer reaction data are compared with the results of DWBA calculations, using bound state form factors evaluated in the framework of the particle-vibration coupling model [17], in order to assess the magnitude of this effect.

2 Experiment and results

The ^{11}Be(p, d)^{10}Be reaction was studied in inverse kinematics, using a ^{11}Be secondary beam of 35.3 MeV/nucleon, produced by fragmentation of ^{15}N in the SISSI device at GANIL. The ^{10}Be nuclei were analyzed by the energy-loss

SPEG spectrometer placed at 0°. A 50-μm thick $(CH_2)_n$ target was used. Particle identification and momentum and angle measurements were provided by the standard SPEG focal plane detection system. Information on the incident angle at the target position was provided by two XY drift chambers placed in the beam line before the analysing magnet. Deuterons in coincidence with ^{10}Be were detected by CHARISSA, an array of ten position sensitive sheet-resistive silicon detectors (5 x 5 cm^2 and thickness 500 μm) located in the target chamber at angles between ~5° and 35°. The efficiency of the detection system as function of the scattering angle was calculated by a simulation program which accounted for the large emittance and beam spot size of the secondary beam. The ^{11}Be intensity was $\sim 3 \times 10^4$ pps, and was monitored throughout the experiment by a small plastic detector placed at the high momentum end of the focal plane.

Focal plane spectra are displayed in fig. 1. Three peaks are observed in the lower panel, corresponding to the population of known bound states in the ^{10}Be nucleus via the (p,d) reaction. The 2^+ state at 3.368 MeV is well separated from the 0^+ ground state and the unresolved multiplet of states at 5.958 MeV (2^+), 5.960 MeV (1^-), 6.179 MeV (0^+) and 6.263 MeV (2^-). A large Doppler broadening is observed for excited states in ^{10}Be, due to the in-flight emission of γ-rays of several MeV (v/c=0.28). The background observed in the singles ^{10}Be spectrum originates from the reaction ^{12}C(^{11}Be,^{10}Be)^{13}C on the carbon nuclei of the polypropylene target and from the high energy tails of the ^{11}Be$\rightarrow^{10}$Be+n and d$\rightarrow$p+n breakup reactions near threshold. This background is removed completely by conditions applied to the CHARISSA energy signals which select only coincident recoil deuterons. Differential cross sections measured within the angular acceptance of the SPEG spectrometer ($\theta_{lab} < 2°$) for the 0^+_{gs} and 2^+_1 states are plotted with statistical error bars in fig. 2. They are compared with DWBA predictions under different form factor assumptions as described in the following sections.

3 Bound state form factors

Bound state form factors for neutron transfer were calculated assuming a vibrational coupling between the ^{10}Be core and the halo neutron. The assumption of a vibrational ^{10}Be core is based on the known second 0^+ and 2^+ states at about twice the energy of the first 2^+ state. The interaction Hamiltonian was taken from ref. [17] and the radial form factors $u_{lj}(r)$ were calculated by solving the resulting set of coupled equations [18] using the code CCVIB [19]. The configuration space for the $1/2^+$ ground state was limited to a single neutron in the $2s_{1/2}$ or $1d_{5/2}$ orbitals, coupled to the 0^+_{gs} and 2^+_1 core states in ^{10}Be, respectively. Calculations were performed using the experimental $\beta_2 R$ value of 1.84 fm from the analysis of ^{10}Be(p,p') data [15] and two different sets of

geometrical parameters of the Woods-Saxon well, (1) corresponding to standard values r_0=1.25 fm, a=0.65 fm, and (2) taken from the parametrization of ref. [20] for p-shell nuclei. The well depth V and the spin-orbit strength V_{so} were adjusted in order to reproduce the experimental separation energies of the $1/2^+$ ground state (0.50 MeV) and $1/2^-$ first excited state (0.18 MeV) simultaneously, assuming admixtures of $[0^+ \otimes p_{1/2}]$ and $[2^+ \otimes p_{3/2}]$ configurations in the $1/2^-$ wave function. These parameters, labelled VIB-1 and VIB-2 are listed in table 1. In spite of the resulting different radial shapes of $u_{\ell j}(r)$ for the two well geometries, both calculations predict the same calculated spectroscopic factors $S_{th}(0^+)$=0.84 and $S_{th}(2^+)$=0.16. It is interesting to note the large V_{so} values (about twice the usual spin-orbit value) needed to reproduce the parity inversion. More standard V_{so} values corresponding to the usual[21] Thomas spin-orbit λ factor were also used in calculations VIB-3 (well geometry (1), V=53.0 MeV, V_{so}=7.3 MeV) and VIB-4 (well geometry (2), V=61.6 MeV, V_{so}=8.5 MeV). A smaller core excitation is deduced from these two calculations ($S_{th}(2^+)$=0.09 and 0.11, for VIB-3 and VIB-4 respectively), in closer agreement with the value of 0.07 from the vibrational coupling approach of Vinh-Mau [6]. However, in this case it is not possible to reproduce the experimental energy of the $1/2^-$ state with the same well depth.

Figure 3 shows the vibrational coupling form factors obtained with parameters VIB-1, and normalized to 1 by dividing them by the corresponding spectroscopic amplitude. They are compared with standard form factors $U_{\ell j}^{sp}$ deduced from the SE prescription using the same well geometry (1). The coupling causes only minor changes for $s_{1/2}$, but significantly shifts the $d_{5/2}$ form factor outwards, increasing its magnitude in the asymptotic region outside the nucleus. As transfer reactions are known to take place at the surface of the nucleus, leading to a dependence of the cross sections on the square of the asymptotic tail, the result of the coupling is a large enhancement of the 2^+ cross section (by a factor of about 1.7) compared with standard DWBA analyses neglecting coupling effects.

4 Calculation of transfer cross sections

Theoretical cross sections were calculated with the zero-range DWBA code DWUCK4 [21] using a (p,d) normalization factor of 2.29. These calculations were performed without finite-range and non-locality corrections. Various sets of proton and deuteron optical potentials, generally extrapolated from available elastic scattering analyses of medium to heavy mass nuclei, were tried. The calculated curves in fig. 2 were obtained using the adiabatic approximation of Johnson and Soper [22,23] which accounts for the effects of the deuteron break-up in the nuclear field. Both proton and adiabatic deuteron optical parameters were generated by the Watson global nucleon potential [20]. They are

listed in table 1. This optical parameter set, which correctly reproduces the shapes of angular distributions at forward angles, also predicts the largest ratio of 2^+ and 0^+ cross sections for a given bound state form factor, compared to all other combinations of potentials investigated. Experimental spectroscopic factors extracted by normalizing the calculated curves to the four most forward angle data points are given in table 2. The SE-1 and SE-2 S-values are deduced from standard DWBA calculations using the SE prescription and geometrical parameters (1) and (2) for the neutron potential well, respectively. They differ by about 20% for the ground state and 30% for the 2^+ state, but the ratio $R_{ce}=S(2^+)/[S(0^+)+S(2^+)]$ measuring the core excitation admixture in $^{11}Be_{gs}$ is only slightly dependent on well geometry, being equal to 0.30 for SE-1 and 0.32 for SE-2. Thus, a lower limit of about 30% for the experimental core excitation admixture is deduced from a standard DWBA analysis using conventional SE form factors.

Theoretical cross sections calculated using vibrational coupling form factors VIB-1 and VIB-2, both corresponding to the same theoretical spectroscopic factors $S_{th}(0^+)=0.84$ and $S_{th}(2^+)=0.16$, are shown in fig. 2 without any further normalization to the data. As discussed above, the calculated 2^+ cross sections are substantially enhanced compared to standard DWBA-SE predictions for the same spectroscopic factor, due to the modification of the form factors by coupling effects, whereas the 0^+ cross sections remain essentially unchanged. Calculations using the VIB-3 and VIB-4 form factors (with correspondingly lower calculated spectroscopic factors) give too small a 2^+ cross section. The best agreement between experimental and theoretical 2^+ cross sections (see fig. 2) is obtained using the VIB-1 form factor, calculated with a standard well geometry and a rather large spin-orbit value (see table 1), and corresponding to a predicted 16% core excitation admixture. Direct transfer calculations were also performed with radial form factors from the core excitation model (CEM) of Nunes et al. [8]. This model assumes a rotational structure for ^{10}Be core and possible population of the $2s_{1/2}$, $1d_{5/2}$ and $1d_{3/2}$ by the valence neutron, with spectroscopic factors of 0.85, 0.13 and 0.02, respectively [8]. The cross sections for the CEM model are shown as dashed lines in fig. 2. They are rather similar to the results of the vibrational form factors VIB-1 and reproduce the data fairly well.

Spectroscopic factors deduced from the DWBA analysis using vibrational coupling form factors are compared in table 2 with the corresponding SE results and model predictions. For a given well geometry, coupling effects reduce the $S(2^+)$ values by a factor $\sim$1.7. Using VIB-1 form factors and optical potentials in table 1, the resulting core excitation admixture in $^{11}Be_{gs}$ is $R_{ce}=0.20$, close to the corresponding theoretical value of 0.16, obtained directly from the vibrational coupling model. The present $S(0^+)$ values are also in rather good agreement with the predicted spectroscopic factor and consistent with the values of 0.73 (ref.[15]) and 0.77 (ref.[24] extracted from the inverse reaction

^{10}Be(d,p)^{11}Be. However one has to note that all these values were obtained without taking the effects of ^{11}Be recoil and break-up of into account. Such effects should be included in future analyses of transfer reactions involving halo nuclei, as recent calculations[25] have shown that they could affect cross sections significantly. In particular, the predicted enhancement of ^{11}Be(p,d)^{10}Be cross sections at forward angles[25] would multiply the present S(0^+) and S(2^+) values by factors estimated to $\sim$0.6-0.7. However, it can be expected that the resulting core excitation admixture, defined as a ratio of spectroscopic factors, should not be strongly affected by these effects.

Two-step processes involving inelastic excitation in ^{10}Be and ^{11}Be may also significantly modify the 2^+ cross section. This has been checked by performing Coupled Reaction Channel calculations with the zero range code CCZR [26]. These will be described elsewhere. The two-step processes are found generally to increase the 2^+ cross section at forward angles, by a factor which is unfortunately strongly dependent on the optical potentials. For the optical parameter set discussed above, the calculations show that interference effects modify the slope of the angular distribution, but change the cross section at forward angle by less than 15% relative to single step transfer. Hence, the calculated cross sections are still in good agreement with the present data below 14°. It is concluded that nuclear model predictions can only be compared with (p,d) experimental data via a consistent analysis, using the model radial wave functions as form factors, and at the same time considering the effect of two-step processes.

5 Summary

The ^{1}H(^{11}Be,^{10}Be)^{2}H reaction has been investigated in order to provide insight on the structure of ^{11}Be$_{gs}$. The present analysis has attempted to relate the large cross section experimentally observed for the excitation of the 2^+ state at 3.37 MeV with the amount of [$2^+\otimes$1d] core excited component in the ground state wave function. A standard (p,d) reaction analysis using single particle form factors in DWBA calculations gives a core excitation admixture $\geq$ 30%. However, the validity of these standard form factors is challenged by coupled-channels calculations of the ^{11}Be structure, performed in the framework of the particle-vibration coupling model. It is shown that the radial wave function of the $d_{5/2}$ transferred neutron is strongly modified by the interaction with the ^{10}Be deformed core, thereby enhancing the 2^+ cross section relative to classical DWBA predictions. An admixture of 84% [$0^+\otimes s_{1/2}$] and 16% [$2^+\otimes d_{5/2}$] configurations is predicted for ^{11}Be$_{gs}$. One-step transfer theoretical cross sections with form factors calculated in the present vibrational coupling approach, or in a core excitation model based on the assumption of a rotational ^{10}Be core [8] are found to be in agreement with the present data. A

20% core excitation admixture in $^{11}Be_{gs}$ is deduced from the present DWBA analysis using vibrational coupling form factors.

This study has been the first investigation of the microscopic structure of the halo nucleus $^{11}Be_{gs}$ via a one-nucleon transfer reaction. The present work has pointed out some of the problems which may be encountered in analyzing such experiments which involve weakly bound and deformed nuclear systems. In particular, it is shown that coupled-channel effects on bound state form factors and reaction mechanisms should not be neglected. In conclusion, this letter demonstrates the feasibility and interest of transfer experiments induced by radioactive beams, providing unique information on the shell structure of nuclei far from stability.

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Table 1
Optical potential parameters used in the calculations of vibrational coupling form factors and DWBA cross sections. Potential depths are in MeV and distances in fm.

channel		V	r_0	a	V_{so}	r_{so}	a_{so}	W_s	r_i	a_i
n+^{10}Be	VIB-1	51.5	1.25	0.65	15.4	1.25	0.65			
n+^{10}Be	VIB-2	60.3	1.15	0.57	13.3	1.15	0.57			
p+^{11}Be	ref.[20]	59.2	1.12	0.57	5.5	1.12	0.57	10.5	1.12	0.50
d+^{10}Be$_{gs}$	*a*)	106.3	1.133	0.602	5.5	1.133	0.57	15.9	1.133	0.531
d+^{10}Be$_{2+}$	*a*)	107.3	1.135	0.602	5.5	1.135	0.57	16.1	1.135	0.531

a) adiabatic potential folded from the nucleon potential of ref. [20].

Table 2
Results of the DWBA analysis of the p(^{11}Be,^{10}Be)d reaction, using the optical potential parameters reported in table 1, and form factors deduced from either the Separation Energy (SE) prescription or vibrational (VIB) coupling calculations. Experimental spectroscopic factors for two different well geometries are compared with the corresponding theoretical predictions (see text).

E_x	J^π	SE-1	VIB-1	VIB-1	SE-2	VIB-2	VIB-2
(MeV)		S_{exp}	S_{exp}	S_{th}	S_{exp}	S_{exp}	S_{th}
0	0^+	0.66	0.67	0.84	0.79	0.79	0.84
3.368	2^+	0.28	0.17	0.16	0.38	0.22	0.16

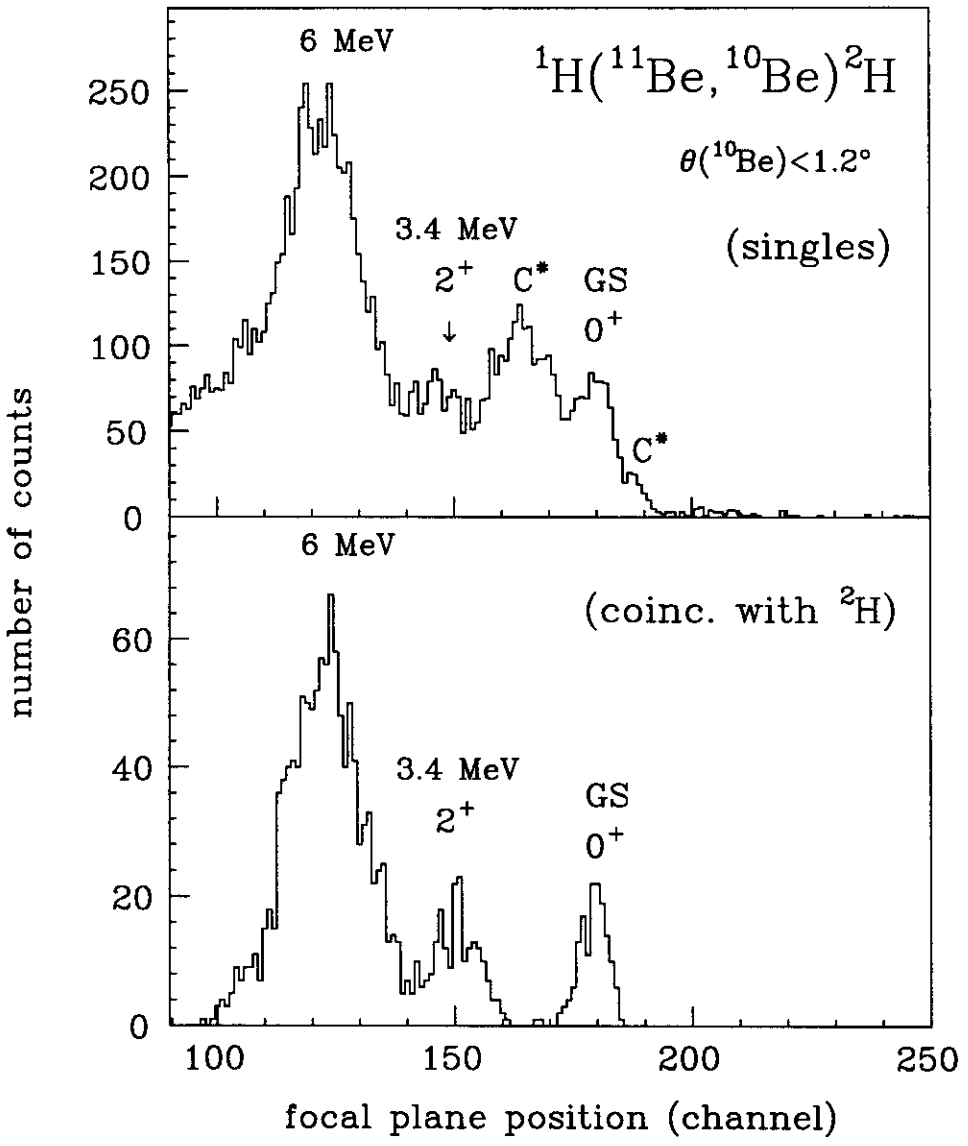

Fig. 1. Focal plane spectra measured for singles ^{10}Be (top) and ^{10}Be in coincidence with deuterons (bottom)

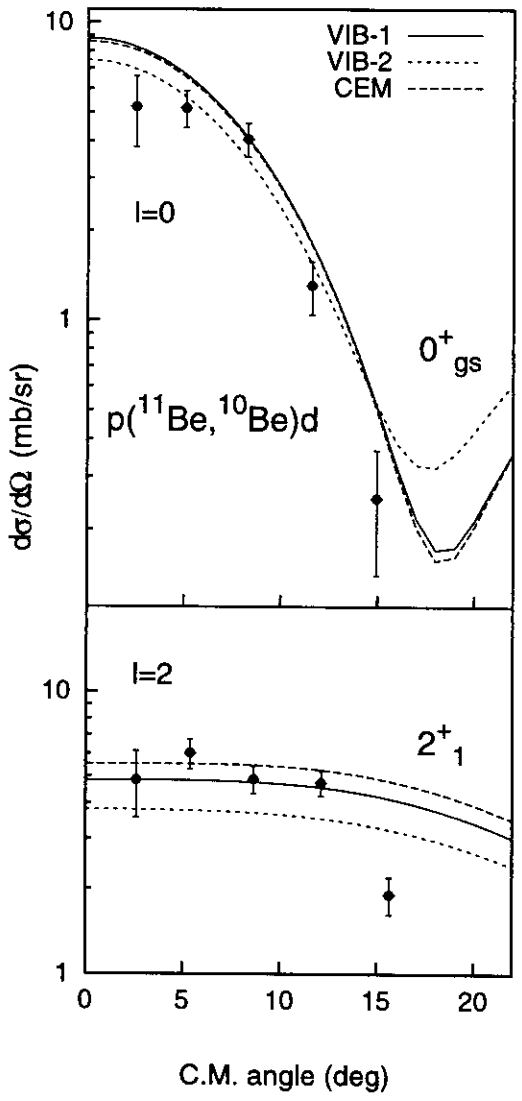

Fig. 2. Experimental cross sections compared with DWBA predictions using vibrational coupling form factors (see text). Results obtained with form factors from the Core Excitation Model(CEM) of ref. [8] are also shown.

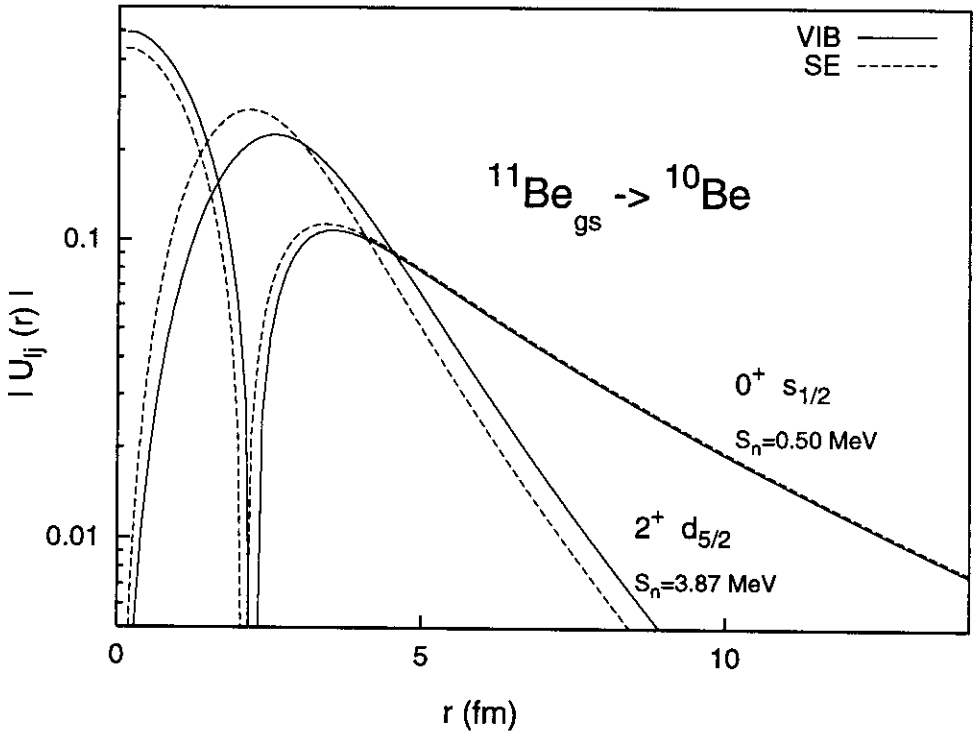

Fig. 3. Comparison of neutron form factors, deduced from particle-vibration coupling calculations and normalized to 1, with single-particle form factors using the standard separation energy (SE) prescription.