Journal of Physics G: Nuclear and Particle Physics

Production of neutron-rich fragments with neutron number $N > N_{projectile}$ in the reaction ^{48}Ca (60 MeV/nucleon) + Ta

To cite this article: S Lukyanov *et al* 2010 *J. Phys. G: Nucl. Part. Phys.* **37** 105111

J. Phys. G: Nucl. Part. Phys. **37** (2010) 105111 (9pp) doi:10.1088/0954-3899/37/10/105111

Production of neutron-rich fragments with neutron number $N > N_{\text{projectile}}$ in the reaction ^{48}Ca (60 MeV/nucleon) + Ta

S Lukyanov[1], F de Oliveira Santos[2], C Borcea[3], G Adamyan[1], M Assie[2], R Astabatyan[1], R Borcea[3], A Buta[3], L Caceres[2], G Georgiev[4], S Grevy[2], M N Harakeh[2,5], O Kamalou[2], M Lewitowicz[2], V Maslov[1], M Mocko[6,7], Yu Penionzhkevich[1], L Perrot[8], R Revenko[1], F Rotaru[3], M-G Saint-Laurent[2], M Stanoiu[3], C Stodel[2], J-C Thomas[2], B M Tsang[7] and P Ujic[2]

[1] FLNR, JINR, 141980 Dubna, Moscow region, Russia
[2] Grand Accélérateur National d'Ions Lourds BP 5027 F-14076 Caen Cedex, France
[3] Horia Hulubei National Institute of Physics and Nuclear Engineering, PO Box MG6, Bucharest-Margurele, Romania
[4] CSNSM, F-91404 Orsay, France
[5] Kernfysisch Versneller Instituut, University of Groningen, 9747 AA Groningen, The Netherlands
[6] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[7] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[8] IPN, IN2P3-CNRS, F-91406 Orsay, France

E-mail: lukyan@nrmail.jinr.ru

Received 11 March 2010
Published 24 August 2010
Online at stacks.iop.org/JPhysG/37/105111

Abstract

The goal of the present paper is to attempt to clarify the nuclear reaction mechanism leading to the production of fragments at zero degree with neutron number larger than that in the ^{48}Ca projectile, at about 60 MeV per nucleon. The production cross sections of the extremely neutron-rich Si and P isotopes were measured. Concerning the nuclear reaction mechanism leading to the production of these isotopes, one should probably refer to a particular type of transfer mechanism, which results in low excitation energy for the fragments, rather than to the 'genuine' fragmentation mechanism. An upper limit of about 0.05 pb was estimated for the production cross section for the ^{47}P isotope for which no count was observed.

The experimental determination of the neutron drip line is a milestone on the road to the understanding of the nuclear structure. One of the most efficient ways to produce rare isotopes is projectile fragmentation [1–7]. This reaction mechanism has been effectively used for exploring the neutron-rich drip line using zero-degree fragment separators at GANIL (France), RIKEN (Japan), NSCL/MSU (USA), GSI (Germany), etc.

At relativistic energies, 'pure' projectile fragmentation is generally considered as taking place via a two-step (fast and slow) process [8]. In the first stage, highly excited pre-fragments are formed from projectile or target nuclei. Their de-excitation involving particle evaporation produces the final observed residues. Due to the short interaction time, there is no full equilibration in N/Z. As a result, fragments have a memory effect of the interacting nuclei in the incoming channel. To produce the most neutron-rich fragments (especially with $Z < 20$), one of the best choices of the projectile is a ^{48}Ca beam.

When using a ^{48}Ca beam, a striking feature is that the neutron numbers of some of the produced isotopes are larger than the projectile neutron number ($N = 28$). This phenomenon was first observed at the projectile energy $E \sim 55$ MeV/nucleon [2]. Indeed, plenty of new nuclei with neutron numbers larger than the projectile neutron number were observed. Among them were $^{49–51}$Ar, $^{46–49}$Cl and $^{45–47}$S. Fragment production with neutron numbers larger than that in the projectile was also mentioned by the discovery of ^{42,43}Al [7] and ^{43,44}Si [9] 'in a net of neutron pickup process'.

At present, the neutron-pickup reactions from the target may be the best way to produce isotopes with high neutron excess, even though the projectile energy is fairly high (60–100 MeV/nucleon).

The renewed interest in transfer reactions is mainly due to an opportunity to populate nuclei moderately rich in neutrons (see [10, 11] and references therein) by multinucleon transfer channels. Neutron transfer channels that could lead to the production of fragments with N larger than N_{proj} of the projectile had also been observed in deep-inelastic collisions, which were studied a few decades ago at a low projectile energy $E \sim 10–20$ MeV/nucleon [12]. From a reaction mechanism point of view, it is interesting to note the presence at intermediate energies of yet relatively strong reaction channels with the pickup of a few neutrons and simultaneous stripping of protons. These transfer reactions could provide an alternate way to fragmentation toward reaching the neutron drip line for light–medium weight nuclei.

In the higher beam energy ($E/A > 20$ MeV/nucleon) domain, multinucleon transfer reactions have been used for producing exotic nuclei for many years. In these binary reactions that take place in a rather narrow range of impact parameters, the excitation energies of the products are smaller than those in the fragmentation reactions. The production cross sections of neutron-rich isotopes of Mg–Ti from the reactions of ^{48}Ca (64 MeV/nucleon, 140 MeV/nucleon) + ^{181}Ta [13] and ^{48}Ca (142 MeV/nucleon) + ^{nat}W [9] were analyzed in the framework of the transfer reaction mechanism. The good agreement of the calculations with the available experimental data allowed a conclusion about the validity of the theoretical description of the multinucleon transfer mechanism as an almost peripheral collision at intermediate energies. On the other hand, the persistence of this reaction mechanism (diffusive nucleon transfer) at the very high excitation energies that comes into play at bombarding energies of $E \sim 100$ MeV/nucleon is surprising. In these collisions, a short-living dinuclear system (DNS) is probably formed in which the diffusion of nucleons occurs. The primary neutron-rich nuclei formed should be as cold as possible; otherwise they will decay into secondary nuclei with smaller excess of neutrons because of preferred de-excitation by the neutron emission. This implies a weak radial damping, which further restricts the range of impact parameters contributing to such a process.

For very heavy interacting systems, but at lower projectile energy, a comparison [14] of experimental heavy residue cross sections from the reactions ^{86}Kr + ^{64}Ni, ^{112,124}Sn at 25 MeV/nucleon energy with the modified model of deep-inelastic transfer [15] was carried out. As a result, the peripheral nucleus–nucleus collisions could be well described theoretically using the model of deep-inelastic transfer in combination with a de-excitation model.

Therefore, it is interesting to examine more closely the dependence of the neutron pickup process on the projectile energy, implying higher excitation.

The present paper is an experimental attempt to clarify the nuclear reaction mechanism leading to production of fragments with a neutron number larger than that in the projectile at energies around 60 MeV/nucleon.

Experimental method

The experiment was carried out at GANIL (Caen, France) using the LISE spectrometer. A ^{48}Ca beam was used with an average intensity of about 200 pnA and with an energy of 60 MeV/nucleon. We used a Ta (215 μm) target and a Be (216 μm) wedge. The experiment benefited from the upgrade of the LISE spectrometer to the LISE 2000 [5] level. The upgrade includes an increase in the maximum magnetic rigidity to 4.3 Tm, an increase by a factor of 2.5 in the angular acceptance and a new line with improved optics. As a consequence, a total increase of a factor 10 in the production rate of the drip-line nuclei has been achieved with respect to the use of the standard LISE spectrometer. The reaction fragments were collected and analyzed by the LISE 2000 spectrometer operated in an achromatic mode and at the maximum values of momentum acceptance (5%) and solid angle (2.5 msr). To reduce the overall counting rate due to light nuclei, a beryllium wedge was placed at the momentum dispersive focal plane.

In addition to the standard identification method of the fragments via time-of-flight (ToF), energy loss (ΔE) and total kinetic energy (TKE), a multiwire proportional detector (CAVIAR) was placed in the dispersive plane of the LISE 2000 spectrometer [5]. This detector allowed the measurement of the magnetic rigidity of each fragment via its position in the focal plane, improving the mass-to-charge resolution (A/Q). The sensitive area of this detector was 10 cm $\times$ 5 cm covering the full momentum acceptance of the spectrometer. The cathode wires were individually read out. A spatial resolution of 0.5 mm was achieved with a counting rate of 10^4 particles per second. The typical efficiency of this particle detector was about 90%.

The mass-to-charge ratio (A/Q) was obtained with an accuracy of 1%. The selected fragments were implanted in a telescope consisting of seven silicon detectors for their identification. In the data analysis, the fully stripped fragments were selected by putting gates on the total kinetic energy measured with the silicon telescope.

Results and discussion

Fragments with $N_f < N_{\text{projectile}}$

In a first step, we checked the detection system and measured the efficiency by detecting fragments located near the valley of stability, i.e. with fragment neutron number, N_f, smaller than 28. The magnetic rigidity setting for the spectrometer was 2.581 and 2.499 Tm for the analyzing section $B\rho_1$ and compensating section $B\rho_2$ of the LISE 2000, respectively.

In figure 1, the total production cross sections for the observed fragments from the reaction ^{48}Ca (60 MeV/nucleon) on tantalum are shown as a function of the mass number (Na–Cl). For comparison, the cross sections obtained with a ^{48}Ca beam at 140 MeV/nucleon [13] are shown as open symbols. For each product, the value of transmission (deduced with LISE++ [16]) was accounted for.

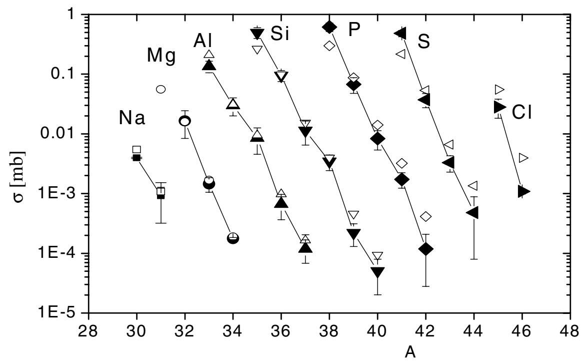

Figure 1. The production cross sections for fragments near the valley of stability, produced in the reaction ^{48}Ca (60 MeV/nucleon) on a tantalum target, are shown as a function of the mass number. Data obtained in the present experiment are shown by solid symbols. For comparison, data obtained in [13] in the reaction ^{48}Ca(140 MeV/nucleon) + Ta are shown by open symbols. The lines through the points are to guide the eyes.

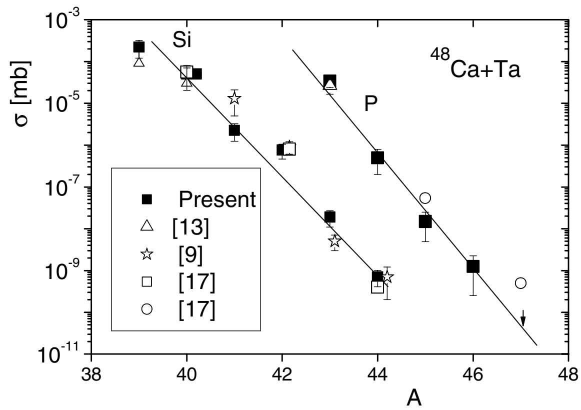

Figure 2. The production cross sections for the neutron-rich Si and P isotopes, produced in the reaction ^{48}Ca (60 MeV/nucleon) + Ta, are shown as a function of mass number. Data obtained in the present experiment are shown by solid symbols. For comparison, data obtained in [9, 13] in the reaction ^{48}Ca (140 MeV/nucleon) + Ta are shown as open triangles and stars. Results of calculations for the $^{45–47}$P isotopes obtained using the transfer nuclear reaction mechanism [17] are shown by open symbols (open squares (□) for Si and open circles (○) for P isotopes). The lines through the experimental points are to guide the eyes.

Apart from some discrepancies and a slight systematic effect (probably due to a transmission correction), the trend in figure 1 shows rather good agreement between our data (solid symbols) and data from [13] obtained in the reaction ^{48}Ca (140 MeV/nucleon) + Ta (open symbols). Our study indicates that the production cross sections are practically independent of the projectile energy in the region of energies 60–140 MeV/nucleon.

Fragments with $N_f > N_{\text{projectile}}$

To detect nuclei with $N_f > 28$, one should tune the LISE-2000 spectrometer to higher $B\rho$ values (2.86/2.76 Tm) than for the previous region of nuclei with $N_f < N_{\text{projectile}}$.

For this setting, figure 2 shows the production cross sections versus mass number for the neutron-rich Si and P isotopes, produced in the reaction ^{48}Ca(60 MeV/nucleon) on tantalum. Data obtained in the present experiment are shown by solid symbols. For comparison, data

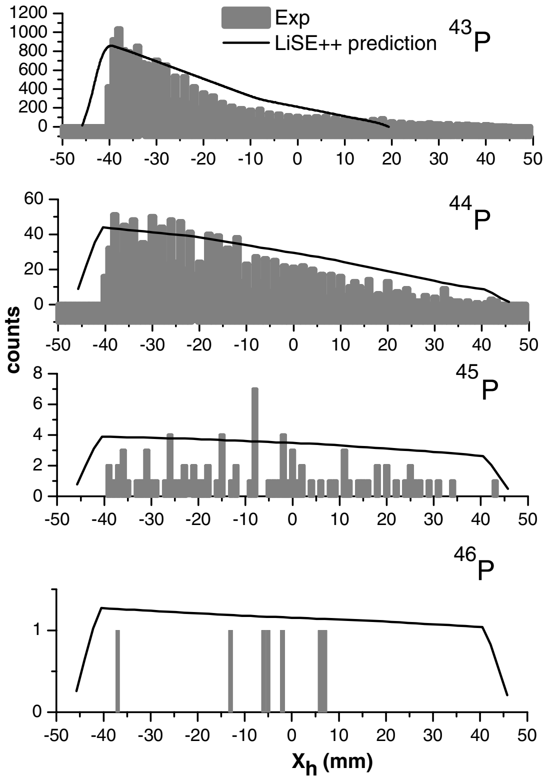

Figure 3. Experimental distributions of the horizontal positions at the intermediate focal plane of the LISE-2000 spectrometer. The position distribution of P isotopes (solid histogram) is also in agreement with the calculations (solid lines).

obtained in [9, 13] in the reaction ^{48}Ca (140 MeV/nucleon) + Ta are shown by open symbols. This figure shows the good agreement between the data obtained in the present experiment and earlier data obtained for Si isotopes and ^{43}P [9, 13]. The two different $B\rho$-settings of the fragment separator in the present experiment allowed us to observe both ^{40,41}Si isotopes. This overlap helped us to control both the production rates and transmission.

Calculations for the production cross section of ^{45}P and ^{47}P isotopes done in the frame of transfer reaction mechanism [17] are shown as open diamond symbols. They slightly overestimate the experimental data of ^{47}P. It seems that ^{47}P is less bound than predicted. Note that the masses of the very neutron-rich nuclei in this region of mass have not been measured. The theoretical model reproduces the experimental data. The discrepancies between calculations and data may be attributed to the lack of precise measurements of the masses of these isotopes, which are an important ingredient in the calculations.

Using the main setting to detect the neutron-rich P isotopes, we optimized $B\rho_1$ keeping $B\rho_2$ constant. An additional transmission control was performed by detecting ^{43,44}Si isotopes. While the $B\rho$-distribution for the ^{44}Si isotope is expected to be very similar to the $B\rho$-distribution of ^{47}P, finally, we observed four events of ^{44}Si but no ^{47}P events. This sets an upper limit of about 0.05 pb for the production cross section of the nuclide ^{47}P.

To control the production rate, the horizontal position distributions of the isotopes transmitted to the intermediate plane were measured with the CAVIAR detector and an example is given in figure 3. The curves in this figure show the positions of the centroids of various

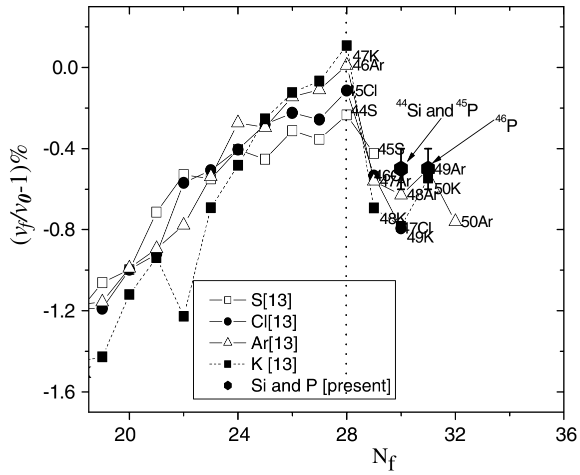

Figure 4. Deviation from the projectile velocity ($v_f/v_0 - 1$) in percent versus the fragment neutron number N_f for some fragments in the reaction with the ^{48}Ca (140 MeV/nucleon) projectile on a Ta target. Data were taken from [13]. Data for the ^{44}Si and ^{45,46}P isotopes are shown by solid hexagonal symbols and obtained based on the histograms given in figure 3.

isotope distributions estimated by using the LISE code [16] in which the velocity ratio was set to 0.995 (see below). We found that the experimentally measured centroids for the ^{45,46}P isotopes were at the center of the position-sensitive detector, in agreement with the calculations. This consistency assured that the tuning of the LISE-2000 spectrometer was optimal for the neutron-rich Si–P isotopes.

Special attention was paid to the correct $B\rho$-value calculation according to the production mechanism. We chose the ratio of the fragment and projectile velocities $v_f/v_p = 0.995$ according to [16]. We also varied the $B\rho$-setting, corresponding to a velocity ratio up to a value of 0.93. Only the setting with $v_f/v_p = 0.995$ allowed us to observe very neutron-rich phosphorus isotopes with a neutron number higher than that in the projectile in a reasonable measurement time. This indicates that there is no significant velocity damping as would have been expected in the case of deep-inelastic collisions. In [17], the lack of velocity damping is justified by the special matching conditions imposed on angular momentum, as implied in the fragmentation mechanism.

The fragment velocity is one of the experimental observables sensitive to the dynamics of the nuclear collision. It allows one to disentangle (to a certain degree) the fast and slow reaction dynamics. Figure 4 shows the deviation from the projectile velocity ($v_f/v_p - 1$) in percent versus fragment neutron number N_f for some fragments produced in the reaction of ^{48}Ca (140 MeV/nucleon) projectile on a Ta target (data were taken from [13]). Two different trends are observed: though the velocity ratio decreases on both sides of $N = 28$, the slope is less steep on the left ($N_f < 28$) side while at the right side, after a sudden drop, the velocity damping seems to stabilize at a smaller value. Ar and K isotopes were not available in the present experiment, while Si and P isotopes with neutron number larger than 28 were not measured in [13], but they were observed in our experiment. Due to low production cross sections, it is very difficult to measure the momentum distribution for these nuclei. Therefore we tried to extract the centroids of the momentum distributions for ^{45,46}P isotopes from figure 3. The extracted values of the velocity ratio for these isotopes together with data from [13] (where the full momentum distributions were measured) are shown in figure 4. Our values are based on the experimental distributions given in figure 3, where the horizontal positions at the intermediate focal plane are given for P isotopes. Even if these histograms are just a part of the momentum distribution (figure 3), they still preserve some information about the velocity distribution, especially on the position of the maximum.

Looking at both sets of data (present data and [13], which complete each other) assembled in figure 4, we may observe some systematic trends concerning the production of isotopes with $N_f > N_{\mathrm{proj}}$ in the overall region from Si to Ar. This trend is different from the observed one for the $N < N_{\mathrm{proj}}$ production mechanism (abrasion products). Velocities of the fragments with $N_f > 28$ are, as seen in figure 4, very close to the projectile velocity and so are the velocities for which Si and P isotopes were observed in the present experiment, as already mentioned. These facts give a hint of a fast process. In this case the neutron exchange must take place in a very short time.

Moreover, in [9], it was pointed out that the sequential evaporation of light particles from sufficiently excited nuclei follows a general pattern that leads to a somewhat uniform distribution of final products. The prompt light-particle evaporation leads to the cooling of the very excited, extremely neutron-rich pre-fragments. According to [18], neutrons will be emitted preferentially from excited nuclei until the point at which the ratio of the widths for statistical emission of neutrons to charged particles becomes small. In this case, the extremely neutron-rich fragments are produced in the first steps of the interaction, and they will lose the neutron excess after neutron emission.

Similar conclusions about the pre-fragments de-excitation by particle evaporation are arrived at in the previous study of the influence of the neutron excess of the projectile on producing neutron-rich isotopes [19]. The comparison between ^{58}Ni and ^{68}Ni projectile fragmentation in [19] leads to the following two observations: (i) the peak positions of the isotope distributions shift to more neutron-rich isotopes with increasing neutron richness of the projectile, and (ii) this shift is not proportional to the neutron-excess differences of the projectiles. The relatively small shift in the peak position of the isotope distributions can be understood as a result of the process in which neutron-rich pre-fragments created in the fragmentation process decay through neutron emission toward the valley of stability.

For the present experiment, one may conclude that the observed events of ^{43,44}Si and $^{44–46}$P isotopes more likely correspond to a first phase of a fragmentation-type mechanism leading to cold fragments and small velocity damping, rather than to a deep-inelastic collision leading to the transfer of a few neutrons and sizable velocity damping.

Another remarkable fact is that the production cross sections of ^{43,44}Si isotopes at a projectile energy of 60 MeV/nucleon are similar to those obtained at a higher beam energy (140 MeV/nucleon) [9]. This is additional evidence of a reaction mechanism of isotope production in which the energy dependence is rather weak, while the deep-inelastic mechanism is known to have a strong energy dependence on a maximum cross section at rather low energies close to the Coulomb barrier. The definition and transition between these two mechanisms should be rather smooth and strongly depend on the bombarding energies, impact parameters, etc. The weak dependence of fragment velocity on incident energy suggests that the reactions proceed via a transfer mechanism as described in [17], which results in low excitation energy for the fragments. In [17], the authors demonstrate that the proposed transfer mechanism does not imply large velocity changes. Moreover, their model predicts a weak dependence on incident energy. Then, one should probably refer to the mechanism responsible for production of neutron-rich fragments with neutron number $N > N_{\mathrm{proj}}$ as a 'transfer mechanism', which results in low excitation energy for the fragments, rather than referring to it as a mechanism of genuine fragmentation. Another interesting aspect of the nucleon transfer was revealed in [11], where the particle transfer was considered as a source for dissipation of the energy.

Obviously further studies are needed concerning the possibility of exploiting peripheral nucleus–nucleus collisions in the Fermi-energy domain for producing neutron-rich isotopes. As pointed out in [14], a process with a short timescale, such as the very peripheral collisions, could be sensitive to the details of neutron and proton density profiles of the interacting nuclei. As a consequence, an enhanced flow of neutrons from target to the projectile may occur [14], and the gradient of this flow may be revealed with respect to the flow toward isospin equilibration.

Finally, to stress the complexity of the interaction mechanism, one may quote a recent work [20] performed at an energy of 1 GeV/nucleon, where the production of isotopes via the charge-pickup channel was observed.

Conclusion

An experimental study of the production cross sections of the nuclei with neutron number $N > N_{\mathrm{proj}}$ was performed at GANIL in the reaction ^{48}Ca (60 MeV/nucleon) + Ta. Comparing the present experimental data at the projectile energy of 60 MeV/nucleon with the data at 140 MeV/nucleon, one may conclude that a weak energy dependence on the cross section for fragmentation is observed in this energy domain.

A transfer-type mechanism leading to the formation of cold fragments (in the sense of excitation energies comparable or lower than the neutron separation energy) seems to be able to explain the production of fragments with a neutron number larger than that of the projectile at energies above 50 MeV/nucleon.

Acknowledgments

We thank the staff members of the GANIL cyclotrons facility and the staff of the ECR-source for the high-quality beams they provided to the experiment. We also acknowledge the fruitful discussions with Dr N Antonenko. The technical assistance of R Hue, S Le Moal, V Morel and E Markaryan was highly appreciated. This work was supported by the IN2P3-Dubna and IN2P3-Bucharest collaboration agreements, Russian (RFBI) foundation (09-07-02-00251, 09-02-91056) and partly supported by CNCSIS—UEFISCSU (project number PNII IDEI 933/2007).

References

[1] Westfall G D *et al* 1979 *Phys. Lett.* **43B** 1859
[2] Guillemaud-Mueller D *et al* 1989 *Z. Phys.* A **332** 189
[3] Sakurai H *et al* 1999 *Phys. Lett.* B **448** 180
[4] Tarasov O B *et al* 1997 *Phys. Lett.* B **409** 64
[5] Lukyanov S *et al* 2002 *J. Phys. G: Nucl. Part. Phys.* **28** L41
[6] Notani M *et al* 2002 *Phys. Lett.* B **542** 49
[7] Baumann T *et al* 2007 *Nature* **449** 1022
[8] Pfaff R *et al* 1995 *Phys. Rev.* C **51** 1348
[9] Tarasov O *et al* 2007 *Phys. Rev.* C **75** 064613
[10] Corradi L *et al* 2002 *Nucl. Phys.* A **701** 109
[11] Corradi L *et al* 2009 *J. Phys. G: Nucl. Part. Phys.* **36** 113101
[12] Volkov V V 1989 *Treatise on Heavy-Ion Science* vol 8 ed D A Bromley (New York: Plenum) p 101
[13] Mocko M *et al* 2006 *Phys. Rev.* C **74** 054612
Mocko M 2006 *PhD Thesis* NSCL/MSU, http://groups.nscl.msu.edu/nscl_library/Thesis/Mocko,%20Michal.pdf
[14] Veselsky M and Souliotis G A 2006 *Nucl. Phys.* A **765** 252–61

[15] Tassan-Got L and Stefan C 1991 *Nucl. Phys.* A **524** 121
[16] Tarasov O B and Bazin D 2004 *Nucl. Phys.* A **746** 411
[17] Adamyan G *et al* 2008 *Phys. Rev.* C **78** 024613
[18] Charity R J *et al* 1998 *Phys. Rev.* C **58** 1073
[19] Lukyanov S *et al* 2009 *Phys. Rev.* C **80** 014609
[20] Benlliure J *et al* 2008 *Phys. Rev. C* **78** 054605