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Abstract

Cross sections and momentum distributions of “Be in its ground state and only bound excited state, produced in one-neutron knockout reactions of ^{12}Be on a ^{9}Be target at ‘78 MeV/u, are presented. The measurements are analyzed using recently developed eikonal models of the reaction mechanism to obtain the spectroscopic factors for the ^{11}Be ground and excited state configurations in the ^{12}Be ground state. The extracted spectroscopic factors are important for understanding the role of intruder configurations in this region of the chart of nuclei. In this work we measure a dominant branch to the ^{11}Be ground state with a characteristic s-state momentum distribution thus providing the first direct evidence for the disappearance of the $N = 8$ shell closure in the neutron rich ^{12}Be.

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With the advent of radioactive beams, the study of nuclei near the driplines has shown several novel aspects of their small separation energy. These include the presence of halo structure [1] and indications of unexpected deformation (intruder state configurations) near the N = 20 closed shell [2,3]. In this letter we report spectroscopic factors for the removal of a neutron from the ground state of the neutron rich nucleus ^{12}Be, populating the $1/2^+$ ground state and the $1/2^-$ excited state of ^{11}Be, by use of a recently developed technique [4]. This involves measurements of the partial cross sections and momentum distributions of individual final states of the residue formed in one nucleon knockout reactions on a light target and their analysis using reaction and structure models. The derived spectroscopic factors are interpreted using the shell-model to understand the breakdown of the $N = 8$ shell closure and hence the role of the intruder configurations in this region of light nuclei. The relatively small configuration space in this mass region makes the interpretation of this breakdown simpler than for heavier nuclei.

A classic example of an intruder configuration is the $1/2^+$ ground state of ^{11}Be [5]. The normal *0p*-shell configuration of $1/2^-$ lies at 320 keV in excitation energy. This inversion of the $0p$ and $0d1s$ states can be understood in the framework of shell-model configuration mixing as a combination of shell-quenching, quadrupole-deformation and pairing-energy effects [6,7]. A recent study of the 2n-halo nucleus ^{11}Li by Simon *et al.* [8] has shown evidence for the admixture of different parity states in the ground state. Although the intruder-state situation in ^{11}Be has been known for almost 40 years, its consequence for the structure of nearby nuclei, such as ^{12}Be, is unclear. The configuration mixing and interaction used in a shell-model which reproduces the ^{11}Be spectrum predicts that the energies of the lowest $(0p)^8$ and $(0p)^6$-$(0d1s)^2 0^+$ configurations in ^{12}Be are degenerate [9]. Barker [10] discussed the importance of this admixture to understand the properties of the ground and excited states of ^{12}Be from a study of low lying $T = 2$ states. The study of the ^{10}Be(t,p) reaction [11], and analysis [12] of the quenching of the Gamow Teller transitions lead to conclusions similar to those of Barker. An alternative description of the structure of ^{12}Be is provided by core-particle models such as the three-body model of [13]. This also predicts a significant $(0d1s)^2$ ground-state admixture when a ^{10}Be(2^+) core configuration is included.

The most direct way to measure the ground-state structure of ^{12}Be is to determine the spectroscopic factors for the removal of a neutron, leaving ^{11}Be in its $1/2^+$ ground state or $1/2^-$ excited state [9]. In the simplest model, of two $p_{1/2}$ neutrons outside of a ^{10}Be core, the spectroscopic factor would be 2 and 0 for the $p_{1/2}$ and $s_{1/2}$ single-particle states, respectively. The large measured cross section for populating the ^{11}Be ground state, reported here, with a characteristic s-wave momentum distribution, is a direct and model independent evidence for the presence of a significant sd component in the ^{12}Be ground-state wave function. The measured ground and excited state partial cross sections and momentum distributions are interpreted using an eikonal model [14,15] to extract the associated spectroscopic factors and to clarify the structure of the ^{12}Be ground state.

The experiment was performed at the NSCL at Michigan State University. Secondary beams produced from the fragmentation of a 100 MeV/u ^{15}N primary beam on a ^{9}Be target were momentum analyzed using the A1200 fragment separator. A beam of ^{12}Be at 78 MeV/u with an intensity of 2×10^3 particles/s and a momentum spread of 0.5% was transmitted to the high-acceptance S800 spectrograph [16] operated in a dispersion-matched mode. The beam was incident on a 151 mg/cm^2 ^{9}Be target which was surrounded by an array of 38 NaI(Tl) position-sensitive γ-ray detectors [17]. Projectile residues formed in the one-nucleon knockout reactions ^{9}Be(^{12}Be,^{11}Be(γ))X were detected and identified at the focal plane of the spectrograph using time of flight and the energy deposited in an ion chamber and two plastic scintillators. Coincident γ rays from the decay of the ^{11}Be excited state identified the state of the residue. The γ-ray spectrum measured in the projectile rest frame in coincidence with ^{11}Be fragments is shown in Fig. 1.

FIGURES

=5.5cmgbe12.ps

FIG. 1. Measured gamma-ray spectrum in the projectile rest frame in coincidence with ^{11}Be residues. The dashed line is the result of a fit to the measured spectrum using the line shape of the 320 keV gamma ray obtained from a simulation using GEANT [20] and an exponential background.

The low γ background at higher energies was attributed to reactions of the knocked out neutron with the target and surrounding materials. The longitudinal momentum distribution of the ^{11}Be fragments was reconstructed from the measured positions at the focal plane [16,18]. The measured inclusive longitudinal momentum distribution was separated into the constituent distributions for the $1/2^-$ and $1/2^+$ states, shown in Fig. 2. The momentum distribution for the $1/2^-$ state was obtained by gating on the 320 keV γ ray and subtracting the contribution from the background. The absolute intensity of the excited state of 35.4(4.5)% was obtained by fitting a GEANT [19] simulation of the line shape and an exponential background to the measured spectrum (dashed line in Fig. 1).

=5.5cmpbe12.ps

FIG. 2. Measured longitudinal momentum distributions in the laboratory frame for ^{11}Be residues in the ground state (a) and excited state (b) after one-neutron removal reactions of ^{12}Be. The solid(dashed) curves are eikonal model calculations [16] for l=0(1) neutron removal, normalized to the measured cross section. The errors shown are only statistical. Shown in (a) is the resolution of the spectrograph for the incident ^{12}Be beam (height and central momentum have been adjusted for display purposes).

The reliability of the simulation was confirmed by being able to reproduce source intensities to within 5% as well as the line shapes. The ground-state momentum distribution (Fig. 2a) is obtained by subtracting the excited state distribution from the inclusive momentum distribution. The measured cross sections and branching ratios are given in Table 1. The measured total one-neutron removal cross section is 49.5(4.5) mb. The two experimental facts, viz. the large 64.6(4.5)% cross section leading to the ground state of ^{11}Be and the characteristic s-wave signature of the knocked-out neutron in this transition, give a direct indication of significant occupancy of the $1s_{1/2}$ state in ^{12}Be and hence the breakdown of the N=8 shell closure.

The measured one-neutron removal cross sections and the core momentum distributions are compared with theoretical models. The calculated cross sections are a product of spectroscopic factors (S) and single-particle removal cross sections (σ_{sp}) [4,14]. Such calculations have been applied successfully to understand the structure of ^{11}Be, some neutron-rich Carbon and neutron-deficient Phosphorus isotopes [4,20].

TABLES

TABLE I. Measured cross sections σ_{exp} and deduced spectroscopic factors S_{exp} for the $1/2^+$ and $1/2^-$ ^{11}Be states populated in ^{9}Be(^{12}Be,^{11}Be)X at 78 MeV/u. S_{exp} are obtained by dividing the experimental cross section by the single-particle cross section (σ_{sp}) and the mismatch factor (see text). Calculated spectroscopic factors (S_{th}) from the WBT shell-model and three-body model (3B) are also given.

j^π	E	σ_{exp}	σ_{sp}	S_{exp}	S_{th}		
	(MeV)	(mb)	(mb)		WBT	WBT§	3B
$1/2^+$	0	32.0(4.7)	75.9	0.53(0.08)	0.51	0.69	0.7
$1/2^-$	0.32	17.5(2.6)	47.2	0.45(0.07)	0.91	0.58	0.26
$5/2^+$	1.8	-	-	-	0.40	0.55	-

In the sudden approximation, and the rest frame of the projectile, the momentum of the projectile residue is equal to that of the knocked-out nucleon. The measured residue momentum distribution reflects the Fourier transform of the part of the wave function sampled by the reaction [15]. Eikonal calculations of longitudinal momentum distributions for the projectile residues are shown in Fig. 2. These were obtained by integrating the momentum probability, expressed as one dimensional Wigner transform of the wave packet created by the reaction, over the impact parameter. These calculations were made in a black disc approximation [4,15]. A comparison with the data indicates that the ground and excited states correspond to a removal of an s and p-wave nucleon, respectively.

The partial cross sections σ_{sp} to the ^{11}Be(j^π) final states are calculated using the spectator core model of Refs. [4,14]. The cross sections include the contributions from the removal of the neutron due to the target absorption (stripping) and diffraction dissociation (elastic breakup) mechanisms. Explicit formulae are given in Ref. [14]. The essential ingredients are the interactions of the residue and the neutron with the target, their elastic S-matrices S_{11} and S_n, and the bound state wave function of the knocked-out nucleon.

Since the ^{11}Be residues are weakly bound, the relative motion degrees of freedom (and breakup) of these ^{10}Be+neutron two-body sub-systems are included. The ^{11}Be(j^π)-target $S_{11}^{j\pi}$ are thus computed as $\langle {}^{11}\mathrm{Be}(j^\pi)|S_{10}S_n|{}^{11}\mathrm{Be}(j^\pi)\rangle$, where S_{10} is the ^{10}Be-target S-matrix, and which results in a reduced survival probability [14]. The S_n are calculated from the target density using the optical limit (NN) approximation, as is S_{10}, and also from the Jeukenne, Lejeunne and Mahaux (JLM) effective interaction [21].

The ^{11,12}Be structures enter these calculations through the removed nucleon single-particle overlaps for the $1/2^+$ and $1/2^-$ final states, with separation energies of 3.17 and 3.49 MeV respectively. When considering these overlaps, there are two different types of terms which need to be considered; the shell-model spectroscopic factor and the radial mismatch factor. The shell-model spectroscopic factor takes into account the configuration mixing between the $0p$ and $0d1s$ shells. The mismatch factor takes into account the reduction from unity in the overlap between the radial wave functions in ^{11}Be and ^{12}Be due to the change in the average potential between these two nuclei. The shell-model Hamiltonian already implicitly contains to some extent this mismatch factor in its effective Hamiltonian, but the expectation values and overlaps using these wave functions must explicitly take into account the radial wave function overlaps.

These overlap functions are calculated as single-particle wave functions in Woods-Saxon (WS) potentials with geometries taken (i) as $(1.25, 0.7)$ fm, typical of shell-model (SM) single-particle states, and (ii) from the three-body (^{10}Be+n+n) calculation of Ref. [13].

There WS formfactors are fitted to those computed from three- and two-body wave functions for ^{12}Be and ^{11}Be (Be12-b of Table 9). While this three-body (3B) overlap will account for the spatial mismatch of the wave functions of the second (unstripped) valence nucleon between the initial and final states, this is not the case for the shell-model overlap. The squares of the overlaps, between neutron single-particle states with 3.17 and 3.49 MeV binding energy in the initial states and 0.504 and 0.184 MeV in the final states, are 0.79 for the $1s$ and 0.83 for the $0p$ configurations, respectively. The resulting experimental spectroscopic factors are given in Table 1. The comparison with the shell-model spectroscopic factors given in the table will be discussed below.

The ratio of the calculated σ_{sp} to the two ^{11}Be states (1.60) is insensitive to the bound state potential geometry or neutron distorting potential used. It follows that the relative spectroscopic factors for the two transitions will be well determined by the experiment. Deduced absolute spectroscopic factors, however, will depend on the interactions and, more sensitively, on the wave function used to calculate σ_{sp}. As an indication of this sensitivity the total one-nucleon removal cross sections, calculated using the NN interaction, the wave functions of geometries (*i*) and (*ii*) and the corresponding spectroscopic factors, are 66.2 and 80.5 mb. The largest sensitivity is to the radii of the nucleon binding potentials. The cross sections and the experimentally derived spectroscopic factors shown in Table 1 use the NN interaction and the SM wave function geometry, as in our study of other nuclei [20]. Calculations using the JLM interaction yield very similar results, consistent with earlier studies [14]. The leading corrections to these calculations, expected to arise from dynamical coupling between the ^{11}Be core states, have been estimated to lead to a cross section error of less than 1 mb and hence have been neglected.

We now compare the experimental spectroscopic factors with those obtained from shell-model calculations. We use the WBT Hamiltonian [6] which is appropriate for a model space with active configurations of the type $(0p)^n$-$(0d1s)^m$. (The calculations are done within the full $0s$-$0p$-$1s0d$-$1p1f$ basis in order to remove the spurious states, but the main configurations for this mass region are $(0s)^4$-$(0p)^n$-$(0d1s)^m$). The low-lying levels for ^{11}Be obtained with the WBT interaction are 0.0 MeV ($1/2^+$) and 1.52 MeV ($5/2^+$) [$(0p)^6$-$(0d1s)^1$] and 0.30 MeV ($1/2^-$) [$(0p)^7$], in good agreement with experiment.

The energies of the lowest $(0p)^8$ and $(0p)^6$-$(0d1s)^2$ 0^+ states in ^{12}Be are degenerate to within 50 keV. The spectroscopic factors for these pure configurations leading to the low-lying states in ^{11}Be are $S(1/2^-) = 1.82$ for the $(0p)^8$ to $(0p)^7$ transition, and $S(1/2^+) = 1.02$ and $S(5/2^+) = 0.81$ for the $(0p)^6$-$(0d1s)^2$ to $(0p)^6$-$(0d1s)^1$ transitions.

An excited 0^+ state is suggested experimentally to be at 2.730 MeV [11]. In a two-level model this would require an off-diagonal matrix element of about 1.35 MeV, which is much larger than the energy difference between the theoretical unmixed states. Thus the mixed ground state has a 50% admixture of the two configurations. The spectroscopic factors for the mixed ground state are given in Table 1 (WBT) and compared to experiment. The $5/2^+$ is unbound to neutron decay and thus would not be observed in the present experiment. The experimental spectroscopic factor for the $1/2^-$ state is smaller than obtained with the WBT two-component model, indicating that the actual ^{12}Be ground-state wave function contains a smaller $(0p)^8$ (neutron closed-shell) component. To match the ratio of the experimental spectroscopic factors an admixture of about 32% $(0p)^8$ and 68% $(0p)^6$-$(0d1s)^2$ would be required, leading to WBT§ results given in Table 1. The $(0p)^6$-$(0d1s)^2$ configuration has a low-lying 2^+ state with a large B(E2) value of 85 $e^2 fm^4$. Taking the WBT§ solution for the ground state and a pure $(0p)^6$-$(0d1s)^2$ 2^+ configuration gives B(E2) = 58 $e^2 fm^4$. It would be interesting to measure it in a Coulomb excitation experiment.

The present experimental observation of about equal s and p spectroscopic factors is similar to the recent results of Simon *et al.* [8] for ^{11}Li where about an equal s and p admixture was also found. Indeed, the shell-model structure of ^{11}Li is predicted to be very similar to that of ^{12}Be; both have degenerate $(0p)^n$ and $(0p)^{n-2}$-$(0d1s)^2$ 0^+ ground-state configurations with the WBT interaction [9]. However, about 1/3 of the spectroscopic strength for ^{12}Be is predicted to go by d-wave pickup to the unbound, $5/2^+$ state at 1.78 MeV in ^{11}Be. It would be important to design an experiment for ^{12}Be to look for the neutrons from the decay of this low-lying state. Also the possibility for a significant d-wave contribution in

^{11}Li should be considered in future analyses. Improved shell-model calculations for ^{11}Li and ^{12}Be will require a consideration of complete mixing between all configurations, and perhaps an expansion of the model space to allow more than two neutrons to be excited across the $N = 8$ shell gap. The interaction which is appropriate for the expanded model space as well as the halo nature of these nuclei needs to be investigated.

In summary, direct evidence of the occupancy of the $s_{1/2}$ particle state, and hence a breakdown of the $N = 8$ shell closure, has been obtained from the measurement of the knockout of a neutron from ^{12}Be leading to the $1/2^+$ or $1/2^-$ states in ^{11}Be. The spectroscopic factors for the $s_{1/2}$ and $p_{1/2}$ configurations have been derived. Comparison with shell-model calculations indicates that the ^{12}Be ground state has only about 32% of the neutron closed-shell configuration.

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REFERENCES

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[1] P.G. Hansen, A.S. Jensen and B. Jonson, Annu. Rev. Nucl. Part. Sci. **45**, 591 (1995).

[2] D. Guillemand-Mueller et al., Nucl. Phys. **A426**, 37 (1984).

[3] T. Motobayashi *et al.*, Phys. Lett. B **346**, 9 (1995); B.V. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).

[4] A. Navin *et al.*, Phys. Rev. Lett. **81**, 5089 (1998).

[5] I. Talmi and I. Unna, Phys. Rev. Lett. **4**, 469 (1960).

[6] E.K. Warburton and B.A. Brown, Phys. Rev. C **46**, 923 (1992).

[7] H. Sagawa, B.A. Brown and H. Esbensen, Phys. Lett. B **309**, 1 (1993).

[8] H. Simon *et al.*, Phys. Rev. Lett. **83**, 496 (1999).

[9] B.A. Brown, in *Proc. ENAM95*, ed. by M. de Saint Simon and O. Sorlin, Editions Frontieres (1995) p451; B.A. Brown, *International School of Heavy-Ion Physics, 4th Course: Exotic Nuclei*, ed. by R.A. Broglia and P.G. Hansen (World Scientific, Singapore, 1998) p1.

[10] F.C. Barker, J. Phys. G **2**, L45 (1976).

[11] H.T. Fortune, G.B. Liu and D.E. Alburger, Phys. Rev. C **50**, 1355 (1994).

[12] T. Suzuki and T. Otsuka, Phys. Rev. C **56**, 847 (1997).

[13] F.M. Nunes *et al.*, Nucl. Phys. A **609**, 43 (1996).

[14] J.A. Tostevin, J. Phys. G: Nucl. Part. Phys. **25**, 735 (1999); J.A. Tostevin, *Spectroscopy of halo nuclei from reaction measurements*, in *Second International Conference on Fission and Properties of Neutron-rich Nuclei*, (World Scientific, Singapore), in press.

[15] P.G. Hansen, Phys. Rev. Lett. **77**, 1016 (1996).

[16] J.A. Caggiano, Ph.D. thesis MSU (1998); B.M. Sherrill *et al.*, to be published.

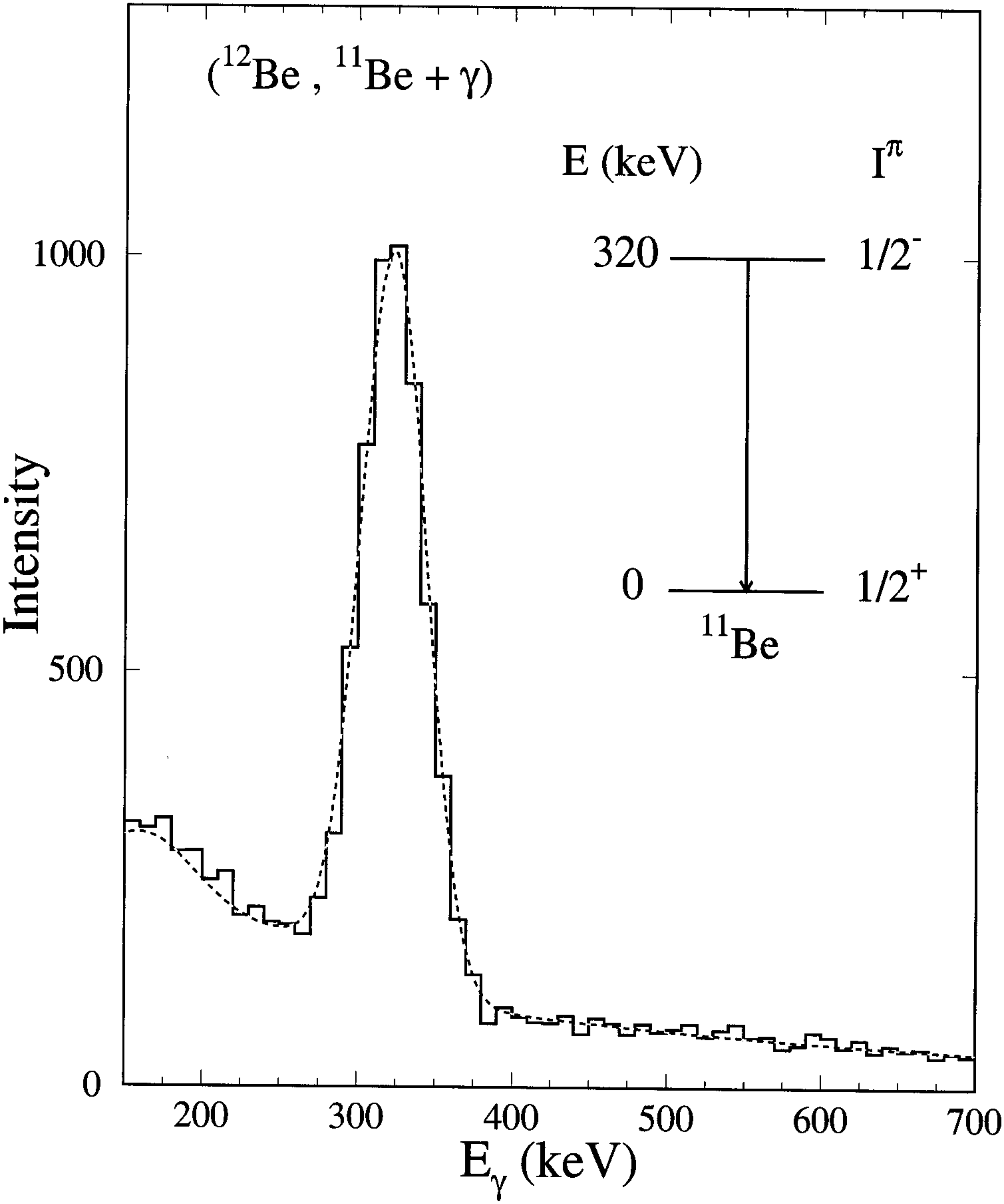
[17] H. Scheit *et al.*, Nucl. Inst. Meth. **A** 2, 124 (1999).

[18] M. Berz *et al.*, Phys. Rev. C **47**, 537 (1993).

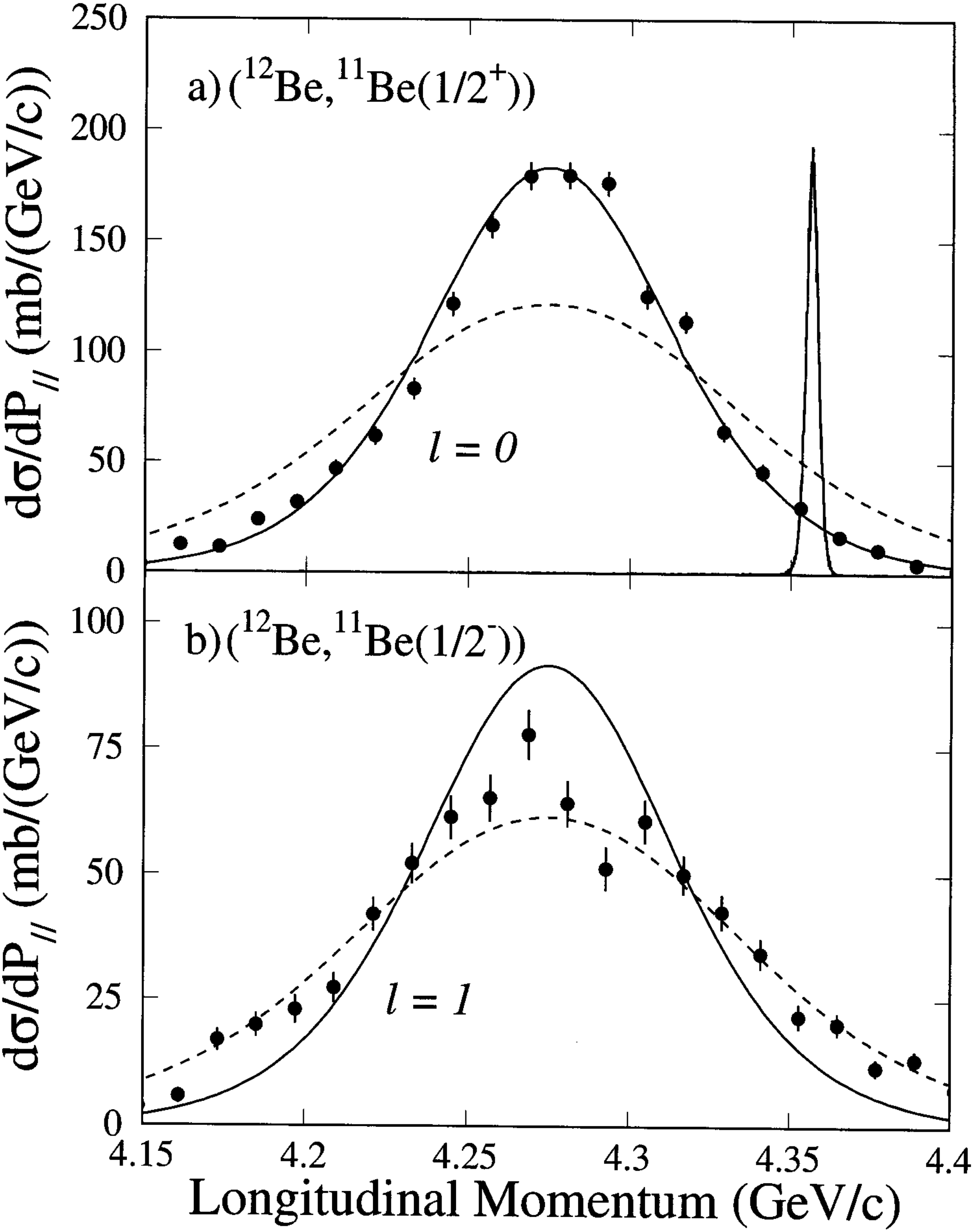
[19] GEANT, Cern Library Long Writeup W5013 (1994).

[20] T. Aumann *et al.*, to be published; V. Maddalena *et al.*, to be published; A. Navin *et al.*, Nucl. Phys. A (in press).

[21] J.P. Jeukenne, A. Lejeunne and C. Mahaux, Phys. Rev. C **16**, 80 (1977).



(^{12}Be , ^{11}Be + γ)
E (keV)
I^π
320
$1/2^-$
0
$1/2^+$
^{11}Be
Intensity
1000
500
0
200
300
400
500
600
700
E_γ (keV)


a) (^{12}Be, ^{11}Be(1/2$^+$))
l = 0
b) (^{12}Be, ^{11}Be(1/2$^-$))
l = 1
dσ/dP$_{//}$ (mb/(GeV/c))
dσ/dP$_{//}$ (mb/(GeV/c))
250
200
150
100
50
0
100
75
50
25
0
4.15
4.2
4.25
4.3
4.35
4.4
Longitudinal Momentum (GeV/c)