Title
CHARGE-EXCHANGE PRODUCTS OF BEVALAC PROJECTILES

Author
Rasmussen, J.

Publication Date
1982-11-01

LBL-15284

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Conference on High-Energy Physics with Nuclear Emulsion, Cairo, Egypt, November 22-29, 1982

CHARGE-EXCHANGE PRODUCTS OF BEVALAC PROJECTILES

John Rasmussen

November 1982

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

LBL-15284

Charge-Exchange Products of BEVALAC Projectiles

John Rasmussen

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94702

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

Charge-Exchange Products of BEVALAC Projectiles

John Rasmussen
Univ. of Calif. Lawrence Berkeley Laboratory
Berkeley, California 94720, U.S.A.

1. Introduction

It has recently seemed of interest to re-examine of some of the earliest BEVALAC work, the classic studies of projectile fragmentation by Dr. Harry Heckman's group using a small-angle magnetic spectrometer.[1]

You will recall their main finding that there is a substantial production of fragments of all masses lighter than the projectile, such fragments being centered in a narrow region of velocity space around the beam velocity. The exciting studies about anomalons[2] deal with the curious enhanced reactivity of some of these secondary fragments. I want to direct attention here to the rather rare fragments of the same mass number as the projectile but differing in charge by one unit. We shall also keep track, as a frame of reference, of the products that have lost one neutron from the projectile.

2. Formation of Momentum-shifted Isobars

Table I is an excerpt of the table in the paper of Greiner et al.[3]. Their fragmentation study was made with full energy (2.1A GeV) ^{16}O and ^{12}C and with half-energy ^{12}C. Note that the isobaric products are characterized by larger negative momentum shifts than the products which have lost one or more nucleons. Though we do not show the many other products here, their momentum downshifts are more typical of the smaller values of the one-neutron loss products. Furthermore, the parallel velocity dispersion seems systematically smaller for the isobaric products. We have also included in the table two other fragments which show large negative downshifts and, like the isobars, cannot be made by simple knockout of nucleons, but must involve some charge-exchange process in addition. These momentum shifts and dispersions are averaged over all the targets where these products were observed, the targets being H, Be, C, Al, Cu, Ag, and Pb.

In Table II I have excerpted as yardsticks (metersticks?) a few cross sections from the large table in the report of Lindstrom et al.[4] That is, Table II contains just the 1-neutron loss products for just the targets H, Be, and C. I contend that for these products of bare peripheral collisions the lightly bound neutron in the ^{9}Be target will play a large role, enabling us to study the target isospin dependence of the production.

For most fragments target factorization holds; that is, the proportion of various fragments is independent of the target, and the only target dependence is through an overall target factor that increases with target mass number. Contrary to this general result, it is evident that ^{12}N formation from 1.05 GeV/n C has a marked target isospin dependence, as the ratios of Table III attest. The dependence has the sign to be expected, that is, the hydrogen target most effectively drives the projectile toward the higher-charged isobar. This dependence is essentially absent for the 2.1A GeV carbon beam, and it is absent for the ^{12}B formation. We defer discussion on the other products. We note from Table I that the case with the strongest target isobar effect has the least momentum downshift. It would seem that this case of ^{12}N formation at 1.05A GeV is proceeding mainly by simple charge exchange without the formation of a pion in the final state. The other cases, which all have the large momentum downshift, are mainly going by pion formation with capture of one of the final nucleons in the inelastic collision.

Why should ^{12}N and ^{12}B formation show such different behavior? Examination of their level schemes provides a clue. The nucleus ^{12}N has only one particle-bound state, the 1+ analog state of the giant M1 state in ^{12}C at 15.11 MeV. The collective nature is indicated by the fast beta decay (log ft = 4.1) from the 1+ ground states of ^{12}N and ^{12}B to the ^{12}C ground state. Now the ^{12}B has four additional bound excited states of spins 2+, 2−, 1−, and 0+, ranging up to 2.72 MeV. We can conclude that the lack of target isospin dependence and the somewhat larger cross sections for ^{12}B relative to ^{12}N are due to formation in these excited states.

Deutchman and Townsend[5] have made theoretical calculations of pion production with concurrent formation of giant M1 excited state in one collision partner. He has estimated that a substantial fraction of pion production, at least at lower beam energies, goes via this process. However, we see that generally of the order of 0.1 mb of cross section goes to the 1+ isobars, and the total charged pion production at 2.1A GeV is of the order of a barn. Why is the coherence enhancement not realized for the 1+ states in the processes we are examining here? Perhaps it is the bad momentum mismatch that is to blame. When a nucleon-nucleon collision forming a pion (or delta) takes place, the final-state nucleons in their c.m. frame have a total energy that is reduced by at least the rest mass of the pion, or 140 MeV. To form the isobaric product requires that one of these momentum-shifted nucleons be recaptured by the projectile. We examine the magnitude of these momentum shifts in the next section.

3. Momentum-shift Estimates

Let us view the nucleon-nucleon inelastic collision in its center-of-mass frame. With the three-body final state, including the pion, there are many possible momentum-shift values depending on the final momentum of the pion. Since the pion rest mass is much smaller than those of the nucleons, the dependence will not be strong. Thus, for orientation we calculate the simplest case, with the pion at rest in the c.m. frame.

At threshold for pion production we have two nucleons initially each with 70 MeV kinetic energy, coming to rest in the final state. The momentum shift in the center-of-mass or projectile frame is 368 MeV/c. At 1.05 GeV lab kinetic energy we have the two nucleons with c.m. kinetic energy each of 228 MeV before and 158 MeV afterward. This corresponds to an initial rapidity y_i of 0.684 and a final rapidity y_f of 0.573, for a rapidity change of 0.111, corresponding to a momentum shift of −104 MeV/c. At 2.1 GeV lab kinetic energy the momentum shift is −70 MeV/c.

Note that these momentum shifts at 1.05 and 2.1 GeV beam energy are about the same as the observed momentum shifts recorded in Table I, thus supporting the proposed nucleon-recapture mechanism. It is evident that the momentum mismatch becomes worse as the beam energy is lowered. Thus, at lower energies, stretched shell-model particle-hole final states will be even more favored. It is interesting in this connection to note how the (p,pi$^-$) reaction favors stretched two-particle, one-hole final states.[6]

4. Further Deductions about Favored States

In section 2 we argued that the ^{12}B production from ^{12}C mainly went through the 1+ state, with less than half going into the other four bound states. For ^{16}O the p-shell is filled, and there is no available counterpart to the 1+ state. (We cannot observe ^{16}F, since its ground state is unstable with respect to proton emission, but experiments detecting a beam-velocity proton in coincidence with ^{15}O could add valuable information, with or without simultaneous detection of a pi$^-$ or pi^0.)

Despite the lack of the spin-flip 1+ state the production of the ^{16}N from oxygen occurs with an even greater cross section than the analogous production of ^{12}B from carbon ions. The nucleus ^{16}N has four particle-bound states with spin-parity of 2-, 0-, 3-, and 1-, ranging in excitation energy up to 0.397 MeV. Of these, the 0- and 3- have no bound counterparts in ^{12}B. It is reasonable to guess that the 3- state, a collective linear combination of proton p-hole and neutron d-particle state, may account for most of the production cross section. Its larger spin may accommodate better the momentum mismatch. In Table III we see that the target-isospin dependence is not the simple monotonic behavior seen for the carbon products. Instead the carbon target is especially effective for the isobar production. There is no obvious explanation.

Now examine the two remaining products showing large negative momentum shifts, namely, ^{11}Be from carbon and ^{15}C from oxygen. These products have lost one mass unit and two charge units with respect to the projectile, and they show momentum shifts comparable to the others for recapture of one nucleon that was slowed in the process of pion production. These products cannot arise from proton decay of an excited intermediate, since their proton-unstable states lie far too high. We must presume they arise from events in which two nucleon-nucleon collisions occur in the same event. The target-isospin dependence is as expected, the neutron-rich Be target being the most effective, or in the case of ^{11}Be, the only target for which the product was observed. That the hydrogen target produced ^{15}C from ^{16}O is remarkable. The target proton must have made two successive collisions with projectile protons. One must have been inelastic with a pi^{+} and neutron forming, with the neutron recapturing. The other collision must merely have knocked out a projectile proton, with or without pion formation. It seems likely that these double-charge-loss, single-nucleon-loss products generally come from one inelastic collision with pion escaping, with a knockout collision occurring also.

The two double-charge-loss products each have but two particle-bound states, the ^{15}C having 1/2+ and 5/2+ states, and the ^{11}Be having 1/2+ and 1/2- states. It may be that the relative enhancement of the ^{15}C formation is due to the bound $d_{5/2}$ state into which the momentum-shifted neutron can more easily capture.

5. Future Work

I have been deliberately speculative in constructing detailed conclusions from tiny cross sections, some of which are stated to be accurate only within a factor of two. Nevertheless, taken together the evidence is that shell-structure effects are of real importance in these peripheral processes, even at GeV energies. It appears that charge exchange is significant in the initial nucleon-nucleon collision where no pion is formed at 1.05A GeV. However, the lack of target isospin dependence at the higher bombarding energy makes it appear that neutral boson exchange dominates the initial delta-formation collision, that is, that quarks of like flavor, u with u or d with d, exchange in preference to those of unlike flavor, u with d.

It is obviously of importance to have this type of reaction studied with other light-ion projectiles, where the products have only one or a few bound states. It would be interesting to move down in energy toward threshold, using at least the targets H, Be, and C, though deuterium would be an interesting addition, too.

Fragmentation experiments in which a beam-velocity proton can be detected in coincidence with the heavy fragment offer the possibility of measuring formation in proton-unstable ground (^{16}F) or excited states. Also the measurement of the pion spectrum associated with the rare isobaric fragment could help to delineate the momentum mismatch question.

As the probability for nucleon recapture into various orbits is understood, we can apply the knowledge to the formation of hypernuclear fragments. Bowen et al.[7] have made spark-chamber studies with BEVALAC ^{16}O beams and deduced a small formation probability. Since the top BEVALAC energy is only slightly above the free nucleon-nucleon threshold for production of K^+ + Lambda, the momentum mismatch for recapture of the Lambda is very large. At 2.1A GeV the c.m. rapidity is 0.92. After associated production with the K^+ at rest in the c.m. the Lambda has a rapidity of 0.37. The rapidity difference of 0.55 means the recapture process is akin to the capture probability of a nucleon incident at about 150 MeV kinetic energy. (In contrast the formation of the isobars after pion production require capture of a nucleon of momentum 100 MeV/c or kinetic energy of 5 MeV.) While it is unlikely that the Lambda can capture to form an isobaric hyperfragment, the Lambda may initiate a nuclear reaction on the spectator fragment, knocking out and evaporating a few nucleons and ending up in a bound orbital. At 10A GeV, the energy of the proposed superconducting upgraded BEVALAC the rapidity shift of the formed Lambda would be only 0.29, and the retenformed Lambda would be only 0.29, and the retention of it in the fragment would be equivalent to the retention of an incident nucleon with 40 MeV kinetic energy. At such energy the probability of forming and retaining two Lambdas in the spectator becomes reasonable, thus opening up to study the doubly strange hypernuclei and the force between Lambdas.

Finally, there is need for new theoretical calculations taking into account specific nuclear shell-model orbitals.

6. Acknowledgements

My thinking on these problems has been much stimulated by phone conversations and communications with Phil Deutchman and Tom Ward, though I take full responsibility for the more speculative aspects. This work was supported by the Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

1. A.S.Goldhaber and H.H.Heckman, Ann. Revs. Nucl. and Particle Sci.**28**, 161 (1978)

2. E.M.Friedlander, R.W.Gimpel, H.H.Heckman, Y.J.Karant, B.Judek, and E.Ganssauge, Phys. Rev.

Lett. **45**, 1084 (1980)

3. D.E.Greiner, P.J.Lindstrom, H.H.Heckman, B.Cork, and F.S.Bieser, Phys. Rev. Lett. **35**, 152 (1975)

4. P.J.Lindstrom, D.E.Greiner, H.H.Heckman, B. Cork, and F.S.Bieser, Lawrence Berkeley Laboratory Report LBL-3650 (1975) unpublished

5. P.A.Deutchman and L.W.Townsend, Phys. Rev. Lett. **45**, 1622 (1980)

6. S.E.Vigdor, T.G.Throwe, M.C.Green, W.W.Jacobs, R.D.Bent, J.J.Kehayias, W.K.Pitts, and T.E.Ward, Phys. Rev. Lett. **49**, 1314 (1982)

7. K.J.Nield, T.Bowen, G.D.Cable, D.A.DeLise, E.W.Jenkins, R.M.Kalbach, R.C.Noggle, and A.E.Pifer, Phys. Rev. C**13**, 1263 (1976)

TABLE I

MOMENTUM DISTRIBUTION WIDTHS AND SHIFTS[a]
(from D. Greiner *et al.*[7])

Beam	Kinetic Energy/A (Gev)	Fragment Z	Fragment A	S_{11}	$\langle P_{11} \rangle$
^{16}O	2.1	6	15	125 ± 19	-132 ± 25
		7	12	153 ± 11	-49 ± 28
		7	13	134 ± 2	-35 ± 4
		7	14	112 ± 3	-27 ± 3
		7	15	95 ± 3	-21 ± 6
		7	16	54 ± 11	-110 ± 15
		8	13	143 ± 14	-57 ± 26
		8	14	99 ± 6	-31 ± 7
		8	15	94 ± 3	-23 ± 3
^{12}C	2.1	4	11	155 ± 40	-102 ± 82
		5	8	151 ± 16	-39 ± 12
		5	10	134 ± 3	-35 ± 7
		5	11	106 ± 4	-23 ± 9
		5	12	63 ± 9	-96 ± 14
		6	9	147 ± 21	-43 ± 30
		6	10	121 ± 6	-42 ± 11
		6	11	103 ± 4	-40 ± 9
		7	12	56 ± 16	-100 ± 11
^{12}C	1.05	4	11	103 ± 37	-104 ± 43
		5	8	139 ± 12	-61 ± 20
		5	10	135 ± 9	-35 ± 8
		5	11	102 ± 11	-30 ± 4
		5	12	88 ± 17	-112 ± 31
		6	9	147 ± 28	-28 ± 17
		6	10	126 ± 8	-46 5
		6	11	105 ± 10	-43 ± 4
		7	12	43 ± 19	-55 ± 19

---

[a] The momentum shift is given in MeV/c in the projectile frame. The width is the variance S_{11} of P_{11} about the mean in MeV/c.

TABLE II

FRAGMENTATION CROSS SECTION OF 1-NEUTRON-OUT PRODUCT
(From P. Lindstrom *et al.*[8])

Beam	Product	Kinetic Energy/A (MeV)	Formation Cross Section (mb) Target H	C	Be
^{16}O	^{15}O	2.1	27.3 ± 2.6	42.9 ± 2.3	43.0 ± 2.1
^{12}C	^{11}C	2.1	26.1 ± 2.4	46.5 ± 2.3	46.7 ± 2.3
^{12}C	^{11}C	1.05	25.0 ± 3.0	44.7 ± 2.8	44.7 ± 2.6

TABLE III

CROSS SECTION RATIOS OF CHARGE-EXCHANGE PRODUCTS TO 1-NEUTRON-OUT PRODUCT
(From data of P. Lindstrom *et al.*[8])

Beam	Energy	Product	Production Ratio (x 10^3) Target: H	^{12}C	^{9}Be
^{16}O	2.1	^{15}C	0.59 ± 0.4	0.93 ± 0.3	1.21 ±0.3
		^{16}N	0.70a	3.00 ± 0.5	1.26 ± 0.4
^{12}C	2.1	^{11}Be	---	---	0.39 ± 0.2
		^{12}B	2.26 ± 0.4	2.24 ± 0.2	3.02 ±0.3
		^{12}N	1.30 ± 0.4	1.70 ± 0.2	1.24 ±0.3
^{12}C	1.05	^{11}Be	---	---	0.40 ± 0.3
		^{12}B	2.00 ± 0.5	2.21 ± 0.3	2.08 ± 0.4
		^{12}N	2.12a	1.14a	0.49 ± 0.3

---

a: Denotes factor of 2 estimate.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720