face R_b, an angular momentum $L_c = k_i R_b / A_i$ is given the final nucleus. Consequently, one would expect to find states of angular-momentum transfer $\approx L_c$ populated with high probability. Figure 2 shows the ratio of the predicted cross section with recoil to that with no recoil ($p=0$) for a typical case.

It should be emphasized that our model for scattering waves, $\chi_i^{(+)}$ and $\chi_f^{(-)}$, represents an extreme case. The one-parameter ring-locus model obtains the maximum diffraction oscillations in the cross section, and more complicated models for $\chi_1^{(+)}$ and $\chi_f^{(-)}$ are expected to produce smoother distributions. In addition, the introduction of a diffuse surface in the absorption region will cause the angular distribution to fall off faster with q than the sharp-cutoff model.[12] Consequently, the q^{-3} dependence also represents an extreme case for the average dependence of σ on q. It is apparent that the predictions of the model are not particularly sensitive to the scattering wave functions,[9] and that the principal effect of recoil and finite-range potentials is to modify the transfer function, $G_{if}^{LM}(\vec{r})$ in Eqs. (5) and (6).

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[10]Generalized adiabatic conditions for rearrangement scattering are taken to mean $\vec{k}_i = \vec{k}_f$ and $A_i = A_f$, so that $\vec{p} \cdot \vec{q} = 0$.

[11]This insensitivity of the angular distribution to any nuclear parameters (except perhaps the nuclear surface thickness) may be of some consequence in the proposed uses of high-energy heavy-ion accelerators. If our predictions are borne out further, then it appears that transfer reactions at high energy provide little identifiable nuclear-structure information.

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PRODUCTION OF VERY HEAVY ELEMENTS IN THERMONUCLEAR EXPLOSIONS—TEST BARBEL*

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The possibility of production of very heavy elements by multiple neutron capture in man-made thermonuclear systems was first demonstrated in the Mike explosion, in which exposure of U^{238} led to creation of nuclides as heavy as mass 255.[1] Unfortunately, the disposition of fuel and target material in the device greatly complicated attempts[2-4] to interpret the mass-abundance data in terms of fundamental nuclear parameters (i.e., a single-valued neutron flux and an appropriate set of cross sections).

Two recent low-yield underground test explosions in Nevada have succeeded for the first time in improving on the performance of the Mike test. Results of the first test ("Par"), conducted by the Lawrence Radiation Laboratory (Livermore), have been described in an earlier Letter.[5] The present Letter describes results of the second ("Barbel"), conducted by the Los Alamos Scientific Laboratory.

The Barbel device contained a U^{238} target in its high-neutron-flux region. Samples of debris from the fused-rock zone were radiochemically analyzed in accordance with four groupings of elements: (1) fission products, plus plutonium, americium, and curium; (2) plutonium and its short-lived americium daughters; (3) the transplutonium actinides up through lawrencium; and (4) the transactinium elements 104 and 105.

In addition to the information obtained by beta, alpha, and fission measurements on the individual elements isolated by these procedures, data on the abundances of isotopes up through mass 250 were obtained by mass spectrometric measurements on plutonium, americium, and curium fractions by C. M. Stevens of the Argonne National Laboratory.

The mass-abundance data for the Barbel test are summarized in Table I. Estimated uncertainties listed are those associated with the laboratory analyses. Additional uncertainties due to geochemical fractionation should be relatively small for the elements of interest. Observed ratios of the fission products Nd^{147}, Eu^{156}, and Mo^{99} were substantially the same as predicted values, and ratios of these products to Pu^{239} did not vary significantly from sample to sample. Abundances of products in the mass range 239-243 are not listed, since the contributions from these products originating in other flux regions could not be assessed reliably. Also omitted are abundances for masses 251 and 256. The only mass-251 product known to be sufficiently long-lived for measurement at the laboratory is ~800-yr Cf^{251}, and its alphas could not be measured in the presence of the much more intense alpha spectrum of Cf^{252}. The first long-lived mass-256 product is believed to be Cf^{256}, discovered in Par debris[6] but not measured in the Barbel debris.

Alpha and spontaneous fission measurements on chemical fractions corresponding to mendelevium through lawrencium (from the actinide column separations) and elements 104 and 105 (by separate radiochemical procedures) showed no credible evidence for isotopes of any of these elements.

The fractional target transformations from the Barbel experiment and the relative mass abundances from the Par[5] and Mike[2,6] experiments are plotted in Fig. 1. Also shown (heavy line) is the pattern of fractional transformations calculated for 7.6 % of the U^{238} target under the following simple assumptions: $\langle\sigma_c v\rangle\int n dt$

Table I. Heavy isotope abundances from Barbel device.

Mass number	Isotope measured	Method	Fraction of total target $N(A)/N_0(238)$
244	Pu^{244}	244/239, mass spectrometry	$(2.3\pm0.4)\times10^{-3}$
245	Am^{245}	β count of Am milked from Pu	$(3.7\pm0.5)\times10^{-4}$
246	Am^{246}	β count of Am milked from Pu	$(2.6\pm0.3)\times10^{-4}$
247	Cm^{247}	247/245, mass spectrometry; 245, Am β count	$(3.1\pm0.5)\times10^{-5}$
248	Cm^{248}	248/245, mass spectrometry; 245, Am β count	$(1.2\pm0.2)\times10^{-5}$
249	Cf^{249}	α count of Bk fraction	$(2.2\pm0.7)\times10^{-6}$
250	Cf^{250}	250/245, mass spectrometry; 245, Am β count	$(5.9\pm1.1)\times10^{-7}$
251		Not measured	...
252	Cf^{252}	α counting	$(5.3\pm1.4)\times10^{-8}$
253	Es^{253}	α counting	$(2.2\pm0.7)\times10^{-8}$
254	Cf^{254}	Fission counting	$(1.8\pm0.7)\times10^{-9}$
255	Fm^{255}	α counting	$(9.1\pm2.0)\times10^{-10}$
256		Not measured	...
257	Fm^{257}	α counting	$(1.3\pm0.4)\times10^{-11}$

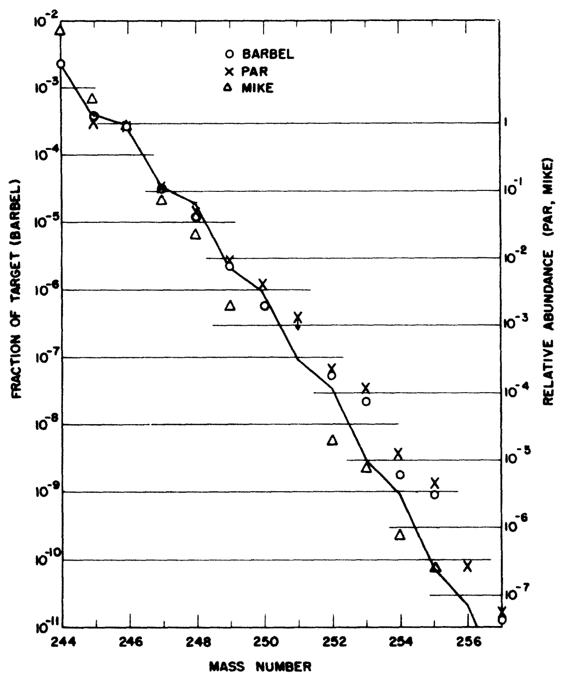

FIG. 1. Heavy element abundances from Barbel, Par, and Mike experiments. Zig-zag line connects points computed from simple one-flux model with σ_c(odds) $= 3\sigma_c$(evens). All experimental abundance patterns arbitrarily normalized at mass 246.

$= 1.505$ for even masses and 4.515 for odd masses, no neutron reactions other than capture, no losses in beta decay chains to products measured. The 92.4% of the U^{238} unaccounted for was assumed to have been destroyed by fission before the start of the multiple capture sequence.

Examination of the abundance distributions reveals two puzzling features: (1) The even-odd abundance pattern reverses around mass 250 from evens more abundant to odds more abundant. This reversal was indicated in the Mike data and is confirmed in the Barbel and Par data. (2) The simple one-flux model requires that σ_c increase with mass in order to fit observed abundances at the higher masses.

It has been suggested[5] that the reversal in even-odd abundance pattern at higher masses is due to spontaneous fission of even-mass members of the long postcapture beta-decay chains, whereas the odd-mass chains survive intact. Although this explanation permits choices of parameters that give a fit to the abundance data, it requires that some of the earlier members of the beta-decay chains have spontaneous fission lifetimes much shorter than those of the known higher-Z members, and that these lifetimes be distributed in such a way as to result in a smooth variation of apparent depletion with mass number. Even with the presently known sensitivity of spontaneous fission probability to nuclear structure factors, rather sharp changes would be needed to override the Z^2/A influence to this degree. Another implication of the data, if the capture cross sections of the uranium isotopes are not to increase with mass, is that there is more than one high-flux zone.

A second hypothesis is based on a suggestion by P. R. Fields and H. Diamond of Argonne National Laboratory, who pointed out that conversion of the uranium to an odd-Z species during neutron capture would lead to the observed change in alternation of abundances. An examination of possible target atom conbinations by Bell[7] indicates that Np-producing (d, n) and $(d, 2n)$ reactions could give two product distributions, one for uranium and another for neptunium, which add up to the one observed. We believe that this hypothesis offers the most plausible explanation of both of the puzzling aspects of the mass-yield curves.

The Barbel device was designed by the Los Alamos Theoretical Division, under the direction of J. C. Mark.

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C-INVARIANCE VIOLATION IN STRONG AND WEAK INTERACTIONS

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One of the most interesting proposals advanced to explain the discovery of a decay mode $K_2^0 \to \pi^+ + \pi^-$ is the suggestion that C invariance is violated directly at the level of strong interactions. Such C-invariance violation could appear at the level of SU(3)-breaking interactions, as originally proposed by Prentki and Veltman,[1] or with a somewhat smaller strength, comparable to that of electromagnetic interactions, as porposed by Lee and Wolfenstein.[2] In this note we wish to consider a more extreme possibility, namely, we will propose that C need not be at all a basic symmetry of strong interactions.

For a limited but important class of phenomena we show that the predictions of C and of T invariance follow (with different degrees of approximation) from the CPT theorem, P conservation,[3] and the approximate isotopic spin [SU(2)] and SU(3) symmetries. That such things could happen has been known for a long time.[4]

The class of phenomena for which theorems are actually stated here includes the coupling of pseudoscalar particles to spin-$\frac{1}{2}$ baryons, and the coupling of vector mesons to conserved currents of spin-$\frac{1}{2}$ baryons and of spinless mesons. Although more extensive theorems can be stated, it is both amusing and interesting to point out some cases where theorems of this kind are not valid, except perhaps under more stringent conditions. These are the coupling of scalar and of axial-vector (1^+) particles to spin-$\frac{1}{2}$ baryons. The interest of this fact in respect to the present theory has been pointed out by Pais, and it is hardly necessary to emphasize its possible implications.

Let us first consider theorems which deal with the coupling of pseudoscalar mesons to spin-$\frac{1}{2}$ particles:

T_1.—The P-conserving coupling of a pseudoscalar neutral particle to a spin-$\frac{1}{2}$ particle on the energy shell is T invariant.

T_2.—If isospin is conserved, the above results are generalized to πN couplings (with N on the energy shell).

T_3.—In the limit of exact SU(3) the above is generalized to the couplings among octet pseudoscalar meson and the baryon octet. It is easy to see that theorems analogous to T_1-T_3 cannot be proved for the case of scalar (0^+) particles interacting with baryons, unless more restrictive assumptions are made.

Let us consider next the matrix elements of a Hermitian conserved vector current among two states of the same particle. Write such a matrix element in the form

$$\langle p'|j_\mu|p\rangle = i\bar{u}(p')[F_1(k^2)\gamma_\mu + F_2(k^2)\frac{1}{2M}\sigma_{\mu\nu}k_\nu + H_1(k^2)\frac{1}{2M}k_\mu]u(p), \quad (1)$$

in the case of a spin-$\frac{1}{2}$ particle, and

$$\langle p'|j_\mu|p\rangle = F_3(k^2)(p+p')_\mu + H_2(k^2)(p-p')_\mu, \quad (2)$$

for a spin-zero particle; F_1, F_2, and F_3 are usually called first-class form factors, H_1 and H_2 second-class form factors.[5] From the fact that j_μ is Hermitian (for $\mu = 0, 1, 2, 3$) and conserved, there follows

T_4.—$H_1(k^2) = H_2(k^2) = 0$; F_1, F_2, and F_3 are real, i.e., the same limitations one would obtain from C and T. Furthermore,

T_5.—If the scalar (or PS) particle in Eq. (2) is self-conjugate under CPT, then also $F_3 = 0$ and the particle is strictly neutral.

These results apply directly to diagonal matrix elements of the electromagnetic current which has all the required properties. The results can be generalized by the further assumption of exact isospin conservation and SU(3) invariance:

T_6.—The matrix elements of the isospin currents among members of a single isospin mul-