New modes of halo excitation in the ^{6}He nucleus

B. V. Danilin,[1,2] T. Rogde,[1] S. N. Ershov,[1,3] H. Heiberg-Andersen,[1] J. S. Vaagen,[1,4] I. J. Thompson,[5] and M. V. Zhukov[6]
[1]*SENTEF, Department of Physics, University of Bergen, Allégt. 55, 5007 Bergen, Norway*
[2]*RRC The Kurchatov Institute, Kurchatov Sq. 1, 123182, Moscow, Russia*
[3]*JINR - Dubna, 141980 Dubna, Moscow region, Russia*
[4]*ECT* European Centre for Theoretical Studies in Nuclear Physics and Related Areas, Trento, Italy*
[5]*Department of Physics, University of Surrey, Guildford GU2 5XH, United Kingdom*
[6]*Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden*
(Received 4 September 1996)

Predictions are made for the structure of a second 2^+ resonance, the soft dipole mode and unnatural parity modes in the ^{6}He continuum. We use a structure model which describes the system as a three-body $\alpha+N+N$ cluster structure, giving the experimentally known properties of ^{6}He and ^{6}Li, and use the distorted-wave impulse approximation (DWIA) reaction theory appropriate for dilute matter. The presence of both resonant and nonresonant structures in the halo excitation continuum is shown to be manifest in charge-exchange reactions as well as inelastic scattering with single nucleons. [S0556-2813(97)50302-5]

PACS number(s): 21.45.+v, 21.60.Gx, 24.30.Gd, 27.20.+n

The known spectrum of ^{6}He contains only the 0^+ bound state and the well known 2^+ ($E^*=1.8$ MeV) three-body resonance, and then a desert in the three-body $\alpha+n+n$ continuum up to the ^{3}H + ^{3}H threshold at about 13 MeV [1]. While for ^{11}Li a response (E1 strength) function has been reconstructed from exclusive experiments [2,3], such information is still lacking for ^{6}He. Except for momentum distributions from fragmentation experiments with ^{6}He beams [4–6], the only data are from charge-exchange reactions with ^{6}Li to the ^{6}He continuum, but with poor statistics and limited angles [7–9].

The recent developments of radioactive nuclear beam techniques and of dynamic approaches to three-body continuum theory [10] make it possible to investigate to what extent our knowledge of the lightest Borromean halo nucleus ^{6}He is complete. What are the specific features of the continuum of a system with a halo ground state? Below we give predictions of a second 2^+ three-body resonance that may be accessible in experiment, and also (a much less pronounced) 1^+ resonance. The so-called ''soft dipole mode'' suggested in [11,12] still needs clarification [13]. According to existing three-body models it is not a simple binary core – point dineutron resonance, neither in ^{11}Li nor probably in ^{6}He, but although this seems now widely accepted, further tests within these three-body models are desirable. It shows no three-body pole structure, as discussed, e.g., in [14], and therefore it is still an open question whether the ''soft dipole mode'' is just a dynamical enhancement arising from final state interactions in the direct excitation of the three-body continuum. It is now possible for experiments to tell whether the three-body frameworks are adequate, since these models are shown in the present paper to give rise to other soft modes of other multipolarities. Such modes were suggested in [15], but need both theoretical and experimental clarification. We believe that the predictions given below are reliable as guide for future experiments, and that the observation of the dipole and other modes predicted here would support the validity of three-body models and their representation of the ''soft dipole mode'' as not being a genuine three-body resonance.

The nucleus ^{6}He has in past years been used as a reference case, with the most reliable information on the binary core-n interaction. Our previous investigations of $A=6$ nuclei [10,16–19] and ^{11}Li [20] and also those of other authors [14,21–25] using a variety of methods, have shown that numerous characteristics of $A=6$ nuclei can be accounted for in a self-consistent way by using ''fundamental'' pairwise interaction potentials which reproduce the binary scattering phases up to disintegration thresholds. Thus, the data from [1,4] on binding energy, geometric and electromagnetic characteristics, form-factor behavior for electron scattering, β decay of ^{6}He and ^{6}Li(n,p)^{6}He charge-exchange cross sections to the ground state have all been reproduced rather well. The sharp 2^+ resonance at 1.8 MeV (width 112 keV) excitation energy is also reproduced, though not with the full width. Also the puzzle with the ^{6}Li quadrupole moment still needs to be solved.

This paper extends our previous studies to nuclear as well as E1 responses, and we also apply the distorted wave impulse approximation (DWIA) to some specific nuclear reactions with simple mechanisms. The task is simplified in these Borromean systems due to the lack of binary bound states.

For very dilute matter, the situation of halo nuclei, it seems justified to try to use the impulse approximation in the reaction calculations over a wider energy range, using the free interaction t matrix [26]. The present calculations employ the standard t-matrix parametrization of Love and Franey, with central, tensor, and spin-orbit components [27]. For charge-exchange reactions to low excitation energies the situation is particularly simple for the $A=6$ system, as only the two halo nucleons take part in the exchange, the $T=0$ α-core being unaffected. The reaction is, however, still a four-body problem: we will return to details of the reaction theory in a larger communication.

The transition amplitudes for the reaction are T matrix integrals of the transition couplings with the incoming and outgoing distorted waves, integrating over the channel radius $\boldsymbol{r}$ between the nucleon N and the $A=6$ system. The reaction form factors are folded structures

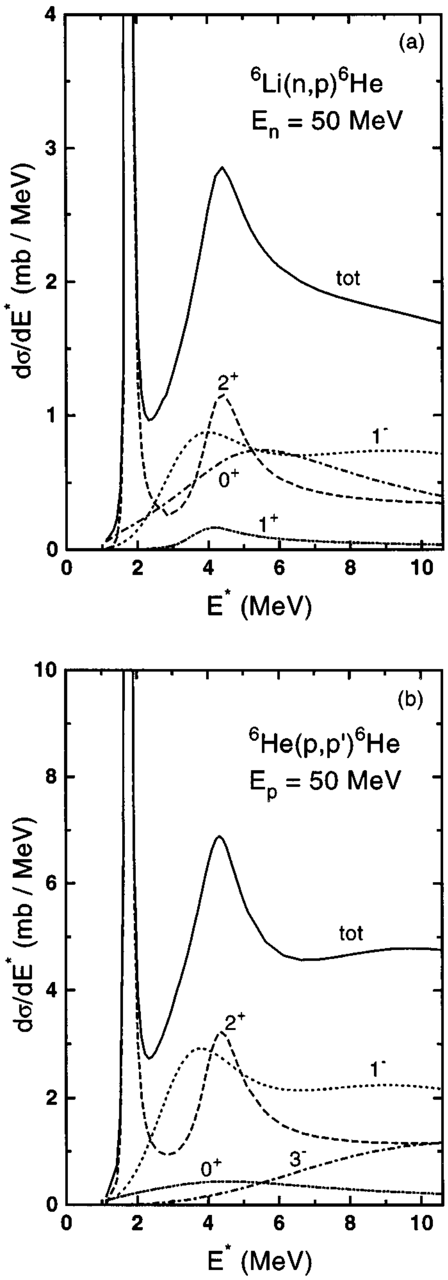

FIG. 1. Charge-exchange (a) and inelastic scattering (b) cross section to ^{6}He continuum. The total amplitude and multipole decomposition are given. E^* is the excitation energy.

$\int dr' r'^2 \; \rho_{lsj,t}(r',E^*) \; t_{l'sj,t}(r,r')$ of the two-body interaction between colliding nucleons, where the transition density matrix elements are given by

$$\rho_{lsj,t}(r,E^*) = \langle J_f \pi_f T_f \| \; \hat{\rho}_{lsj,t}(r) \| J_i \pi_i T_i \rangle \tag{1}$$

$$\hat{\rho}_{lsjm_j,t}(r) = \sum_{i=1,2} \frac{\delta(r-r_i)}{r_i r} [Y_l(\hat{\boldsymbol{r}}_i) \otimes \; \sigma_s(i)]_{jm_j} \; \tau_t(i),$$

$$\sigma_s(i) = \begin{cases} 1, & s=0 \\ \boldsymbol{\sigma}(i), & s=1, \end{cases} \qquad \tau_t(i) = \begin{cases} 1, & t=0 \\ \boldsymbol{\tau}(i), & t=1. \end{cases} \tag{2}$$

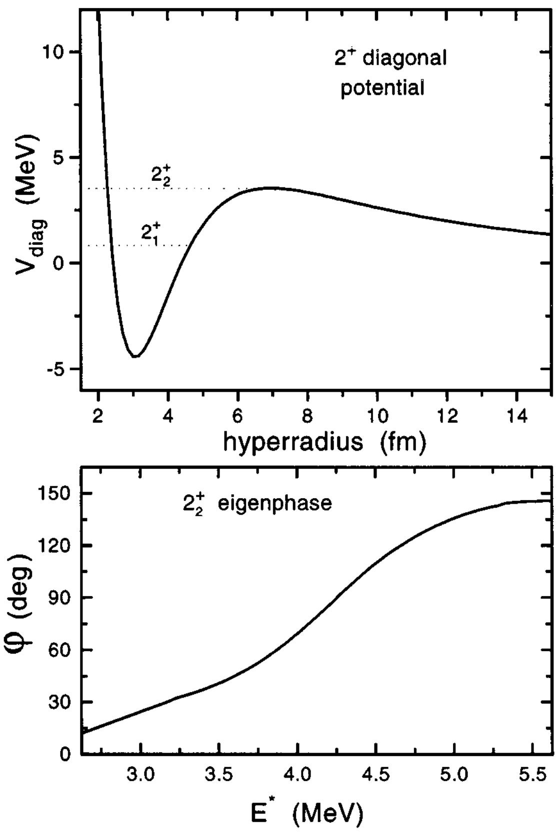

FIG. 2. Diagonal (effective three-body) potential and energy positions for the 2^+ resonance peaks, corresponding to the configuration $|S=1,\, [l_x=1,\, l_y=1]\; L=1\rangle$. The 2_2^+ eigenphase behavior is also shown.

To show a simple measure of the transition strength, we define a 'nuclear response' by integrating the transition density over $\boldsymbol{r}$.

The hyperspherical harmonics (HH) expansion method (see Refs. [10,16,17]) was used to calculate the continuum states entering eq. (0.1) as well as the initial bound state. In the center-of-mass system, the three-body states have the form of products of an intrinsic cluster wave function and functions of the relative motion with orbital momentum L and spin S coupled to total angular momentum J,M_J. Translationally invariant normalized sets of Jacobi coordinates define the relative spatial degrees of freedom with corresponding angular momenta l_x and l_y coupled to L, where, e.g., $l_x = l_{NN}$ and $l_y = l_{(NN)\alpha}$.

We use as binary potentials between the cluster constituents the modified SBB Gaussian type αN interaction [16] with purely repulsive s-wave component and the ''realistic'' GPT NN interaction [28]. These were also successfully employed in our original calculations for bound and lowest excited states of the $A=6$ nuclei [10,16], as well as for our previous calculations of the dipole strength function [18] and electromagnetic (EM) dissociation cross sections [19].

By expanding on the HH basis, the Schrödinger equation for two radial variables x,y is transformed into a one-dimensional coupled channels (CC) problem in hyperradius ρ, containing an additional quantum number called the hypermoment, $K = l_x + l_y + 2n$, $(n = 0,1,2, \dots)$ associated with the extra hyperangle $\tan\alpha = x/y$. We solve the three-body

TABLE I. The main components of interior norms (out to 15 fm) of 2^+ resonances for ^{6}He in LS and Jacobi jj representation $(n\alpha)$ and $n(n\alpha)$. Here $x\sim(nn)$ and $y\sim(nn)\alpha$.

L	S	l_x	l_y	Norm 2_1^+	Norm 2_2^+	Config	Norm 2_1^+	Norm 2_2^+
1	1	1	1	32	58	$p_{3/2}\ p_{3/2}$	33	45
2	0	0	2	45	30	$p_{1/2}\ p_{3/2}$	32	32.5
2	0	2	0	22	11	$s_{1/2}\ d_{5/2}$	21	13
						$s_{1/2}\ d_{3/2}$	14	8.5

Schrödinger equation exactly up to 20 fm for bound states and up to 40 fm for continuum states where this solution was matched with the three-body asymptotics [18]. Our previous investigations [16–18] showed that the main characteristics of the $A=6$ nuclei can be ascribed to only a few HH of the full wave function. The same structures are obtained by a truncation of the K space to $K\leqslant 6$ which is compensated by a renormalization of the αn interaction in the same manner as described in [18], preserving the geometric characteristics and asymptotic binding energy ($R_{\rm rms}=2.45$ fm and $E=-0.78$ MeV). As in most variational calculations, we obtained an upper limit on the position of the resonance and a lower limit on its width.

By a *soft mode* we mean a pronounced accumulation of excitation strength at low continuum energies. Here the three-body model is justified: these are energies low compared with normal shell separations $\hbar\omega$ or the nearest 2-body thresholds. The soft mode may be a resonance, but not necessarily. From a dynamical point of view, a narrow three-body resonant state may be caused by a well-pronounced pocket in one of the diagonal partial wave potentials, which are sums of a nuclear mean field in the hyperradius ρ and three-body centrifugal components of type

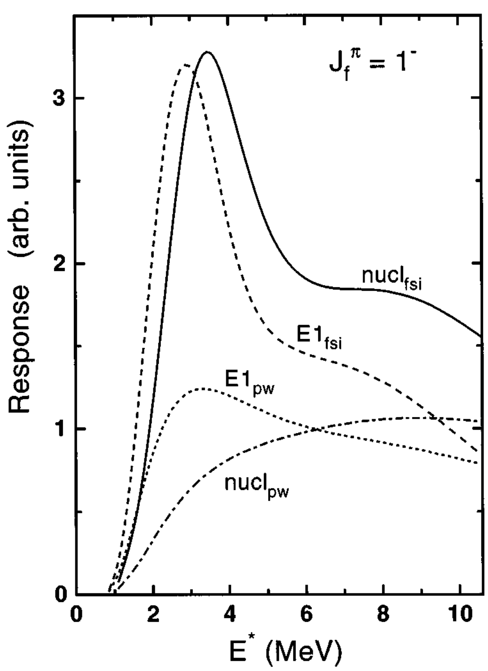

FIG. 3. Electromagnetic and nuclear response functions (all in arb. units) for continuum with both final state interactions (fsi) and plane waves (pw).

TABLE II. Weights of main components of dipole response function of ^{6}He in LS and Jacobi jj representation.

L	S	l_x	l_y	Norm 1^-	Config	Norm 1^-
1	0	0	1	87.5	$s_{1/2}\ p_{3/2}$	58
1	1	1	0	2	$s_{1/2}\ p_{1/2}$	30
1	0	2	1	8.5	$d_{5/2}\ p_{3/2}$	4.5
					$d_{3/2}\ p_{1/2}$	2.5

$(K+3/2)(K+5/2)/\rho^2$. This is possible in our model since all the potentials are local. The pocket structure in the effective three-body potential depends weakly on the details of the NN (central or realistic) and core-N (Gaussian or Woods-Saxon) interactions; it has been found for all resonances discussed in the article. Earlier investigations [10] showed a pocket in the $K=2$ partial component in $A=6$ nuclei for the well known $J^\pi=0^+$ and $2^+(T=1)$ resonances. Resonances may also arise in CC problems from large off-diagonal couplings (see [29]), in which case the eigenphases of the S matrix need to be examined. Sharp resonances will show phase shifts $\delta=\pi/2$, while for the widest resonances we do not have a reliable criterion, just as when analyzing two-body phase shifts.

According to the simplest shell model prescription, $(p_{3/2})^2$, $(p_{1/2})^2$, and $(p_{3/2}p_{1/2})$ would be the ground and excited state positive parity configurations of the ^{6}He continuum, and we could expect excitation structures like 0_2^+, 2^+, and unnatural parity states 1^+ and 3^+ of quadrupole type. To get negative parity states 1^-, 0^-, and 2^- (unnatural parity) of dipole type, we need to involve s and d orbits.

In reality we deal with a strong mixing of configurations; the g.s. configuration resulting from an HH calculation is mainly $(p_{3/2})^2$ with a superposition of $(p_{1/2})^2$ and $(s_{1/2})^2$ and $(d_{5/2})^2$, and we should expect complex structures for the excited states because of a strong nn interaction, competing with the αn interaction.

Figure 1 shows our predictions for inclusive cross sections of inelastic ^{6}He$(p,p')^6$He scattering and charge-exchange ^{6}Li$(n,p)^6$He to the continuum structure of a halo nucleus with a compact core. Configuration mixing is included in the ground state, as well as final-state interactions in the continuum.

2^+ quadrupole resonance. In addition to the sharp 2_1^+ resonance at 1.8 MeV, a second 2_2^+ resonance was calculated

TABLE III. Comparison of resonance positions and widths (in MeV) of ^{6}He. Calculations in the Hyperspherical Harmonics Method (HH), Complex Scaling Method (CS1) from Ref. [14], (CS2) from Ref. [23], and positions known from experiment [1].

	HH		CS1		CS2		Exp.	
J^π	E	Γ	E	Γ	E	Γ	E	Γ
0_1^+	-0.64		-0.6		-0.78		-0.97	
2_1^+	0.75	0.04	0.74	0.06	0.8	0.26	0.822	0.113
2_2^+	3.3	1.2	-	-	2.5	4.7	-	-
1^-	not found		not found		not found		-	-
1^+	3.4	1.8	-	-	3.0	6.4	-	-
0_2^+	5.0	6.0	-	-	3.9	9.4	-	-

at an excitation energy of 4.3 MeV with a width $\Gamma=1.2$ MeV; see again Fig. 1. The resonance ''on the top of a barrier'' behavior is evidenced both by a well defined diagonal potential pocket and eigenphases (Fig. 2). Both LS and Jacobi jj coupling show strong mixing of configurations (Table I).

1^+ resonance. This mode [see Fig. 1(a)] with E^* = 4.5 MeV is almost entirely based on the component $|S=1, [l_x=1, l_y=1]\ L=1\rangle$, corresponding to reorientation of the 14% 0^+ g.s. component with the same quantum numbers [17]. This prevailing component has an interior norm [10] of 94%. (The ''interior norm'' is constructed as the square norm of the diagonal part of the scattering wave function, integrated up to a hyperradius of 15 fm.) In Jacobi jj coupling this transforms completely into the unique configuration $(p_{3/2}p_{1/2})$. The character appears to be that of a wide resonance.

0^+ excitation. The charge-exchange cross section for the 0^+ continuum exhibits a wide distribution peaking at $E^*=5$ MeV. The 0^+ cross section is the integrated result of complex substructures. The competition between αn p wave and nn s wave attraction and αn s wave repulsion takes place in the large space volume characteristic of the halo system. This together with kinematic factors (penetrability of barriers for relative motion) produces structures in both charge-exchange and EM responses. Our calculations show enhancements at about 2.8 MeV and 3.8–6 MeV. Diagonal phases and eigenphases revealed only a rapid growth at 3–4 MeV, but no proper resonant behavior.

1^- soft dipole mode. A central question at the present time is the origin of accumulation of dipole strength at very low continuum energy. Various attempts, based on the same cluster representation of ^{6}He, have not given a definite answer [12,18,14,21]. Our analysis of the effective three-body potentials did not reveal any clear-cut pockets of the kind mentioned earlier, and neither does the energy behavior of the eigenphases justify calling the soft dipole mode a resonance.

A further test is to compare EM and short range nuclear dipole response. With three-body plane wave final states the calculated EM and nuclear responses give concentrations at 3.5 and $\sim$10 MeV, respectively, but the concentrations nearly coincide (at 3 and 4.5 MeV) if coupled three-body continuum wave functions for ^{6}He are used (Fig. 3).

Table II gives the decomposition of the soft dipole peak in both LS and Jacobi jj couplings. The main 1^- component $|S=0, [l_x=0, l_y=1]\ L=1\rangle$ gives about 90% of the intensity at the peak and reflects the strong nn attraction in the $^1S_0$ partial wave. Without the nn interaction, the height of the peak is reduced to less than half its value, with peak position shifted to higher energies.

The shoulder in Fig. 3 at higher energies is due to other components (which may be interpreted as excitation of the next shell) with peak positions at 5 MeV ($|S=1, [l_x=1, l_y=2]\ L=1\rangle$) and 8 MeV ($|S=0, [l_x=2, l_y=1]\ L=1\rangle$ and $|S=1, [l_x=1, l_y=0]\ L=1\rangle$).

We show in Table III the positions and widths of possible resonances obtained in different methods. All of them give very close positions but different widths which should be proved experimentally.

Our calculations also produced 0^- and 2^- unnatural parity dipole modes, but the associated response functions are two orders of magnitude less than that for dipole excitation. The 3^+ quadrupole mode is four orders of magnitude less than for the second quadrupole resonance.

In summary, we have presented predictions for the ^{6}He three-body continuum which are the consequence of using an $\alpha + N + N$ model with realistic interactions between the constituents, interactions which reproduce all observables in the binary subsystems. To carry out this analysis we have used a scattering method to investigate 3+3 scattering. This has the advantage that, even when a resonance is not present as a pole, the continuum structure can still be investigated while taking into account all final state interactions. Our calculations reproduce the 0^+ ground state and also the experimental excitation energy (1.8 MeV) of the well-known 2^+ resonance. Electromagnetic and nuclear responses have been shown, and charge-exchange and inelastic scattering from nucleons have been calculated within the DWIA framework.

Our model predicts a second soft 2^+ mode in the ^{6}He continuum which qualifies as a three-body resonance, and a soft dipole mode which does not.

The results are consistent with the gross features of existing, although sparse, experimental data [7–9]. Since this continuum structure is concentrated in the vicinity of the very dominant first 2^+ resonance, high resolution experiments with detailed angular distributions are needed.

We will return to the characterization of the halo continuum structures in a larger paper where a complete analysis with detailed description of the three-body continuum theory and the four-body DWIA reaction theory is given.

We are grateful to Prof. F.A. Gareev, Prof. T. Engeland, Prof. R. Leonardi, and Prof. A. Richter for useful discussions. This work was done with financial support from Bergen, Surrey, and ECT*.

[1] F. Ajzenberg-Selove, Nucl. Phys. **A490**, 1 (1988).
[2] K. Ieki *et al.*, Phys. Rev. Lett. **70**, 730 (1993); D. Sackett *et al.*, Phys. Rev. C **48**, 118 (1993).
[3] F. Shimoura *et al.*, Phys. Lett. B **348**, 29 (1995).
[4] I. Tanihata, T. Kobayashi, O. Yamakawa, S. Shimoura, K. Ekuni, K. Sugimoto, N. Takahashi, T. Shimoda, and H. Sato, Phys. Lett. B **206**, 592 (1988).
[5] T. Kobayashi, Nucl. Phys. **A538**, 343c (1992).
[6] D. P. Balamuth *et al.*, Phys. Rev. Lett. **72**, 2355 (1994).
[7] F. Brady, G. A. Needham, J. L. Romero, C. M. Castaneda, T. D. Ford, J. L. Ullmann, and M. L. Webb, Phys. Rev. Lett. **51**, 1320 (1983).
[8] J. Jänecke *et al.*, Phys. Rev. C **54**, 1070 (1996).
[9] S. B. Sakuta *et al.*, Europhys. Lett. **22**, 511 (1993); *ibid.* **28**, 111 (1994).
[10] B. V. Danilin and M. V. Zhukov, Phys. At. Nuclei **56**, 460 (1993).
[11] P. G. Hansen and B. Jonson, Europhys. Lett. **4**, 409 (1987); K.

Ikeda, INS Report No. JHP-7, 1988 [in Japanese].

[12] Y. Suzuki, Nucl. Phys. **A528**, 395 (1991).

[13] For a very recent discussion, see A. C. Hayes and S. M. Sterbenz, Phys. Rev. C **52**, 2807 (1995); A. Csótó, *ibid.* **52**, 2809 (1995).

[14] A. Csótó, Phys. Lett. B **315**, 24 (1993); Phys. Rev. C **48**, 165 (1993); *ibid.* **49**, 3035,2244 (1994).

[15] S. A. Fayans, Phys. Lett. B **267**, 443 (1991); S. A. Fayans, S. N. Ershov, and E. E. Svinareva, *ibid.* **292**, 239 (1992).

[16] M. V. Zhukov, B. V. Danilin, D. V. Fedorov, J. M. Bang, I. J. Thompson, and J. S. Vaagen, Phys. Rep. **231**, 151 (1993).

[17] B. V. Danilin, M. V. Zhukov, A. A. Korsheninnikov, L. V. Chulkov, and V. D. Efros, Sov. J. Nucl. Phys. **49**, 351, 359 (1989); **53**, 71 (1991); B. V. Danilin, M. V. Zhukov, S. N. Ershov, F. A. Gareev, R. S. Kurmanov, J. S. Vaagen, and J. M. Bang, Phys. Rev. C **43**, 2835 (1991).

[18] B. V. Danilin, M. V. Zhukov, J. S. Vaagen, and J. M. Bang, Phys. Lett. B **302**, 129 (1993).

[19] L. S. Ferreira, E. Maglione, J. M. Bang, I. J. Thompson, B. V. Danilin, M. V. Zhukov, and J. S. Vaagen, Phys. Lett. B **316**, 23 (1993).

[20] B. V. Danilin, I. J. Thompson, M. V. Zhukov, J. S. Vaagen and J. M. Bang, Phys. Lett. B **333**, 299 (1994).

[21] S. Funada, H. Kameyama, and Y. Sakuragi, Nucl. Phys. **A575**, 93 (1994).

[22] K. Arai, Y. Suzuki, and K. Varga, Phys. Rev. C **51**, 2488 (1995).

[23] S. Aoyama, S. Mukai, K. Kato, and K. Ikeda, Prog. Theor. Phys. **93**, 99 (1995); **94**, 343 (1995).

[24] D. R. Lehman and W. C. Parke, Phys. Rev. C **28**, 364 (1983); *ibid.* **29**, 2319 (1984); **39**, 1685 (1989).

[25] V. I. Kukulin, Nucl. Phys. **A586**, 151 (1995).

[26] A. K. Kerman, H. McManus, and R. M. Thaler, Ann. Phys. (N.Y.) **8**, 551 (1959).

[27] M. A. Franey and W. G. Love, Phys. Rev. C **31**, 488 (1985).

[28] D. Gogny, P. Pires, and R. de Tourreil, Phys. Lett. **32B**, 591 (1970).

[29] A. I. Baz', Zh. Exp. Teor. Fiz. 70, 397 (1976) [Sov. Phys. JETP **43**, 205 (1976)].