Formation of $^{24}$Mg\(^\ast\) in the Splitting of $^{28}$Si Nuclei by 1-GeV Protons

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The $^{28}$Si(p,p\('\gamma_0X)^{24}$Mg reaction has been studied at the ITEP accelerator by the hadron-gamma coincidence method for a proton energy of 1 GeV. Two reaction products are detected: a 1368.6-keV $\gamma$-ray photon accompanying the transition of the $^{24}$Mg\(^\ast\) nucleus from the first excited state to the ground state and a proton p\('\) whose momentum is measured in a magnetic spectrometer. The measured distribution in the energy lost by the proton in interaction is attributed to five processes: the direct knockout of a nuclear $\alpha$ cluster, the knockout of four nucleons with a total charge number of 2, the formation of the $\Delta$Si isobaric nucleus, the formation of the $\Delta$ isobar in the interaction of the incident proton with a nuclear nucleon, and the production of a $\pi$ meson, which is at rest in the nuclear reference frame. The last process likely corresponds to the reaction of the formation of a deeply bound pion state in the $^{28}$P nucleus. Such states were previously observed only on heavy nuclei. The cross sections for the listed processes have been estimated.
1. INTRODUCTION.

Stodolsky [1] proposed to use the coherent properties of an atomic nucleus for the suppression or enhancement of various nuclear reaction mechanisms. The experimental verification of theoretical predictions [1] is difficult, because it is necessary to separate nuclear states with excitation energies ~MeV when incident particle energies are ~GeV.

As shown in [1-6], the fixation of the residual nucleus state allows the effective separation of certain reaction channels. Some reactions can be treated as semicoherent, because certain transitions are associated with the collective excitations of a certain group of particles.

In the MAG magnetic germanium spectrometer [7], used in this experiment, prompt $\gamma$-rays from the transitions of excited nuclei to a state with a lower excitation energy or to the ground state are detected. This makes it possible to determine the state of the residual nucleus including its quantum numbers.

In view of this circumstance, investigation of the formation of $^{24}$Mg in the collision of protons with $^{28}$Si nuclei by the hadron-gamma coincidence method at the MAG spectrometer is of great interest, because the process can be treated in terms of the $\alpha$ cluster model, the $^{28}$Si target nucleus is the $^{12}$C–$\alpha$–$^{12}$C nuclear molecule [8]. In this model, the quasi-free particle can be a target for the incident proton and provide the direct knockout of particles from the nucleus in peripheral interactions.

Central interactions of protons with the nucleus can lead to collective excitations whose energies are higher than the discrete levels and giant resonances [9]. The average excitation energy of the residual nuclei formed after completion of the nuclear cascade induced by 1-GeV protons in the $^{28}$Si is ~0.06 GeV and the excitation energy distribution expands to 0.4 GeV or higher.

The reaction

$$^{28}\text{Si}(p, p'\gamma_0 X)^{24}\text{Mg},$$

that is more general than the quasielastic knockout of particles was investigated at the MAG spectrometer. Here, $p'$ is the secondary leading proton whose momentum is measured by the magnetic spectrometer, $\gamma_0$ is the photon accompanying the transition of the $^{24}$Mg nucleus from the first excited state to the ground state (its energy is used to identify the final nuclear state), and $X$ is any combination of secondary hadrons (nucleons and pions) with a total atomic number of 4 and a total charge number of 2.
The direct knockout reactions correspond to $X = \alpha$. Competitive cascade interactions of the proton with quasi-free nucleons in the nucleus that lead to the emission of four nucleons ($X = 2p2n$) are simultaneously detected. In this work, reaction (1) is investigated in a wide energy-transfer range up to $0.8 T_0$, where $T_0$ is the proton beam energy. This range includes not only the excitations of discrete levels but also $\pi$-meson and isobar nuclear excitations.

2. EXPERIMENTAL PROCEDURE AND DATA PROCESSING

The experiment was carried out with the universal beam of the ITEP proton synchrotron for $T_0 = 1.02$ GeV. Reaction (1) was studied by the hadron-gamma coincidence method using the MAG magnetic germanium spectrometer [7]. The silicon target ($^{28}\text{Si} - 92.23\%, \; ^{29}\text{Si} - 4.67\%, \; ^{30}\text{Si} - 3.1\%$) has a thickness of $x = 6.18$ g/cm$^2$. Gamma-ray photons from the target were detected by the germanium spectrometer based on a Ge(Li) crystal and the leading secondary charged particles (predominantly hadrons) were detected by the magnetic spectrometer based on a wide-aperture magnet. The track part of the spectrometer consists of multiwire proportional chambers placed in front of and behind the magnet. The momenta $p$ of the charged particles were measured in the magnetic spectrometer with the accuracy $\frac{dp}{p} = (0.32p + 0.57)\%$, where $p$ is measured in GeV. Angles were measured with an accuracy of 0.003 rad. The germanium spectrometer was adjusted for detecting prompt photons emitted from the target perpendicularly to the beam direction and for measuring their energy from 50 to 3000 keV. We selected 892 596 events with a $\gamma$-ray photon and one charged hadron emitted from the target at angle $\theta < 15^\circ$ to the beam direction. In the photon-energy distribution of the events, a number of lines corresponding to certain $\gamma$-transitions in the reaction product nuclei are observed against the background. Twenty eight $\gamma$-transitions are identified for 19 product nuclei [10, 11]. To analyze reaction (1) of the formation of $^{24}\text{Mg}^*$, we considered range $A$ of the $\gamma$-ray energies 1350-1380 keV including the line $E_{\gamma_0} = 1368.6$ keV of the transition of the $^{24}\text{Mg}$ nucleus from the first excited state to the ground state.

Two factors distort the angular distributions of secondary protons detected in the magnetic spectrometer. The first factor is associated with random events induced by beam protons that do not interact in the target. Small angles $\theta$ are characteristic of these events. The second factor
is the dependence of the detection efficiency of the magnetic spectrometer on $\theta$. This factor is associated with the limited sizes of track detectors and their rectangular geometry. This factor is noticeable for $\theta > 6.5^\circ$ and, if necessary, is taken into account by correcting coefficients.

3. DATA ANALYSIS FOR $3^\circ < \theta < 6.5^\circ$.

In this region, the random-particle background can be disregarded and the efficiency of the magnetic spectrometer can be taken as $\approx 100\%$. Figure 1 shows the fragment of the energy spectrum of photons for these events near the $E_{\gamma 0}$ line whose tabulated value is indicated by the arrow. The histogram part corresponding to range A are doubly shaded. The number of events in this range is $N_2=1965$. The right and left shaded intervals B, are used to determine the background under peak. The spectrum fragment is approximated by the sum of a normal distribution with the standard deviation equal to the resolution of the $\gamma$-spectrometer [7, 11] and a linear function describing the background. The least squares fit are shown by the smooth curves. The number of events of reaction (1) in interval A is $N_3=745\pm73$ whereas the background from the continuous is $N_b=1217$.

Figure 2 shows the distribution of events of reaction (1) in the energy $\omega = T_0 + M_p - \sqrt{M_p^2 + P^2}$ ($M_p$ - is the proton mass and $P$ - is the scattered-proton momentum measured in the spectrometer) that is transferred by the proton interacting with the target nucleus. This distribution is obtained by subtracting the background from the $\omega$ distribution of $\omega N_2$ events in interval A. The background distribution in $\omega$ is determined in intervals B and is normalized to $N_b$ events.

The peak near $\omega \approx 0$ corresponds to the interaction of beam protons with quasi-free $\alpha$ clusters. Negative values appear due to the errors of the measurement of the momentum $P$ in the magnetic spectrometer. Events in the range $\omega = 0.22-0.6 \text{ GeV}$, where the production of mesons is energetically possible, are attributed to the formation of the isobar and isobaric nuclear excitation. The shape of the distribution of events with the maximum at $\omega_0 \approx 0.145 \text{ GeV}$ is characteristic of the production of a pion that is at rest in the laboratory system or in the system associated with the nucleus.

In order to describe the experimental data, the following processes are simulated:

1) proton scattering on the nuclear $\alpha$ cluster with the emission of the cluster from the nucleus,
2) the formation of the $\Delta\text{Si}$ isobaric nucleus,
3) the formation of the $\Delta_{1232}$ isobar in the interaction of the beam proton with a nuclear nucleon, and
4) the production of a pion that is at rest in the system associated with the nucleus.

The $\omega$ distributions of events for these processes are calculated by the Monte Carlo method using the GEANT-3.21 program. The conditions of the detection of particles in the magnetic spectrometer and the selection of events with respect to the proton scattering angle are reproduced in the simulation program. The momentum of one leading particle, which is emitted from the nucleus at angle $3^\circ < \theta < 6.5^\circ$ and has positive charge, is determined. The possibility of multiple rescattering of the proton with the highest energy in the nucleus is taken into account for processes 1 and 3. The ratio between the probabilities of various multiple scatterings for $^{28}\text{Si}$ is calculated by the Monte Carlo method using the mean free path of the proton in the nucleus and known cross section for the nucleon-nucleon interaction. The ratio $1 : 0.75 : 0.24$ is obtained for the single, double, and triple interactions, respectively. The Fermi momenta of the nucleon and $\alpha$ cluster are taken into account when simulating the interactions of the incident proton with the nuclear nucleon or $\alpha$ cluster. The mean Fermi momenta of the nucleon and cluster, which are determined by the separation energies for these particles, are equal to 0.19 and 0.3 GeV/c, respectively. To ensure the energy conservation in the reaction, the effective target mass at the collision instant is calculated from the condition that the total energy of the target is equal to its rest mass and the momentum is taken as a random value from the Rayleigh distribution.

The conditions under which reaction (1) is energetically possible are satisfied in simulation. Events for process 1 are selected such that the first elastic interaction of the proton occurs with the nuclear $\alpha$ cluster, which acquires an energy sufficient for the emission from the $^{28}\text{Si}$ nucleus, whereas the energy acquired by nuclear nucleons in the subsequent interactions with the proton is insufficient for their emission. Process 2 is simulated by the interaction of the proton with the $^{28}\text{Si}$ nucleus with the excitation of the nucleus to an energy of 0.294 GeV (the average energy of the isobar excitation of the nucleon). The excitation energy in the particular interaction is taken as a random value from the Breit-Wigner distribution with width $\Gamma=0.12$ GeV in agreement with the conclusions made in [12] that the ex-
citation energies of the free isobar and isobaric nucleus are equal to each other. Process 3 is simulated using the channels of the formation and decay of the isobar and their branching ratios presented in [13-15]. In the first interaction of the incident proton with the nucleus, the event selection algorithm for process 3 ensures the energy transfer sufficient for the emission of four nucleons from the nucleus. In the second and third interactions of the proton with a nuclear nucleon, if they occur, events in which the energy transferred to the target proton is lower than its separation energy are selected.

The c.m. scattering angle $\psi$ in two-particle processes 1-3 is simulated as follows. This angle in processes 1 and 2 is taken such that the distribution in the 4-momentum transfer squared is exponential with an argument of 10 and 30 for the $\alpha$-particle and silicon nucleus, respectively. In isobar formation reactions 3, it is assumed that the c.m. angular distribution at its formation stage corresponds to $\cos^4 \psi$ [14]. The isobar decays are simulated as isotropic.

The estimate for the contributions of four indicated processes to events $N_3$ is obtained by using least squares fit of the experimental $\omega$ distribution to the function consisting of the sum of the model distributions for the above-indicated processes. The designed parameters are the numerical contributions of these processes. The fit is performed without the normalization to the number of events in the experimental histogram. The optimum numbers of events of processes 1-4 calculated for the minimum $\chi^2=103$, are equal to 461±41, 132±20, 45±12 and 27±8, respectively, for the number of degrees of freedom $n=80$. The average $\omega$ value for a group of events responsible for process 2 is equal to 0.145 ± 0.003 GeV. The distribution is no wider than the apparatus error so that the physical width of the line is likely no larger than 0.004 GeV. Figure 2 shows the fitting results. The statistical confidence of the existence of process 4 with the $\pi$-meson is estimated as 3.5 standard deviations.

4. ANALYSIS OF THE RESULTS FOR $0^\circ < \theta < 15^\circ$.

In this range, 7040 events accompanied by photons whose energies are in interval A were detected. The statistical treatment of events in this range has three features. First, as shown in [7], losses of events that are due to limited geometric sizes of the coordinate detectors, their shape, and space arrangement cannot be disregarded for $\theta < 15^\circ$. Owing to these losses, the efficiency of the magnetic spectrometer for detecting charged particles
is not equal to 1 and, moreover, depends on the angles and momenta of the particles. The procedure for determining and taking into account the efficiency \( \varepsilon(\theta, p) \), was described in [7]. According to this procedure, each detected event is assigned with the weight \( W = \varepsilon^{-1}(\theta, p) \) and the ”effective” number of events is used in all numerical calculations reported below. For the case under consideration, the sum of the weights of events with \( E_\gamma \in \mathbf{A} \) is equal to \( W_1 = 20\,851 \).

Second, the feature of the procedure concerns the selection of events of reaction (1): in addition to the linear background from the continuous component of the photon spectrum, a noticeable contribution from three additional sources exists in photon-energy interval \( \mathbf{A} \). These sources are \( \gamma \)-transitions in other nuclei, random coincidences, and secondary interactions of the products of reaction (1) with the target nuclei. The background from the continuous component and \( \gamma \)-transitions is numerically determined by using of the least squares approximation of the experimental distribution in \( E_\gamma \) as in Section 3. The contribution of secondary processes is calculated using the reference data on the cross sections for the reactions of the splitting of \( ^{28}\text{Si} \) nuclei by protons and neutrons for various energies. The number of random coincidences is determined using the characteristic angular distribution measured in specially conducted experiments. Table 1 presents the results calculated for the background components.

**Table 1. Background components**

| Linear background, \( W_{b1} \) | 12748±600 |
| \( \gamma \)-transitions in other nuclei with photon energies in interval \( \mathbf{A} \), \( W_{b2} \) | 1241±250 |
| Random-coincidence background from the beam protons, \( W_{b3} \) | 825±125 |
| Background from the secondary processes, in the target, \( W_{b4} \) | 697±154 |

After the subtraction of the background, \( W_{(1)} = 5340\pm450 \) events of reaction (1) remains. Using this value, one can calculate the cross section for reaction (1) for proton scattering angles \( \theta < 15^\circ \) by the formula

\[
\sigma_{(1)} = \frac{4\pi AW_{(1)}}{N_A x \Xi \nu \varepsilon_\tau k m g N_0 \delta},
\]

where \( A \) is the atomic number of the \( ^{28}\text{Si} \) nucleus, \( N_A \) is the Avogadro number, and \( N_0 = 2.36 \times 10^{11} \) is the number of protons incident on the target. The remaining coefficients are presented in Table 2.
Table 2. Coefficients appearing in Eq. (2)

| Description                                                                 | Value        |
|------------------------------------------------------------------------------|--------------|
| Efficiency of the γ-detector at $E_{\gamma 0}=1368.6$ keV                    | $\Xi=0.000777$ |
| Efficiency of the program reconstruction of one-track events                 | $\nu=0.583$  |
| Coefficient corresponding to miscounts due to the spread of the times of the arrival of signals from the germanium detector | $\varepsilon_{\tau}=0.886$ |
| Correction for the absorption of γ-rays in the target                         | $k=0.614$    |
| Correction for the dead time of the germanium detector                        | $m=0.95$     |
| Correction for the cutoff of the distribution edges by the boundaries of interval | $g=0.979$   |
| Correction for the percentage of $^{28}$Si in the target                      | $\delta=0.922$ |

The value $\sigma_{(1)}=(10.1\pm0.9\pm1.5)$ mb is obtained for reaction (1) in the angular range $\theta < 15^\circ$.

The third feature of the processing procedure in this range is that the description of the experimental distribution of events $W_{(1)}$ in energy transfer $\omega$ (see histogram in Fig. 3) by the model curves corresponding to processes 1-4 is supplemented by the following process:

5) the knockout of four nucleons with a total charge number of 2 in the collision of the proton with a nuclear nucleon.

As processes 1 and 3, it is simulated with the inclusion of the multiple rescattering of the proton with the highest energy in the nucleus. The energy of separating four nucleons from the $^{28}$Si, nucleus, which is assumed to be equal to 0.040 GeV, it is spent by the proton in the first interaction event.

As a result of the approximation of reaction (1) by processes 1-5, the minimum value $\chi^2/n=98.9/83$ is obtained. Table 3 presents the numerical results of minimization. The first row presents the contributions of processes in terms of the effective number $W$ of events and the second row contains the cross sections for the corresponding processes. The optimum calculation function is shown by the solid line in Fig. 3 and its components
Table 3. Partial cross sections for processes 1-5

|   | 1          | 2          | 3          | 4          | 5          |
|---|------------|------------|------------|------------|------------|
| $W$ | 1259±214   | 763±162    | 1324±215   | 117±58     | 1652±247   |
| $\sigma$, mb | 2.4±0.3    | 1.4±0.2    | 2.5±0.3    | 0.22±0.11  | 3.1±0.5    |

5. DISCUSSION

In this experiment, the cross section for reaction (1) and partial cross sections for 1) proton scattering on the $\alpha$ cluster with the emission of the cluster from the nucleus, 2) the formation of the $\Delta$Si isobaric nucleus, 3) the formation of the $\Delta_{1232}$ isobar, 4) the production of a pion that is at rest in the system associated with the nucleus, and 5) the knockout of four nucleons with a total charge number of 2 as a result of the collision of the beam proton with a nuclear nucleon are measured using the hadron-gamma coincidence method. The first and last processes occur primarily at low energy transfers $\omega < 0.12$ GeV, which are insufficient for the production of mesons. The direct knockout of nuclear $\alpha$ clusters from the nucleus by protons is well known both theoretically and experimentally [16, 17]. Although $\alpha$ particles are not detected in the MAG setup, their emission is reliably identified, because the residual nucleus $^{24}$Mg is determined (by $E_{\gamma_0}$) and energy transfer, whose average value is equal to the $\alpha$ separation energy, is measured. In contrast to the previous experiments, where the emitted cluster is detected at certain angle $\theta_\alpha$, the method used in this work allows measurement of the cross section for any $\theta_\alpha$. The kinetic characteristics for process 5 of the splitting of the $^{28}$Si nucleus with the emission of four nucleons have not yet measured. Measurement of its probability at the MAG setup became possible due to an experiment inclusive in hadrons, where the distribution in the energy transfer $\omega$ was analyzed.

The formations of the isobar and isobaric nuclei at energy $T_0 \approx 1$ GeV are the most probable processes in the energy transfer range, where inelastic interactions with the production of pions are energetically possible. This conclusion is based on the experimental data for the interaction of protons with free nucleons.

The observation of events for $\omega \approx 0.145$ GeV is likely attributed to the formation of deeply bound $\pi^-$-mesonic atoms $^{28}$P. Such states were predicted theoretically in [18] and were observed experimentally in heavy nuclei Pb [19], Xe [20], and Sn [21]. Such phenomena have not yet observed in intermediate-mass nuclei. Taking into account the threshold of
the p + $^{28}\text{Si} \rightarrow \text{p} + ^{28}\text{P} + \pi^-$ reaction, which is equal to about 0.154 GeV, the binding energy of the $\pi^-$ meson in the phosphorus atom seems to be too high (0.009 ± 0.003 GeV). Another possible explanation is the formation of a deeply bound state of the $\pi^0$ meson with the $^{24}\text{Mg}$ nucleus, which appears after the knockout of the $\alpha$ particle from the $^{28}\text{Si}$ nucleus by the incident proton. In this case, the binding energy would be equal to 0.001–0.004 GeV.

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References

[1] L. Stodolsky, Phys.Rev. 144, 1145 (1966).

[2] I. V. Kirpichnikov, V. A. Kuznetsov, I. I. Levintov, A. S. Starostin, Preprint No. 96-79, ITEP (Inst. of Theoretical and Experimental Physics, Moscow, 1979).

[3] I. V. Kirpichnikov, V. A. Kuznetsov, I. I. Levintov, A. S. Starostin, Preprint No. 119-81, ITEP (Inst. of Theoretical and Experimental Physics, Moscow, 1981).

[4] V. S. Demidov, in Proceedings of XXXV Winter Scholl of Petersburg Institute of Nuclear Physics (St. Petersburg, 2001), p. 30.

[5] V. L. Korotkikh, in Diffractional Interaction of Hadrons with Nuclei, Ed. by A. I. Akhiezer et al. (Naukova Dumka, Kiev, 1987), p. 210 [in Russian].

[6] Yu. A. Simonov, in Diffractional Interaction of Hadrons with Nuclei, Ed. by A. I. Akhiezer et al. (Naukova Dumka, Kiev, 1987), p. 284 [in Russian].

[7] E. T. Bogdanov, A. A. Vasenko, N. D. Galanina, et al., Prib. Tekh. Eksp., 45, 13 (2002) [Instrum. Exp. Tech. 45, 9 (2002)].
[8] Yu. A. Berezhnoi, V. P. Mikhalyuk, and V. V. Pilipenko, Yad. Fiz. 68, 978 (2005) [Phys. At. Nucl. 68, 940 (2005)].

[9] V. S. Barashenkov and V. D. Toneev, Interactions of High-Energy Particles and Nuclei with Nuclei (Atomizdat, Moscow, 1972) [in Russian].

[10] A. A. Vasenko, N. D. Galanina, K. E. Gusev, et al., Preprint No. 12-03, ITEP (Inst. of Theoretical and Experimental Physics, Moscow, 2003).

[11] A. A. Vasenko, N. D. Galanina, K. E. Gusev, et al., Yad. Fiz. 67, 1529 (2004) [Phys. At. Nucl. 67, 1505 (2004)].

[12] E. A. Strokovski and F. A. Gareev, Fiz. Elem. Chastits At. Yadra 24, 603 (1993) [Phys. Part. Nucl. 24, 255 (1993)].

[13] Satoshi Chiba et al., Phys. Rev. C 54, 285 (1996).

[14] Koji Niita et al., Phys. Rev. C 52, 2620 (1995).

[15] B. J. VerWest, R. A. Arndt. Phys. Rev. C 25, 1979 (1982).

[16] V. A. Karmanov, Yad. Fiz. 35, 848 (1982) [Sov. J. Nucl. Phys. 35, 492 (1982)].

[17] O. F. Nemets, V. G. Neudachin, A. T. Rudchik et al., Nucleon Clusters in Nuclei and Multinucleon Transfer Reactions (Naukova Dumka, Kiev, 1988) [in Russian].

[18] H. Toki and T. Yamazaki, Phys. Lett. B 213, 129 (1988).

[19] T. Yamazaki, H. Gilg, A. Gillitzer et al., Z.Phys. A 355, 219 (1996).

[20] M. Andersson, C. Bargholtz, V. Chernyshev et al., Phys. Rev. C 66, 022203 (2002).

[21] K. Suzuki, M. Fujita, H. Geissel et al., Phys. Rev. Lett. 92, 072302 (2004).
Figure 1: Distribution of events with proton emission angle $3^\circ < \theta < 6.5^\circ$ in the $\gamma$-ray energy. Double shaded area A is taken for the selection of the $^{24}$Mg formation reaction. Shaded areas B are used to determine the background distribution shape. The arrow indicates the tabulated energy of the $\gamma$ transition of the $^{24}$Mg nucleus from the first excited state to the ground state.
Figure 2: Distribution of events with angles $3^\circ < \theta < 6.5^\circ$ in the energy transfer $\omega$. The smooth lines are the fits by processes 1-4 (see the main text).
Figure 3: Distribution of weighted events with angles $\theta < 15^\circ$ in the energy transfer $\omega$. The smooth lines are the fits by processes 1-5 (see the main text).