have been observed at high excitation energies. These data may serve as a basis for judging the validity of models which treat the equilibration of the entrance-channel energy between the fragments as well as models of the direct-fission process. As far as the angular-momentum transfer process is concerned, possible biasing of the $l$ distribution due to fission, and a primary depolarization of the heavy fragment's intrinsic angular momentum, provide us with an alternative explanation of the measured out-of-plane fission widths which seems more consistent with $\gamma$-anisotropy data. Thus the sequential-fission process following a deep-inelastic collision seems to be more intriguing than expected insofar as the population of new modes in deep-inelastic collisions is concerned.

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# Experimental Test of the Factorization Approximation in the Reaction $^{40}$Ca$(p, 2p)^{39}$K at 148.2 MeV

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We present data for the reaction $^{40}$Ca$(p,2p)^{39}$K at 148.2 MeV. Energy sharing cross sections for the $\frac{3}{2}^+$ ground state and $\frac{1}{2}^+$ excited state are well described by distorted-wave impulse-approximation calculations. An explicit comparison of the results of the factorization approximation with these experimental results provides considerable support for the usual distorted-wave impulse-approximation treatment.

In order to extract precise nuclear structure information from any nuclear reaction, it is essential to understand the accuracy of the reaction theory used. In the present work we take advantage of the kinematic flexibility of the three-body $(p, 2p)$ reaction[1] to make a detailed test of the two-body factorization approximation inherent in the distorted-wave impulse-approximation (DWIA) treatment of the reaction. This test for the reaction $^{40}Ca(p, 2p)^{39}K$ at 148 MeV serves not only to establish the validity of the assumed reaction mechanism but also provides some measure of the precision of the DWIA analysis.

In the DWIA the three-body cross section for a reaction $A(p, 2p)B$ can be written as[2]

$$\frac{d^3\sigma}{d\Omega_1\, d\Omega_2\, dE_1} = C^2SK\sum_{\Lambda} |T_{BA}{}^{L\Lambda}|^2 \sigma_{pp}, \qquad (1)$$

where $K$ is a known kinematic factor, $C^2S$ is the spectroscopic factor associated with a particular final state, and $\sigma_{pp}$ is the half-off-energy-shell differential cross section for $p$-$p$ scattering. It is usually approximated by the on-shell cross sec- section but can alternatively be calculated[3] directly from a nucleon-nucleon potential. The quantity $\sum_\Lambda |T_{BA}{}^{L\Lambda}|^2$ is the distorted momentum distribution with

$$T_{BA}{}^{L\Lambda} = (2L+1)^{-1/2} \int \chi_{\vec{p}_1}^{(-)*}(\vec{r})\chi_{\vec{p}_2}^{(-)*}(\vec{r}) \times \varphi_L{}^{\Lambda}(\vec{r})\chi_{\vec{p}_0}^{(+)}(\gamma\vec{r})\, d^3r, \qquad (2)$$

where the $\chi$'s are distorted waves for the incoming and outgoing proton channels, $\varphi_L{}^{\Lambda}(\vec{r})$ is the bound proton single-particle wave function, and $\gamma = A/B$. In the plane-wave impulse approximation (PWIA), $T_{BA}{}^{L\Lambda}$ reduces to the momentum wave function of the bound proton evaluated at a momentum $-\vec{p}_3 = \vec{p}_0 - \vec{p}_1 - \vec{p}_2$.

The factorization approximation in DWIA leads to the appearance of the $p$-$p$ cross section as a distinct factor in Eq. (1) rather than the corresponding two-body $t$ operator which would otherwise appear in the amplitude given in Eq. (2). In order to test this approximation we construct the quantity

$$Q(\theta_1, \theta_2) = \frac{d^3\sigma(\theta_1, \theta_2)}{d\Omega_1\, d\Omega_2\, dE_1} \{C^2SK \textstyle\sum_\Lambda |T_{BA}{}^{L\Lambda}|^2\}^{-1}, \qquad (3)$$

where $d^3\sigma(\theta_1, \theta_2)/d\Omega_1\, d\Omega_2\, dE_1$ is the experimental three-body cross section at a laboratory angle pair $(\theta_1, \theta_2)$. Comparing Eqs. (3) and (1) it is evident that, in DWIA, we expect

$$Q(\theta_1, \theta_2) = \sigma_{pp}(E_{pp}, \theta_{pp}^*), \qquad (4)$$

where $E_{pp}$ is the effective laboratory energy for the $p$-$p$ scattering and $\theta_{pp}^*$ is the center-of-mass scattering angle. Thus our experiment consists of measuring the $(p, 2p)$ cross section for various angle pairs $(\theta_1, \theta_2)$ and comparing the angular variation of the quantity $Q(\theta_1, \theta_2)$ with that of two-body cross section $\sigma_{pp}$, each plotted as a function of $\theta_{pp}^*$. In order to improve the precision of this comparison we minimize the variation of $\sum_\Lambda |T_{BA}{}^{L\Lambda}|^2$ with $(\theta_1, \theta_2)$ by considering only data for which $p_3$ is constant. This choice follows from the result that in PWIA $\sum_\Lambda |T_{BA}{}^{L\Lambda}|^2$ is constant for constant $p_3$ and greatly reduces the sensitivity of $Q(\theta_1, \theta_2)$ to the choice of distorting potentials in DWIA. This technique has proved to be very effective in studies of the angular dependence of the $(p, p\alpha)$ cluster knockout reaction[4,5] and the $(\alpha, 2\alpha)$ reaction.[6,7] As in the cluster knockout reaction studies,[4-7] in $(p, 2p)$ it is convenient to select angle pairs such that $p_3 = 0$ is kinematically allowed, since this point corresponds to a maximum in the three-body cross section for $L=0$ transitions. Thus, very roughly $\theta_1 + \theta_2 \approx 90°$ and $\theta_{pp}^* \approx 2\theta_1$ at $p_3 = 0$.

In contrast to the cluster knockout reaction studies,[4-7] for the $(p, 2p)$ reaction at energies near 150 MeV the angular dependence of the two-body cross section is nearly flat except at small angles. This is not due to the dominance of $s$ wave which alone accounts for only 25% of the cross section. Rather the isotropic cross section results from a delicate cancellation of $p$ and $d$ waves, so that one might expect a study of the angular variation of $Q(\theta_1, \theta_2)$ at these energies to be very sensitive to any breakdown in the factorization approximation.

The experiment was carried out using a proton beam from the Indiana University Cyclotron Facility. The beam of 148.2-MeV protons with intensities varying between 50 and 400 nA was energy analyzed to a resolution of approximately 80 keV and was focused on a 4-mg/cm$^2$ self-supporting natural Ca target placed at the center of a 60-cm-diam scattering chamber. The emitted protons from the $^{40}Ca(p, 2p)$ reaction were detected by a solid-state counter telescope and a magnetic spectrograph placed coplanar with and on opposite sides of the beam. The solid-state detector telescope consisted of a 1-mm Si surface-barrier $\Delta E$ detector, a 1-cm-thick intrinsic Ge $E$ detector,[8] and a NaI(Tl) Veto detector. The $\Delta E \circ E \cdot$Veto requirement limited the proton energy detection range from approximately 12.5 to 66.3 MeV. The second proton was detected in the quadrupole-dipole-dipole-multipole spectrograph[9] using a helical wire chamber[10] in the focal plane followed by two plastic scintillators used for particle identification and background suppression. The energy bite of this spectrograph was approximately ±3%. The angular acceptance of the two detectors was $\Delta\theta = 46$ mr, $\Delta\varphi = 33$ mr for the counter telescope and $\Delta\theta = 44$ mr, $\Delta\varphi = 70$ mr for the magnetic spectrograph. The finite resolution effects of these large solid angles were calculated using the program MOMRATH,[11] and were found to be quite small.

The overall binding energy resolution $(E_1 + E_2)$ inherent to the system, was measured to be approximately 150 keV using a hydrogen target (CH). The binding energy resolution for the reaction $^{40}$Ca$(p, 2p)^{39}$K, however, was 350 keV due primarily to target thickness effects. A more complete description of the experimental details can be found in Ref. 12.

The actual experiment consisted of two types of measurements for the reaction $^{40}$Ca$(p, 2p)^{39}$K. The first was a measurement of the energy sharing cross section at a fixed pair of angles ($\theta_{\text{counter}} = 44°$, $\theta_{\text{spectrograph}} = -39°$). In this experiment measurements of the $(p, 2p)$ cross section were made for a series of magnetic field settings covering the energy range 78 to 113 MeV for the ground state (corresponding to the range 62 to 27 MeV in the counter telescope). Typical binding energy spectra are shown in Fig. 1. One observes the marked change in the ground ($\frac{3}{2}^+$) and first excited ($\frac{1}{2}^+$) states of $^{39}$K as the value of the recoil momentum $(p_3)$ increases. The second measurement constitutes our test of the factorization approximation. In this case the $(p, 2p)$ cross section was measured at five angle pairs. The detection angles and energies were chosen so that the central ray accepted by the magnetic spectrograph corresponded to the $p_3 = 0$ MeV/$c$ point. The angle pairs chosen corresponded to an angular range for $\theta_{pp}{}^*$ of approximately 51° to 84° in the two-body $p$-$p$ center-of-mass system.

In Fig. 2 we present the results for the energy sharing experiment for the ground and first excited states of $^{39}$K. These data show qualitative features expected for a direct knockout process; namely, the ground state shows a minimum at $p_3 = 0$ as expected for $L = 2$, and the first excited state shows a maximum at $p_3 = 0$ as expected for an $L = 0$ transition.

DWIA calculations for these data were carried out using the code WAVEPROG written by Chant.[2] The proton distorted waves were calculated using the optical potentials of van Oers,[13] obtained from an energy-dependent analysis of $p + {}^{40}$Ca elastic scattering data. In the DWIA calculations the spin-orbit potential was not included for scatter-

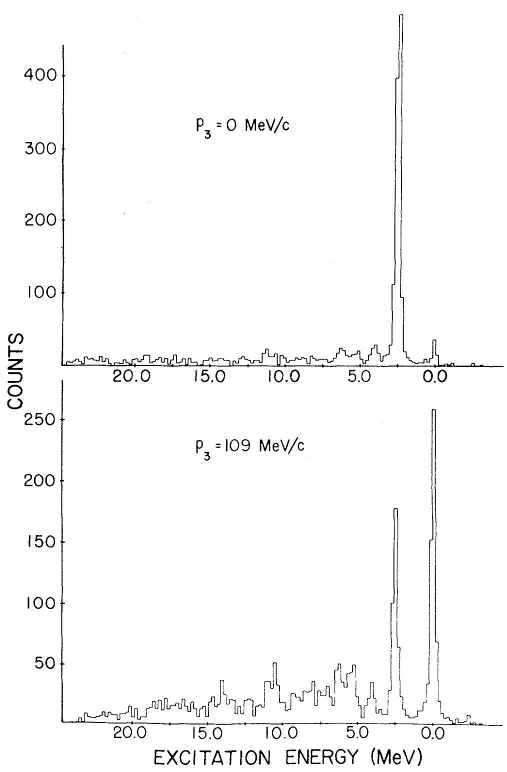


FIG. 1. Summed energy spectra for $^{40}$Ca$(p, 2p)^{39}$K at 148.2 MeV at $(\theta_1, \theta_2) = (44°, -39°)$. The recoil momentum $p_3$ corresponds to the central ray value.

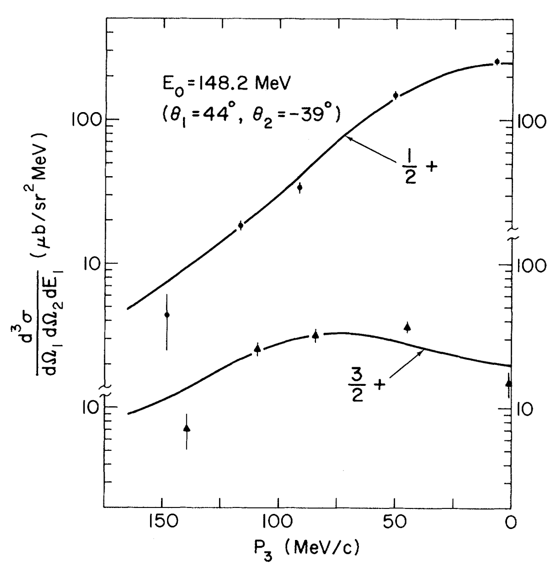


FIG. 2. Energy sharing cross sections for the $1d_{3/2}$ ground state and $2s_{1/2}$ first excited state of $^{39}$K. The solid curve is a DWIA calculation.

ing states. The parameters for the bound-state proton were taken from the work of Elton and Swift.[14] These same parameters provided good fits to the $^{40}$Ca($e, e'p$)$^{39}$K data of Mougey *et al.*[15]

In Fig. 2 the DWIA calculations are shown normalized to the experimental data (solid curve). These calculations provide an excellent fit. The spectroscopic factors obtained from normalizing the DWIA calculations to the experimental data are $C^2S(\frac{3}{2}^+) = 4.0$ and $C^2S(\frac{1}{2}^+) = 1.4$ in quite good agreement with the ($e, e'p$) results[15] and transfer reaction analyses.[16] A more extensive analysis investigating the effects of the distorting and bound-state potentials, as well as additional final states in $^{39}$K is in progress.

Using the above bound-state parameters, calculations were carried out for the points measured in the angular distribution experiment. These calculations were done only for the $\frac{1}{2}^+$ state, since the 2$s$ wave function has a maximum at $p_3 = 0$. The results for the $\frac{3}{2}^+$ state would not be meaningful since the 1$d$ wave function is zero at $p_3 = 0$. Thus neglecting finite-solid-angle corrections the experimental yield is nonzero only as a result of the distortion effects. These data will then be extremely sensitive to the distorting potentials, and would not provide a useful test of the factorization approximation.

In Fig. 3 we present the quantity $Q(\theta_1, \theta_2)$ of Eq. (3) plotted as a function of the two-body $p$-$p$ scattering angle $\theta_{pp}*$ calculated in the rest system of the two outgoing protons. The spectroscopic factor $C^2S$ was taken to be 1.5. The DWIA cross section at 90° is approximately $\frac{1}{6}$ of the PWIA value, so that distortion effects are not too severe. However, the distortion effects do introduce about a factor of 2 variation over the angular range studied in this experiment. The solid line in Fig. 3 represents the two-body on-shell cross-section data at 144 MeV.[17] The measured values of $Q(\theta_1, \theta_2)$ are in excellent agreement with the on-shell cross section. Thus the factorization approximation employed in our DWIA calculations appears to be most satisfactory. This result we regard as strong confirmation of the validity of our DWIA analysis and of the resultant nuclear structure information.

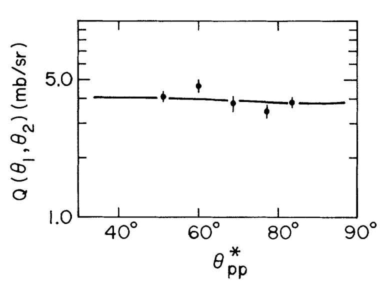


FIG. 3. The extracted $Q(\theta_1, \theta_2)$ for the $2s_{1/2}$ state as of function of the two-body $p$-$p$ scattering angle $\theta_{pp}*$. The curve is the two-body $p$-$p$ cross section at 144 MeV.

In summary, we have measured the reaction $^{40}$Ca($p$, 2$p$)$^{39}$K at 150 MeV with emphasis on the first excited ($\frac{1}{2}^+$) state of the final nucleus $^{39}$K. These data provide one of the first detailed tests of the factorization approximation in ($p$, 2$p$) reactions at intermediate energies. We find that the factorization approximation is satisfied to a very high degree at least in terms of the angular dependence of the reaction. In addition, the results of an energy sharing experiment are well described by the DWIA and lead to spectroscopic factors in good agreement with those obtained from the ($e, e'p$) reaction and transfer reactions.

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# Observation of Positron Creation in Superheavy Ion-Atom Collision Systems

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We report the first observation of positron creation in high-energy $^{208}Pb + {}^{208}Pb$ collisions and establish that a dominant fraction of the positron yield is from nonnuclear origins. The excess positron intensity observed over nuclear emission and its projectile energy dependence is consistent with recent predictions for pair-creation processes in the strong time-varying electric fields produced by the combined nuclear charges of the quasimolecular system formed in the collision.

There has been a long-standing interest in fundamental questions associated with the behavior of a Dirac electron in very strong electric fields originating from charges $Z > 1/\alpha$. In particular, as noted in theoretical studies,[1,2] a qualitatively new phenomenon is expected to occur when the binding energy of the electron exceeds the critical value of twice the electron mass. The filling of a vacancy in such an overcritically bound state without the expenditure of energy leads to a spontaneous emission of positrons with the creation of a charged lowest-energy state, a charged vacuum.[3,4] The observation of this positron-emission process would provide the crucial verification of the predicted transition from the neutral to a charged electron vacuum in overcritical fields.

Although the experimental conditions required to study this process cannot be realized in stable atoms presently, the formation of quasimolecular states in heavy-ion collisions, such as in U on U near the Coulomb barrier, may provide a suitable vehicle for creating overcritical potential binding.[5,6] However, in contrast to the stable-atom situation, in such dynamical systems positron creation also can reflect additional quantum electrodynamic (QED) processes associated with the time-varying electric field produced by the nuclear motion.[7,8] These dynamically induced positron-production processes are not only of considerable interest as background considerations associated with on-going experiments[9] to isolate spontaneous positron emission in heavy-ion collisions, but they are also inherently interesting since they reflect the salient features characterizing the interaction of electrons with very strong electromagnetic fields which, unlike pair creation by light charged particles,[10] cannot be treated in perturbation theory. These mechanisms can be studied independently of spontaneous positron emission by selecting collision systems in which the critical binding of $-2mc^2$ is not exceeded at any stage of the collision.[7] In this connection, the $^{208}Pb + {}^{208}Pb$ system[11] is a

 