Two-proton pickup reaction (^{6}He,^{8}Be) on ^{12}C, ^{16}O, and ^{19}F

M. Milin,[1,*] Đ. Miljanić,[1] M. Aliotta,[2,†] S. Cherubini,[3,‡] T. Davinson,[4] A. Di Pietro,[4,§] P. Figuera,[2] A. Musumarra,[3,§] A. Ninane,[3] A. N. Ostrowski,[4,||] M. G. Pellegriti,[2] A. C. Shotter,[4,¶] N. Soić,[1] C. Spitaleri,[2] and M. Zadro[1]

[1]*Ruđer Bošković Institute, Zagreb, Croatia*

[2]*INFN, Laboratori Nazionali del Sud and Università di Catania, Catania, Italy*

[3]*Institut de Physique Nucléaire, Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

[4]*Department of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*

(Received 3 May 2004; published 7 October 2004)

The first results are reported on (^{6}He,^{8}Be) two-proton pick-up reactions on ^{12}C, ^{16}O, and ^{19}F nuclei. The measurements were done with an 18 MeV beam on ^{6}LiF, ^{7}LiF, $^6Li_2CO_3$, and ^{12}C targets. The measured angular distributions for the ^{12}C(^{6}He,^{8}Be)^{10}Be (g.s.) and ^{12}C(^{6}He,^{8}Be)^{10}Be*(3.37 MeV) reactions show a clear signature of a direct process. Although the contributions from the ^{6}Li(^{6}He,^{8}Be)^{4}H reaction were observed, no clear extraction of the ^{4}H data was possible.

DOI: 10.1103/PhysRevC.70.044603 PACS number(s): 25.60.Je, 27.20.+n

I. INTRODUCTION

Two-nucleon transfer reactions have been extensively used for the study of nuclear structure and also for the determination of nuclear masses close to the drip lines. Among them the two-proton pickup reactions are the least investigated mainly due to their inherent experimental problems. Compared to (p,t), $(p,{}^3\text{He})$ and even (n,t) reactions, experimental results for $(n,{}^3\text{He})$ reactions are very scarce. For example, (according to the CINDA database), the angular distribution for a $(n,{}^3\text{He})$ reaction has been measured only for the ^{40}Ca nucleus [1]. With heavy-ion two-proton pickup reactions, in most cases, one is confronted either with the shadow peaks in the spectra corresponding to different particle-bound states of the detected ejectile, and/or with the problem of the clear separation from neighboring isotopes. One reaction which does not have these problems is (^{6}Li,^{8}B) because the ground state of ^{8}B is the only particle-stable state of the nucleus and because ^{7}B and ^{9}B are unbound [2]. However, this reaction suffers from inadequate overlap of ^{6}Li and ^{8}B wave functions [2] and highly negative Q values.

With $A<20$ stable and radioactive ($T_{1/2}>1$ min) projectiles there are in total seven $2p$ pickup reactions with ejectiles having only one particle bound state (their ground state): $(n,{}^3\text{He})$, (^{6}Li,^{8}B), (^{7}Be,^{9}C), (^{10}B,^{12}N), (^{11}B,^{13}N), (^{12}C,^{14}O), and (^{15}N,^{17}F). There are also five reactions with ejectiles having the difference, ΔE, between the ground and the first excited bound state higher than 1.5 MeV: (^{9}Be,^{11}C), $\Delta E=2.00$ MeV, (^{10}Be,^{12}C), $\Delta E=4.44$ MeV, (^{13}C,^{15}O), $\Delta E=5.18$ MeV, (^{14}C,^{16}O), $\Delta E=6.05$ MeV, and (^{18}O,^{20}Ne), $\Delta E=1.63$ MeV.

Results for a new two proton pickup reaction, (^{6}He,^{8}Be), are reported in this paper. The ^{6}He nucleus is known to have unusual, Borromean structure [3] with two loosely bound neutrons orbiting around an α-particle core. Reactions with radioactive ^{6}He beams have been studied extensively in last few years (see, e.g., Ref. [4] for a recent compilation). Elastic scattering, charge exchange reactions, breakup reactions and transfers of valence neutrons onto different targets have been used mainly to investigate the exotic structure of ^{6}He itself. Nevertheless, a ^{6}He beam may be used to induce a variety of reactions in order to study exotic states in other nuclei, especially light ones.

Although rapidly improving over the last decade, radioactive nuclear beams are still of very low intensity and quality with respect to stable beams and this is, of course, the main experimental problem of measuring the (^{6}He,^{8}Be) reaction. The use of a detector setup that covers a large solid angle and which has fine angular segmentation can partially compensate for this disadvantage.

From a spectroscopic point of view, the (^{6}He,^{8}Be), reaction has several important advantages compared to other two-proton pickup reactions mentioned above. First, both ^{6}He and ^{8}Be have 0^+ ground states. The only other such reaction with no particle stable excited states is the (^{12}C,^{14}O) reaction, recently used for the spectroscopy of exotic states in light nuclei [5,6].

Another important advantage of the (^{6}He,^{8}Be) reaction is its Q value. With a very high $2p$-separation energy in ^{8}Be ($S_{2p}=27.23$ MeV), there are only eight stable nuclei (^{4}He, ^{7}Li, ^{9}Be, ^{11}B, ^{13}C, ^{15}N, ^{18}O, and ^{48}Ca) for which the Q value of the reaction is negative.

Further spectroscopic advantage of the (^{6}He,^{8}Be) reaction concerns the wave-function overlaps between the ^{6}He and ^{8}Be ground states. The shell-model wave function by Boyarkina [7] for the ^{6}He (g.s.) is $\Psi=0.973\ [2]^{31}\text{S}\ -0.230\ [11]^{33}\text{P}$. On the other hand, the largest component of the wave function for the ^{8}Be ground state is $[4]^{11}\text{S}$ with an amplitude of 0.983; other components are much smaller:

*Electronic address: mmilin@lnr.irb.hr

†Present address: Department of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom.

‡Present address: Ruhr Universität Bochum, Germany.

§Present address: INFN—Laboratori Nazionali del Sud and Università di Catania, Catania, Italy.

||Present address: Johannes Gutenberg University, Mainz, Germany.

¶Present address: TRIUMF, Vancouver, Canada.

[31]^{13}P −0.179, [22]^{11}S −0.030, etc. (similar wave functions were obtained also by Barker [8]).

Finally, there is also an important experimental advantage of the (^{6}He, ^{8}Be) reaction. The ^{8}Be nucleus in its ground state is particle unstable by 92 keV for the decay into two α particles. Such a small decay energy makes two α particles from this decay very close in space and energy. The coincident detection and mass identification with a highly efficient and segmented detector system (such as the one used in the present experiment) allows the simple and clear detection of two α particles coming from the decay of the ^{8}Be ground state.

With such a simple identification of ^{8}Be and favorable Q values, wave-function overlaps and spins/parities of ground states, as well as small energy loss and low kinematic spread, (^{6}He, ^{8}Be) reactions may become an additional spectroscopic tool in studies of neutron-rich nuclei. Indeed, in this paper it is shown that interesting results can already be obtained using currently available radioactive beams of limited quality.

II. EXPERIMENT

The experiment was performed at the radioactive beam facility in Louvain-la-Neuve [9]. The average intensity of ^{6}He^{+} beam at the target was $\approx 5\times 10^{6}$ pps and the purity of the beam was excellent (the only detected impurity was the easily recognizable HeH$_2^+$ ions [10]). Outgoing charged particles were detected in three large silicon strip detector arrays (300 μm thick) [11]. The angles covered were $\theta = 4° - 12°$ (detector array "LEDA"), $20° - 65°$ (detector array "LAMP1"), and $115° - 160°$ (detector array "LAMP2"), with $\Delta\phi = 2\pi$ for all of them. The number of ^{8}Be events at backward angles (in LAMP2) was very small. The total solid angle was $\Delta\Omega \approx 4$ sr. A total of 320 strips were used; such a highly efficient and segmented detector setup is especially efficient for ^{8}Be detection [12]. Information on the mass of detected particles was obtained by the time of flight method. The experimental setup is described in more detail in Refs. [13–15].

Monte Carlo simulations have been performed to deduce the efficiency of ^{8}Be detection for each reaction as a function of ^{8}Be energy and angle and this was found to be very high ($\approx 20\% - 70\%$) for ^{8}Be energies higher than 2 MeV and for a large part of the detector arrays (except for their edges). The kinematics and geometry of the detector system, spot size of the beam and its offset, energy thresholds, multiple hits in a single strip, and other effects were included in the simulations. All the excitation spectra shown later are corrected for the calculated efficiency.

III. RESULTS FOR ^{12}C TARGET

A ^{12}C target with a thickness of 105 μg/cm^2 was used in the measurements and the total number of beam particles interacting with this target was 2.3×10^{11}. Results for the elastic and inelastic scattering, as well as for the ^{12}C(^{6}He, α) reaction are given elsewhere [14,15].

The ^{10}Be excitation energy spectra obtained from the ^{12}C(^{6}He, ^{8}Be) reaction for two forward detector arrays are given in Fig. 1. The LEDA spectrum has much better energy resolution mainly due to the smaller angular opening of strips in the array. In both spectra the ground state is the strongest populated state, also with a rather strong population of the first excited state at $E_x = 3.37$ MeV. The quartet of states at $E_x \approx 6.0$ MeV could not be resolved in LAMP1. This also applies to the doublet at $E_x \approx 7.5$ MeV. In the LEDA excitation spectrum, there are two peaks around $E_x = 6.0$ MeV; the stronger one corresponding to the 2^+ and 1^- states at $E_x = 5.96$ MeV (the 2^+ state probably having a stronger population [16]) and the weaker one (by a factor of ≈ 3) to the 0^+ and 2^- states at $E_x \approx 6.2$ MeV. The population of the second 2^+ state at $E_x = 5.96$ MeV is weaker than the one for the first 2^+ state, although the transition to the former one has a much larger theoretical strength [16]. Similar results have been obtained from other two-proton pickup reactions on ^{12}C [2,17–20].

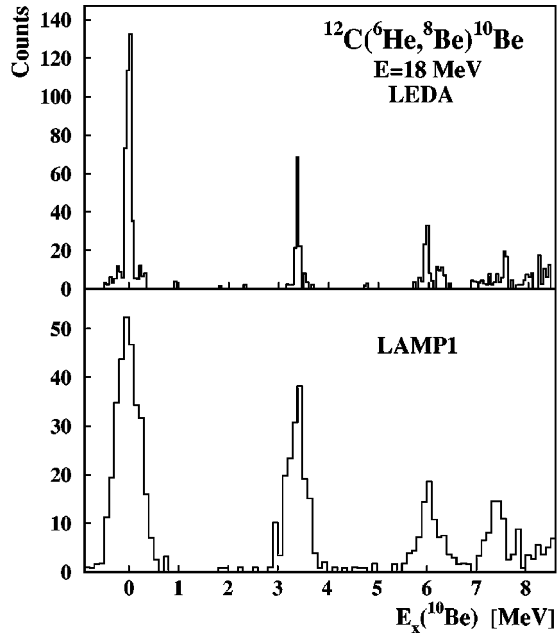

FIG. 1. The ^{10}Be excitation spectrum obtained from the ^{12}C(^{6}He, ^{8}Be)^{10}Be reaction at $E_{\rm lab} = 18$ MeV for detector arrays LEDA (top) covering $\theta_{\rm lab} = 4° - 12°$ and LAMP1 (bottom) covering $\theta_{\rm lab} = 20° - 65°$.

The experimental angular distributions given in Fig. 2 are obviously forward peaked. Since this could indicate that the reaction proceeds via a direct mechanism, the results were compared with the DWBA predictions. The calculations, in the framework of the finite-range distorted-wave Born approximation (FRDWBA), have been performed with the computer code FRESCO [21]. The transferred pair of protons was treated as a cluster with internal quantum numbers $L = S = 0$, and the formalism of the one-step one-particle transfer reactions was used. Optical potentials with volume absorption for the entrance and exit channels were taken from Refs. [22,23].

The angular distributions are normalized to the most forward experimental points. The agreement of the DWBA calculation with the shape of the experimental data is satisfactory, which supports the assumption that the direct reaction

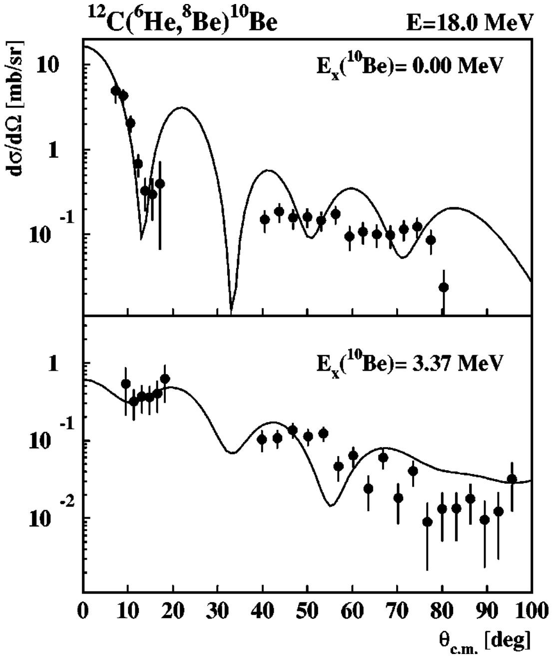

FIG. 2. The experimental angular distributions of the ^{12}C(^{6}He, ^{8}Be) reaction forming the ground and first excited state of ^{10}Be, compared with the FRDWBA calculations.

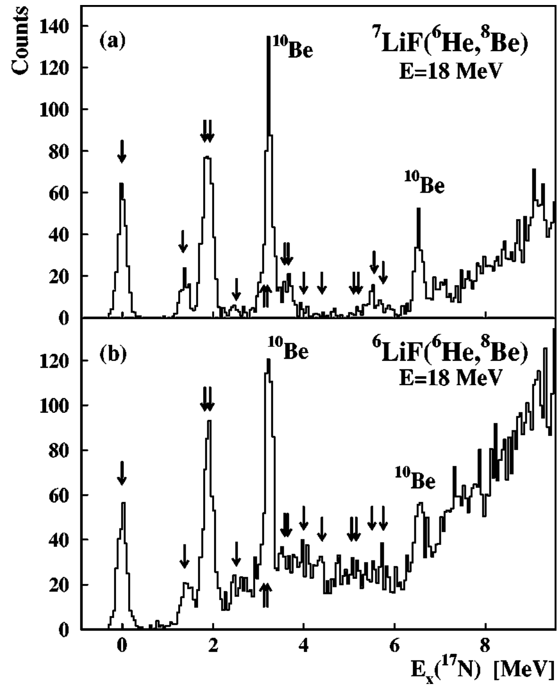

FIG. 3. The composite spectrum of the (^{6}He, ^{8}Be) reaction on the (a) ^{7}LiF target and (b) ^{6}LiF target (both with carbon backing). The ^{17}N excitation energy is given on the *x* axis. The data were collected with ^{8}Be detected at $\theta_{lab} < 12°$. The energies of the fifteen lowest-lying ^{17}N states are marked with arrows. Peaks corresponding to the ^{12}C(^{6}He, ^{8}Be) reaction are labeled as "^{10}Be".

mechanism is dominant even though the incident energy is only 3 MeV per nucleon.

Although the performed DWBA calculation is not intended to give the precise fit to the data, it is interesting to note that the ratio of extracted spectroscopic factors $S_{0+}/S_{2+} \approx 2.9$ is in very good agreement with the ratio of spectroscopic strengths for these states, $S_{MAG}/D_{MAG} \approx 2.3$, as calculated by Cohen and Kurath [16]. The differential cross sections in Fig. 2 are a factor of more than 20 larger than those quoted for the ^{12}C(^{6}Li, ^{8}B) reaction [2] at an incident energy of 13.3 MeV per nucleon, illustrating the advantages of the (^{6}He, ^{8}Be) reaction discussed above. Of course, one should not forget the large ^{6}Li beams intensities as a major advantage of (^{6}Li, ^{8}B) reactions.

IV. RESULTS FOR ^{7}Li TARGET

The ^{6}He+^{7}Li reactions were studied with a 440 μg/cm^2 thick ^{7}Li target (isotopically enriched in ^{7}Li up to 99%) on the 50 μg/cm^2 carbon backing. The total number of beam particles incident on the target was 7.9×10^{11}. Results for elastic scattering and other reactions are given elsewhere [15,24,25].

The measured ^{8}Be spectrum for this target is given in Fig. 3(a). Since most of the peaks are due to the ^{19}F(^{6}He, ^{8}Be)^{17}N reaction, the ^{17}N excitation energy is given on the *x* axis. The two lowest states of ^{10}Be are also very strong (due to the carbon backing of the target).

Some of the known low-lying ^{17}N states [26] can be recognized in the excitation spectrum. The strongest ^{17}N peak at $E_x \approx 1.9$ MeV most likely corresponds to the $1/2^+$ state at $E_x = 1.85$ MeV (the other state of this doublet is the $5/2^-$ state at $E_x = 1.91$ MeV). This state is considered as two $p_{1/2}$ proton holes (with $J=0$) coupled to the $K=1/2^+$ band in ^{19}F [27] so it *should* be strongly populated in the two-proton pickup reactions.

This two-proton pickup spectrum can be compared with a one-proton pickup spectrum obtained with the ^{18}O(d, ^{3}He) reaction at $E_d = 52$ MeV [28]. The significant difference between these two spectra is a very strong population of the $3/2^-$ state at $E_x = 5.52$ MeV in the ^{18}O(d, ^{3}He) reaction (due to its $p_{3/2}^{-1} \otimes {}^{18}O_{g.s.}$ configuration [28]), while the doublet at $E_x \approx 1.9$ MeV is populated rather weakly compared to our results. The state at $E_x = 2.53$ MeV is barely visible in Fig. 3 whereas it is populated rather strongly through the ^{18}O(d, ^{3}He) reaction.

With the ^{7}LiF target one could also search for the ^{5}H contributions through the ^{7}Li(^{6}He, ^{8}Be) reaction. The threshold for the ^{6}He+^{7}Li$\rightarrow$^{8}Be+t+2n events in Fig. 3(a) is above the second "^{10}Be" peak. However, in the region of interest (several MeV above the threshold) the extraction of the events corresponding to ^{5}H was not possible due to strong contributions from other reactions, as well as large influence of the detection efficiency.

V. RESULTS FOR ^{6}LiF TARGET

The ^{6}He+^{6}Li reactions were studied with a 490 μg/cm^2 thick ^{6}LiF target (isotopically enriched in ^{6}Li up to 96%) on the 60 μg/cm^2 carbon backing. The total number of beam particles incident on this target was 5.6×10^{11}. Results for

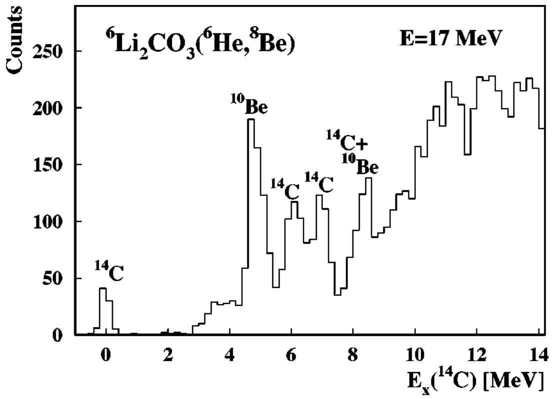

FIG. 4. The composite spectrum of the (^{6}He,^{8}Be) reaction on the $^6Li_2CO_3$ target (with carbon backing). The ^{14}C excitation energy is given on the x axis. The data were collected with ^{8}Be detected at $\theta_{lab} < 12°$.

elastic scattering and other reactions are given elsewhere [15,24,25].

The ^{17}N excitation spectrum given in Fig. 3(b) is very similar to the one measured for the ^{7}LiF target. The most obvious difference is a large number of "background" events in the region between $E_x \approx 2$ and 6 MeV which cannot be seen in the spectrum obtained with the ^{7}LiF target (this background will be discussed in detail).

VI. RESULTS FOR $^6Li_2CO_3$ TARGET

In the first run of the experiment [13] the ^{6}He+^{6}Li reactions were studied also with a 600 μg/cm^2 thick Li_2CO_3 target (isotopically enriched in ^{6}Li up to 96%) on a 50 μg/cm^2 carbon backing. Both the energy resolution and statistics were worse than in the ^{6}LiF target case (and the beam energy was 17 MeV rather than 18 MeV). Apart from the two lowest states of ^{10}Be, the ^{8}Be spectrum was dominated by the peaks produced in the ^{16}O(^{6}He,^{8}Be)^{14}C reaction.

The ^{14}C excitation spectrum is given in Fig. 4. The ^{14}C ground state and two unresolved states at E_x=6.90 and 7.01 MeV are clearly seen in the spectrum (the 0^- state at E_x=6.90 MeV having unnatural parity is probably only weakly populated in this reaction). The ^{14}C state at E_x=8.32 MeV is mixed with the first excited state of ^{10}Be. The surprising difference between the spectrum in Fig. 4 and other published results for two-proton pickup from ^{16}O is the relatively strong peak at E_x=6.1 MeV in the ^{14}C excitation spectrum. It coincides with the ^{14}C 1^- state which has a $p_{1/2} \otimes s_{1/2}$ configuration of two neutrons (see Ref. [29] for the detailed discussion of ^{14}C spectroscopy). No alternative interpretation for the appearance of this peak was found. As expected, the second 0^+ state at E_x=6.59 MeV is not strongly populated since it is not a p-shell state [29].

VII. THE ^{6}Li(^{6}He,^{8}Be)^{4}H REACTION

As already said, by comparing the spectra in parts (a) and (b) of Fig. 3, there is a "background" for the ^{6}LiF target at excitation energies of 2–5 MeV which is completely absent from the ^{7}LiF part of the figure. This "background" can also be seen for the $^6Li_2CO_3$ target though the situation there is much less clear due to the worse resolution.

The main difference between these two targets is in the lithium isotope so one is tempted to check if this "background" might be coming from the ^{6}Li(^{6}He,^{8}Be)^{4}H reaction. The two spectra of Fig. 3 were therefore subtracted taking into account the differences between the thickness of the ^{19}F and carbon backings in the two targets. The resulting spectrum has a wide structure with the center at $\approx$3.5 MeV above the ^{3}H+n threshold. This seems to be in agreement with the results for the ^{6}Li(^{6}Li,^{8}B) reaction measured at 80 and 93 MeV [30] and the ^{4}H level diagram from the most recent compilation [31].

However, our results for the $^6\text{He}+^6\text{Li} \rightarrow 2\alpha+t+n$ reaction obtained from triple coincidences [15,25] show that such an interpretation is still not clear. Namely, it was found that most of the events with forward detected ^{8}Be and backward detected triton proceed through the sequential decay of the ^{9}Be nuclei produced in the ^{6}Li(^{6}He,^{9}Be)^{3}H reaction. The *same* events produce a wide structure with the center at $\approx$4.0 MeV above the ^{3}H+n threshold if the ^{4}H excitation energy is calculated. Further subtraction of these events and the search for the clear ^{4}H resonances for the present low quality data was not attempted.

The "contamination" of the ^{8}Be events with the sequential decay of ^{8}Be (or ^{9}Be) might be a general feature of the (^{6}He,^{8}Be) reaction when particle unstable states of light nuclei are investigated. Such reactions have at least four particles in the exit channel and the precise determination of the reaction process is not trivial. By detecting most of the produced particles in coincidence ambiguities in the data interpretation can be minimized.

VIII. CONCLUSION

The (^{6}He,^{8}Be) reactions on ^{7}LiF, ^{6}LiF, $^6Li_2CO_3$, and ^{12}C targets have been studied with an $\approx$18 MeV ^{6}He radioactive beam. The measured angular distributions for the ^{12}C(^{6}He,^{8}Be)^{10}Be(g.s.) and ^{12}C(^{6}He,^{8}Be)^{10}Be*(3.37 MeV) reactions show clear signatures of a direct process. The pickup of two protons from ^{16}O and ^{19}F was also observed. The ^{4}H resonance centered at $\approx$3.5 MeV (above the t+n threshold) was found in the ^{6}Li(^{6}He,^{8}Be)^{4}H reaction, but the data were contaminated with the neutron decay of the ^{9}Be* after the $^6\text{He}+^6\text{Li} \rightarrow ^9\text{Be}+t$ reaction.

The (^{6}He,^{8}Be) two-proton pickup has a potential as a rather simple reaction with respect to both experimental method and reaction dynamics. The measurement of this reaction with the same targets used here, but at higher beam energies, may provide interesting results and establish this reaction as a standard spectroscopic tool for studies of exotic nuclei.

With the rapid improvement of radioactive beams one is tempted to consider other possible, exotic reactions. For example, the (^{6}He,^{10}C) reaction can be used as a four-proton pickup process for spectroscopy of extremely neutron-rich nuclei. This reaction has most of the favorable characteristics discussed in the introduction for the (^{6}He, ^{8}Be) reaction. Its Q value is not very negative, e.g., for the ^{40}Ca target it is $Q=-2.29$ MeV which already enables experiments at rather low ^{6}He beam energies. This, as well as other interesting processes, makes further studies of ^{6}He induced reactions very intriguing.

ACKNOWLEDGMENTS

The authors would like to thank the technicians and staff of the RNB Facility in Louvain-la-Neuve for their support during the experiment. Thanks are also due to Carmelo Marchetta from LNS for target preparation and to Wilfried Galster for help in planning the experiment.

[1] Đ. Miljanić, M. Zadro, and D. Rendić, Nucl. Phys. **A419**, 351 (1984).
[2] R. B. Weisenmiller, N. A. Jelley, D. Ashery, K. H. Wilcox, G. J. Wozniak, M. S. Zisman, and J. Cerny, Nucl. Phys. **A280**, 217 (1977).
[3] M. V. Zhukov, B. V. Danilin, D. V. Fedorov, J. M. Bang, I. J. Thompson, and J. Vaagen, Phys. Rep. **231**, 151 (1993).
[4] D. R. Tilley, C. M. Cheves, J. L. Godwin, G. M. Hale, H. M. Hofmann, J. H. Kelley, C. G. Sheu, and H. R. Weller, Nucl. Phys. **A708**, 3 (2002).
[5] H. G. Bohlen, A. Blažević, B. Gebauer, W. von Oertzen, S. Thummerer, R. Kalpakchieva, S. M. Grimes, and T. N. Massey, Prog. Part. Nucl. Phys. **42**, 17 (1999).
[6] H. G. Bohlen *et al.*, Phys. At. Nucl. **66**, 1494 (2003).
[7] A. N. Boyarkina, Izv. Akad. Nauk SSSR, Ser. Fiz. **28**, 337 (1964).
[8] F. C. Barker, Nucl. Phys. **83**, 418 (1966).
[9] D. Darquennes *et al.*, Phys. Rev. C **42**, R804 (1990).
[10] Đ. Miljanić *et al.*, Nucl. Instrum. Methods Phys. Res. A **447**, 544 (2000).
[11] T. Davinson *et al.*, Nucl. Instrum. Methods Phys. Res. A **454**, 350 (2000).
[12] E. W. Macdonald, A. C. Shotter, D. Branford, J. Rahighi, T. Davinson, N. J. Davis, Y. El Mohri, and J. Yorkston, Nucl. Instrum. Methods Phys. Res. A **317**, 498 (1992).
[13] M. Milin *et al.*, Europhys. Lett. **48**, 616 (1999).
[14] M. Milin *et al.*, Nucl. Phys. **A730**, 285 (2004).
[15] M. Milin, Ph.D. thesis, University of Zagreb, 2003.
[16] S. Cohen and D. Kurath, Nucl. Phys. **A141**, 145 (1970).
[17] Th. Stolla, H. G. Bohlen, B. Gebauer, S. M. Grimes, R. Kalpakchieva, T. N. Massey, W. von Oertzen, A. N. Ostrowski, M. Wilpert, and Th. Wilpert, Z. Phys. A **356**, 233 (1996).
[18] A. V. Belozyorov, J. Vincour, S. Piskor, R. Kalpakchieva, Yu. E. Penionzhkevich, V. S. Salamatin, and V. E. Zhuchko, Nucl. Instrum. Methods Phys. Res. A **411**, 343 (1998).
[19] J. A. Caggiano, D. Bazin, W. Benenson, B. Davids, B. M. Sherrill, M. Steiner, J. Yurkon, A. F. Zeller, and B. Blank, Phys. Rev. C **60**, 064322 (1999).
[20] H. G. Bohlen, R. Kalpakchieva, A. Blažević, B. Gebauer, T. N. Massey, W. von Oertzen, and S. Thummerer, Phys. Rev. C **64**, 024312 (2001).
[21] I. J. Thompson, Comput. Phys. Rep. **7**, 167 (1988).
[22] D. E. Trcka, A. D. Frawley, K. W. Kemper, D. Robson, J. D. Fox, and E. G. Myers, Phys. Rev. C **41**, 2134 (1990).
[23] L. Jarczyk, B. Kamys, A. Magiera, A. Strzalkowski, A. Szczurek, K. Bodek, M. Hugi, J. Lang, R. Muller, and E. Ungricht, J. Phys. G **11**, 843 (1985).
[24] M. Milin *et al.*, Nucl. Phys. A (to be published).
[25] M. Milin *et al.* (to be published).
[26] D. R. Tilley, H. R. Weller, and C. M. Cheves, Nucl. Phys. **A564**, 1 (1993).
[27] D. W. O. Rogers, J. A. Becker, T. K. Alexander, N. Anyas-Weiss, T. A. Belote, S. P. Dolan, N. A. Jelley, and W. L. Randolph, Nucl. Phys. **A226**, 424 (1974).
[28] D. Hartwig, G. Th. Kaschl, G. Mairle, and G. J. Wagner, Z. Phys. **246**, 418 (1971).
[29] W. von Oertzen, H. G. Bohlen, and M. Milin *et al.*, Eur. Phys. J. A (accepted for publication).
[30] R. B. Weisenmiller, N. A. Jelley, K. H. Wilcox, G. J. Wozniak, and J. Cerny, Phys. Rev. C **13**, 1330 (1976).
[31] D. R. Tilley, H. R. Weller, and G. M. Hale, Nucl. Phys. **A541**, 1 (1992).