man, and J. T. Jacobs, Bull. Amer. Phys. Soc. 17, 103 (1972); P. Wurfel and I. P. Batra, *ibid.* 17, 1182 (1972).

[7] H. Shibata and H. Toyoda, J. Phys. Soc. Jap. 17, 404 (1962).

[8] V. P. Dudkevich *et al.*, Izv. Akad. Nauk USSR, Ser. Fiz. 35, 1952 (1971) [Bull. Acad. Sci. USSR, Phys. Ser. 35, 1773 (1971)]; V. G. Gavrilyachenko, V. P. Dudkevich, and E. G. Fesenko, Kristallografiya 13, 342 (1968) [Sov. Phys. Crystallog. 13, 277 (1968)].

[9] J. T. Jacobs and K. Keester, to be published.

[10] C. B. Sawyer and C. H. Tower, Phys. Rev. 35, 269 (1930).

[11] P. Wurfel and W. Ruppel, in *Proceedings of the Third International Conference on Photoconductivity, Stanford, California, 1969* (Pergamon, New York, 1972), p. 379.

[12] S. R. Hofstein and G. Warfield, Solid State Electron. 8, 321 (1965).

Nuclear Reactions of V with 300-GeV Protons and Co with 11.5-, 200-, and 300-GeV Protons*

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Cross sections of a large variety of spallation products from V and Co do not change appreciably as the beam energy increases from 11.5 to 300 GeV. The mean ratio σ_{300}/σ_{29} for V is 0.96 ± 0.04; for Co, $\sigma_{200}/\sigma_{11.5} = 0.95 \pm 0.06$ and $\sigma_{300}/\sigma_{11.5} = 1.02 \pm 0.09$. It was assumed that the monitor cross section is constant above 10 GeV.

We are reporting the first measurements of spallation cross sections for 200- and 300-GeV protons. Similar studies have been carried out previously on a number of target nuclei at energies up to 29 GeV, and have been summarized in a recent review article.[1] The 200- and 300-GeV irradiations were performed in an external proton beam in the neutrino hall at the National Accelerator Laboratory (NAL). The vanadium targets were analyzed at Brookhaven National Laboratory (BNL) and the cobalt targets at Argonne National Laboratory (ANL). Two irradiations of Co were also done with 11.5-GeV protons in the circulating beam of the ANL zero-gradient synchrotron so that a direct comparison could be made of the higher-energy results with data from the energy region investigated previously. A detailed study of the nuclear reactions of V at 3 and 29 GeV was recently completed.[2]

The target foils (6×6 cm^2) were irradiated together with aluminum monitor foils, and each was sandwiched between guard foils to avoid cross contamination and to compensate for recoil effects. The total thickness of each Co foil stack was ~100 mg/cm^2; two of the V stacks were ~150 mg/cm^2, and the third was ~30 mg/cm^2. The beam intensity varied from 10^{10}–10^{11} protons/pulse and irradiation times were 8–21 h. An area of 2–3 cm^2 of each stack was punched out for counting; nearly all of the radioactivity was within this area. The aluminum monitor foils were counted to determine the amount of ^{24}Na formed. The V and Co target foils were counted without any chemical separation with calibrated Ge(Li) spectrometers of 4096 channel capacity and magnetic-tape readout. The more intense characteristic γ rays of each radioactive product were measured at various times after bombardment in order to establish that they decayed with the correct half-life; V samples were followed for 1 month, and Co samples for at least 2 months after irradiation. The spectra were analyzed by means of a computer program[3] which found all significant peaks and computed their areas and decay rates. The nuclides were identified unambiguously by their γ-ray energies and half-lives. Disintegration rates were computed from measured photopeak intensities, the calibrated photopeak efficiencies of the detector, and known γ-ray abundances.[4,5] When necessary, corrections were made for summing of coincident γ rays. In order to calculate product cross sections from disintegration rates, it was assumed that ^{24}Na is produced in the Al monitor with the same cross section as at 10–28 GeV, i.e., 8.6 mb.[6]

TABLE I. Cross-section ratios σ_{300}/σ_{29} of radionuclides produced from vanadium by 300- and 29-GeV protons, along with the absolute cross sections in mb at 29 GeV (σ_{29}) and the ratios σ_{29}/σ_3 (Ref. 2). The cross section of the monitor reaction $^{27}Al \rightarrow ^{24}Na$ is assumed to be constant above 10 GeV, with a value of 8.6 mb.

Product	σ_{29} (mb)	σ_{300}/σ_{29}	σ_{29}/σ_3
^{48}V	6.84 ± 0.48	0.91 ± 0.04	0.91 ± 0.04
^{48}Sc	4.26 ± 0.30	0.99 ± 0.04	0.98 ± 0.04
^{47}Sc	10.6 ± 0.7	0.99 ± 0.04	0.99 ± 0.04
^{46}Sc	13.9 ± 1.0	0.97 ± 0.05	0.91 ± 0.05
^{44m}Sc	4.38 ± 0.31	0.94 ± 0.04	0.81 ± 0.03
^{47}Ca	0.47 ± 0.03	0.96 ± 0.05	1.04 ± 0.06
^{43}K	4.00 ± 0.28	0.97 ± 0.04	0.97 ± 0.04
^{42}K	6.73 ± 0.52	0.93 ± 0.05	0.90 ± 0.04
^{28}Mg	0.73 ± 0.05	0.95 ± 0.04	1.12 ± 0.05
^{24}Na	5.04 ± 0.36	0.99 ± 0.04	1.04 ± 0.04
^{22}Na	2.77 ± 0.28	0.97 ± 0.06	1.00 ± 0.05
^{7}Be	9.34 ± 0.68	0.95 ± 0.05	1.45 ± 0.06

TABLE II. Cross-section ratios $\sigma_{200}/\sigma_{11.5}$ and $\sigma_{300}/\sigma_{11.5}$ of radionuclides produced from cobalt by 200-, 300-, and 11.5-GeV protons, along with the absolute cross sections in mb at 11.5 GeV ($\sigma_{11.5}$). The cross section of the monitor reaction $^{27}Al \rightarrow ^{24}Na$ is assumed to be constant above 10 GeV, with a value of 8.6 mb.

Nuclide	$\sigma_{11.5}$ (mb)	$\sigma_{200}/\sigma_{11.5}$	$\sigma_{300}/\sigma_{11.5}$
^{58}Co	43 ± 3	0.95 ± 0.12	1.13 ± 0.10
^{57}Co	20 ± 2	0.87 ± 0.10	1.10 ± 0.12
^{56}Co	5.1 ± 0.4	0.95 ± 0.12	1.04 ± 0.10
^{55}Co	0.66 ± 0.10	1.03 ± 0.34	1.02 ± 0.17
^{54}Mn	19 ± 2	0.92 ± 0.13	1.06 ± 0.12
^{52}Mn	5.4 ± 0.5	0.90 ± 0.13	1.04 ± 0.12
^{51}Cr	21 ± 2	0.99 ± 0.14	1.01 ± 0.11
^{48}Cr	0.28 ± 0.02	0.92 ± 0.11	0.93 ± 0.08
^{48}V	9.4 ± 0.7	0.88 ± 0.11	1.00 ± 0.09
^{48}Sc	0.60 ± 0.07		0.95 ± 0.12
^{47}Sc	2.7 ± 0.2	0.96 ± 0.12	1.05 ± 0.09
^{46}Sc	6.7 ± 0.5	0.99 ± 0.12	1.01 ± 0.09
^{44m}Sc	4.8 ± 0.3	0.90 ± 0.10	1.03 ± 0.10
^{43}K	1.28 ± 0.11	0.93 ± 0.16	0.98 ± 0.13
^{42}K	3.9 ± 0.5	0.95 ± 0.16	0.85 ± 0.12
^{28}Mg	0.51 ± 0.04	1.00 ± 0.17	1.06 ± 0.11
^{24}Na	4.43 ± 0.25	0.96 ± 0.08	1.02 ± 0.09
^{7}Be	10.2 ± 1.1	1.00 ± 0.19	1.15 ± 0.17

The results of these measurements are summarized in Tables I and II. Absolute cross sections are shown for radionuclides produced from V at 29 GeV and from Co at 11.5 GeV. The 200- and 300-GeV results are presented as ratios of cross sections in order to show most clearly the relationship to lower-energy cross sections. The data of Table I are based on three runs. In one of these the peak beam intensity was slightly off the edge of the target, and hence there was a slight misalignment of the target and monitor foils. Therefore, this run was normalized, at ^{48}Sc, to the average of the other two runs. These two gave cross-section values that agreed with each other to ±2%. In Table II the 11.5-GeV data are averages of two runs; those at 200 and 300 GeV represent one run each. The uncertainties quoted represent estimates of the precision based on the fit of the decay curves with half-lives from the literature, and on the differences in calculated disintegration rates based on different γ rays for the same nuclide. All of the data at various beam energies for each target element were obtained from measurements made with the same Ge(Li) detector, and therefore the counter efficiencies canceled when the ratios were calculated. These efficiencies were shown to be stable during the time span of all the measurements.

It appears from Tables I and II that for V and Co the relative spallation cross sections for all the products measured at 200–300 GeV are very nearly the same as at 11.5–29 GeV. The mean cross-section ratio σ_{300}/σ_{29} for all measured products from V is 0.96 ± 0.04; for Co the mean ratios are $\sigma_{200}/\sigma_{11.5} = 0.95 \pm 0.06$, and $\sigma_{300}/\sigma_{11.5} = 1.02 \pm 0.09$. No systematic variation in the ratios with mass of the product is observed, although they vary from a simple (*p*,*pn*) product (^{58}Co) down to the light fragment ^{7}Be. It seems reasonable to conclude that all of these absolute cross sections, as well as the monitor cross section, are essentially constant over the energy range 11.5–300 GeV. In earlier work[2,7,8] significant changes were observed in the yield patterns of spallation products from medium-weight elements as the beam energy was increased from 3 to 29 GeV (Table I). However, virtually all of these changes[7] are probably between 3 and 10 GeV. The present results at much higher energies indicate that spallation cross sections from medium-weight nuclei (at least up to $A \approx 60$) do indeed level off above 10 GeV. Thus we infer from this that the spectrum of excitation energies deposited in the nucleus appears to be independent of bombarding energy above 10 GeV for this range of target nuclei. Although pion production increases with energy, most of the pions must escape from the nucleus without deposition of much energy.

It should be recognized that an overall distribution of product yields by itself is not a sensitive indicator of mechanism. More definitive studies, such as recoil-range and angular-distribution measurements of the products from light-, medium-, and heavy-element targets are needed to establish any differences in nuclear reaction mechanisms.

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[1] J. Hudis, in *Nuclear Chemistry*, edited by L. Yaffe (Academic, New York, 1968), pp. 169–272.

[2] L. Husain and S. Katcoff, Phys. Rev. C 7, 2452 (1973).

[3] R. Gunnink, H. B. Levy, and J. B. Niday, University of California Radiation Laboratory Report No. UCID-15140 (unpublished); modified by B. R. Erdal.

[4] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967), 6th ed.

[5] M. A. Wakat, Nucl. Data, Sect. A 8, 445 (1971).

[6] J. B. Cumming, Annu. Rev. Nucl. Sci. 13, 261 (1963).

[7] J. Hudis, I. Dostrovsky, G. Friedlander, J. R. Grover, N. T. Porile, L. P. Remsberg, R. W. Stoenner, and S. Tanaka, Phys. Rev. 129, 434 (1963).

[8] S. Katcoff, H. R. Fickel, and A. Wyttenbach, Phys. Rev. 166, 1147 (1968).

Origin of *j* and *Q* Dependence in Heavy-Ion Transfer Reactions

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A semiclassical treatment of heavy-ion–induced reactions is used to analyze experimental results on the $(^{16}O, {}^{15}N)$ and $(^{14}N, {}^{13}C)$ reactions at 80 MeV and the $(^{12}C, {}^{11}B)$ reaction at 95 MeV, on a ^{54}Fe target. It is shown that kinematical conditions and angular momentum coupling are sufficient to explain the strong j effect and Q dependence observed in the selective population of the various states.

Studies of heavy-ion–induced single-nucleon transfer reactions reveal a strong j dependence in the relative cross sections. This j effect depends on the nature of the projectile and more specifically on the orbital from which the nucleon is transferred. So far, this effect has been accounted for with the aid of the no-recoil distorted-wave Born-approximation (DWBA) selection rules.[1-4] Recently, it has been shown[5,6] that the complete treatment including the recoil terms is necessary in some cases to reproduce the experimental data, and therefore that the no-recoil selection rules cannot be used *a priori*. In this paper, we show that the observed j and Q dependence can be deduced from a simple discussion of the physics of the problem.

We recall that a semiclassical treatment[7] can be used to describe heavy-ion reactions provided the condition $\eta = Z_1 Z_2 e^2/\hbar v \gg 1$ is satisfied. It leads[8,9] to two momentum-matching conditions which must be simultaneously satisfied if the transfer probability is to be large. The first condition comes from conservation of the transferred-nucleon velocity. The second condition comes from total angular momentum conservation. For one-nucleon transfer reactions, taking the transferred-nucleon spin into account, these conditions are[9]

$$l_c - \lambda_i R_2/R_1 = \lambda_f \quad \text{(Condition II)}, \qquad (1)$$

$$L_i + \lambda_i + \sigma_i = L_f + \lambda_f + \sigma_f \quad \text{(Condition I)}, \qquad (2)$$

where $l_c = k_i R_2/\mu_i$ is the average angular momentum due to center-of-mass motion (k_i is the rela-