Properties of the 7.10-MeV Level of Na^{23}†

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Some properties of the 7.1-MeV level of Na^{23} have been studied using the resonance fluorescence technique with the $F^{19}(p,\alpha)O^{16*}$ reaction serving as the source of Doppler-broadened radiation. By comparison with the (7.115±0.003)-MeV level of O^{16} the energy was determined to be 7.10±0.02) MeV. The angular distribution of the scattered radiation is $W(\theta)=1+(0.47\pm0.09)P_2+(0.32\pm0.03)P_4$, which is consistent only with $\frac{5}{2}$ for the spin. The values allowed for the quadrupole-dipole amplitude ratio, δ, are $-1.8>\delta>-2.2$ and $2.5<\delta<3.0$. Using this spin value and the results of the self-absorption measurement, the partial width for the ground-state transition becomes equal to $\Gamma_0=(0.62\pm0.07)$ eV. With the observed branching of 63% to the ground state, the total width becomes $\Gamma=(0.98\pm0.12)$ eV. This large value of the width combined with the large value of δ defines the parity of the state as positive.

I. INTRODUCTION

TWO years ago a study[1] was conducted at this laboratory to determine which of the light elements have levels that could be resonantly excited by the Doppler-broadened gamma rays from the $F^{19}(p,\alpha)O^{16*}$ reaction. At a proton energy of 2.5 MeV, the only levels of O^{16} which are excited to any degree in this reaction are those at 7.12, 6.91, 6.14, and 6.06 MeV. Since the spins of the 6.06-MeV state and ground state are zero, this 6.06-MeV level decays by pair emission. The lifetime of the 6.14-MeV state is about 10^{-11} sec, and, therefore, nearly all of the recoiling O^{16*} nuclei would have come to rest before emission of gamma radiation. Consequently, the 6.14-MeV radiation will not be Doppler broadened. The only gamma rays, then, that can be responsible for any resonance fluorescence effect are those with energies of 6.91 and 7.12 MeV.

From other studies it is known that a level exists in Na^{23} at about 7.2 MeV. Grüebler and Rossel,[2] using the $Ne^{22}(d,n)Na^{23}$ reaction, determined the energy to be 7.21±0.05 MeV and the spin and parity to be $\frac{3}{2}+$ or $\frac{5}{2}+$. Singh *et al.*[3] and Braben *et al.*[4] both report to have excited a state of about this energy using the $Ne^{22}(p,\gamma)Na^{23}$ reaction. However, they do not agree as to the intensity of excitation nor to the manner of decay, and no spin assignments are given.

II. EXPERIMENTAL PROCEDURE

Targets of 99.5% pure BaF_2 about 100 and 200 keV thick for 2.5-MeV protons were prepared by vacuum evaporation onto 10-mil-thick tantalum backings. BaF_2 was selected over several other possible target materials as giving the largest gamma-ray yield from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction relative to the number of neutrons. The tantalum backings were held in a water-cooled assembly described previously.[5] These targets showed no deterioration under beams up to 8-μA spread over an area about $\frac{3}{16}$ in. in diameter.

For the previous studies on the 6.91- and 7.12-MeV levels of O^{16},[6] thick CaF_2 targets were used. In order to ascertain how much improvement the reduced neutron intensity might give, a scattering experiment using a water scatterer was conducted and compared with the previous studies. This comparison indicated that the signal-to-noise ratio was improved by a factor of about 2.5. The principal source of background remaining was attributed to resonance scattering from the room in general; i.e., from the oxygen of the air and of the floor, ceiling and wall materials plus possible resonance scattering from other elements in these surfaces.

The gamma rays from the target were monitored by a 5-in.-diam by 4-in.-long NaI crystal placed about 8 ft from the target. The axis of the crystal was in line with the target and a lead shield with a $\frac{3}{4}$-in.-diam hole was used to collimate the gamma rays. This increased the relative intensity of the full energy peak, and only this peak was used in the monitoring. No effort, however, was made to differentiate between the 6.91- and the 7.12-MeV gamma rays.

Figure 1 shows the geometries used in the self-absorption and the angular distribution measurements. The scatterers measured 10 in. i.d., 15 in. o.d., and $\frac{3}{4}$ in. in width, and 14 in. i.d., $16\frac{1}{4}$ in. o.d. and 3 in. in width, respectively. The geometry used in the initial scattering studies was essentially the same as that used in the self-absorption experiment and the scatterer used had an i.d. of 14 in., an o.d. of $15\frac{1}{2}$ in., and a width of 3 in. These scatterers were either the same or at least made in the same manner as described previously.[7] In all these measurements aluminum was used as the

† Assisted by the U. S. Office of Naval Research.
[1] P. F. Hinrichsen and C. P. Swann, Bull. Am. Phys. Soc. 8, 357 (1963).
[2] W. Grüebler and J. Rossel, Helv. Phys. Acta 34, 479A (1961).
[3] J. J. Singh, V. W. Davis, and R. W. Krone, Phys. Rev. 115, 170 (1959).
[4] D. W. Braben, L. L. Green, and J. C. Willmott, Nucl. Phys. 32, 584 (1962).
[5] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. 123, 1386 (1961).
[6] C. P. Swann and F. R. Metzger, Phys. Rev. 108, 982 (1957).
[7] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Nucl Phys. 13, 95 (1959).

comparative scatterer since it was observed in earlier studies that aluminum gave no resonance fluorescence effect.

The scattered radiation was detected in a 3-in.-diam by 3-in.-long NaI crystal the output of which was analyzed by an RIDL 34–12 analyzer. The intensity of the incident radiation was measured by placing this crystal directly in the gamma-ray beam at a distance of 8 ft from the target and at the same angle relative to the proton beam as seen by the scatterer. The monitor served as the common factor for determining the relative intensity of the scattered radiation.

III. LEVEL ENERGY

The purpose of the initial scattering experiment was to establish whether the 6.91-MeV radiation, the 7.12-MeV radiation, or both radiations were responsible for the resonance effect. For a proton energy of about 2.5 MeV, the 6.91- and 7.12-MeV gamma rays are broadened in energy by about 115 keV. Since this represents quite a broad energy region it is possible that more than one level are involved. The scattered radiation, however, will not have any Doppler broadening and the question of resolving different-energy gamma rays will depend on the resolution of the detector. In the case of the O^{16} levels the scattered 6.91- and 7.12-MeV radiations are partially resolved. This, then gives a limit on energies which are resolvable. Because of the Doppler spread, however, the 6.91- and 7.12-MeV gamma rays come to within 105 keV of each other and gamma rays this close in energy could not be resolved. To some extent this may be settled by selecting different resonances in the $F^{19}(p,\alpha\gamma)O^{16}$ reaction which favor one or the other of the two gamma rays.

From the excitation curves for the associated alpha particles as reported by Swann and Metzger,[6] and from the more recent work of Trail and Raboy[8] on the distribution of the gamma rays, it may be seen that the intensity of the 7.12-MeV radiation relative to the 6.91-MeV radiation changes considerably between a proton energy of 2.0 and 2.4 MeV. In our case the monitor pulses were selected so that the 6.91- and 7.12-MeV gamma rays were detected with approximately equal efficiencies. For a given number of monitor counts, then, the ratio of the 7.12-MeV radiation to the total radiation at the 2.0-MeV resonance should be about twice that at the 2.4-MeV resonance, and the same ratio for the 6.91-MeV radiation at the 2.0-MeV resonance should be about a third of that at the 2.4-MeV resonance.

The experiment was carried out using the 100-keV-thick target and the bombarding energies were 2.1 and 2.5 MeV. The ratio of the resonance effect obtained at 2.1 MeV to that at 2.5 MeV was 2.05 ± 0.10 which is

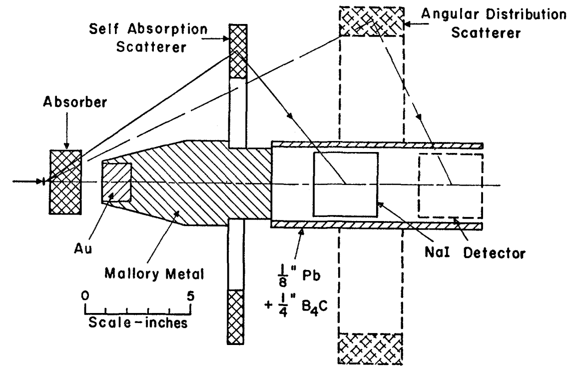

FIG. 1. Scattering geometries. The solid lines indicate the absorber and scatterer and crystal position used in the self-absorption measurement. The dashed lines indicate the scatterer and crystal position used in the angular-distribution studies. The crystal position shown is for 90° scattering. Other angles were obtained by moving the crystal towards the attenuator.

in good agreement with that expected assuming the effect was caused by the 7.12-MeV gamma rays. This does not preclude, of course, more than one level being excited by the 7.12-MeV radiation, but it does limit the energy to the region between 7.080 and 7.195 MeV.

The energy of this state was further defined by comparing the spectrum obtained for oxygen using the water scatterer with that for sodium. As pointed out above the scattered radiation will not be Doppler broadened and except for a small energy loss going to the recoiling nuclei on emission of the gamma ray, the gamma-ray energy should be the level energy. For Na^{23} and O^{16} the recoil energy loss for a 7.1-MeV gamma ray is 1.15 and 1.65 keV, respectively. From the comparison of the scattering from Na and H_2O it was found that the full energy peak for the Na^{23} gamma ray was 0.5 ± 0.3 of a channel lower than that for O^{16}. With the energy calibration of 80 keV per channel, this becomes 40 ± 24 keV. However, the Doppler spread only allows for a decrease of 35 keV. Therefore, one may say that the energy for this level in Na^{23} must be less than the energy of the O^{16} level but no more than 35 keV less. Taking the O^{16} level energy as 7.115 ± 0.003 MeV[9] the Na^{23} level energy becomes 7.10 ± 0.02 MeV. It might be noted that these measurements were made for a gamma-ray angle relative to the proton beam of about 30°.

IV. BRANCHING RATIOS

Below the 7.1-MeV level in Na^{23} there are 13 reported levels in addition to the ground state.[10] Figure 2 presents the decay scheme for these levels as now known with the probable spins and parities. In considering the decay of the 7.1-MeV state is may be seen from this scheme that a minimum gamma-ray energy of about

[8] C. C. Trail and S. Raboy, Argonne National Laboratory (private communication).

[9] C. P. Browne and I. Michael, Phys. Rev. **134**, B133 (1964).

[10] *Nuclear Data Sheets* (National Research Council–National Academy of Science, Washington, D. C., 1959).

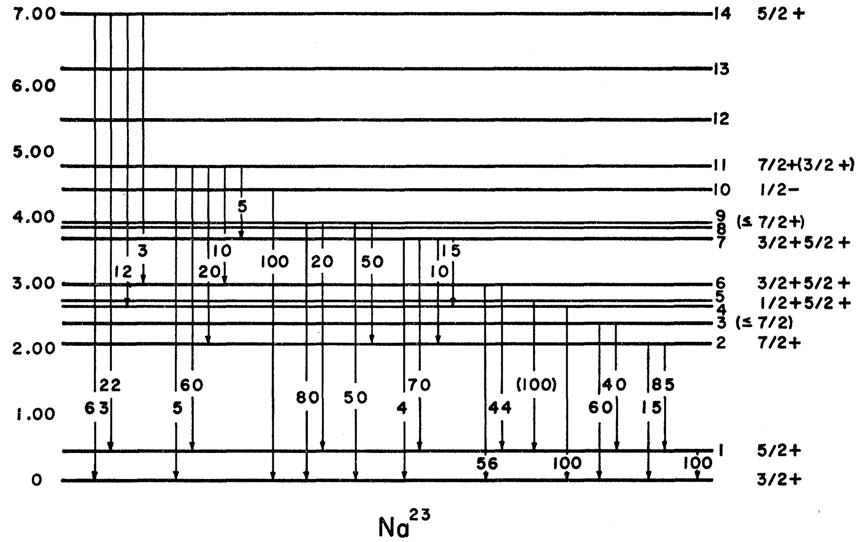

FIG. 2. Energy-level diagram of Na^{23}. The cascades shown are those given by Braben *et al.*[4] with the exception of the 7.09-MeV state, which is the result of the present study.

3.25 MeV would result no matter how this 7.1-MeV state decays. Figure 3 gives the pulse-height distribution obtained for the 7.1-MeV radiation resonantly scattered from sodium. The analysis of this spectrum shows the presence of several gamma rays along with the predominant ground-state transition. The energies of these gamma rays are 6.66, 4.48, 4.10, and 2.60 MeV. The first is assumed to be the result of branching to the 440-keV first-excited state. The second is either from branching to the 4.43-MeV state, the 2.64-MeV state or to both. The third could result from either the 4.78- or the 2.98-MeV state or both. Finally, the 2.60-MeV peak may be either the 2.64-MeV gamma ray related to the 4.43-MeV gamma ray or could be a composite of this 2.64-MeV radiation and the 2.54-MeV radiation resulting from the decay of the 2.98-MeV state. In this regard there is some evidence for the presence of a 2.98-MeV gamma ray. The one level which is definitely absent in this spectrum is that at 2.08 MeV for this would require a 5.02-MeV gamma ray. Assuming then that only the 440-keV state, the 2.64-MeV state, and the 2.98-MeV state are involved, the branching ratios become $(63\pm3)\%$ to the ground state, $(22\pm3)\%$ to the 440-keV state, $(12\pm3)\%$ to the 2.64-MeV state and $(3\pm2)\%$ to the 2.98-MeV state.

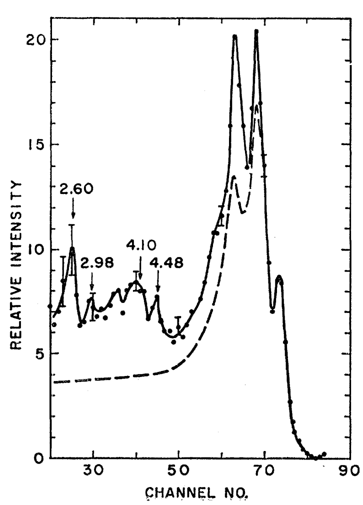

FIG. 3. Pulse-height distribution. The solid curve gives the difference between the Na and Al scatterers. The dashed curve represents our best estimate of a 7.1-MeV line shape based on the results of the O^{16} resonance scattering.

V. TRANSITION PROBABILITIES

For a thin scatterer the number of scattered quanta is proportional to $N(E_R)g\Gamma_0^2/\Gamma$.[11] $N(E_R)$ is the number of gamma rays per unit energy interval at the resonance energy, g is the statistical weighting factor, and Γ_0 and Γ are the partial width for the ground-state transition and the total width of the level, respectively. For an absorption measurement, the ratio of the scattering effect with and without an absorber is proportional to $g\Gamma_0/\Delta$,[11] where Δ is the thermal Doppler width of the level. This relation is satisfactory as long as Δ is large compared to Γ and the percent absorption is not too large. For this case Δ is 11 eV, whereas Γ is about one eV and the absorption for the thickest absorber used was only about 25%.

Figure 1 shows the geometry used for the self-absorption measurements. Absorbers of sodium metal 1 and $1\frac{1}{2}$ in. thick were used and aluminum was used for the comparison absorbers. The measurements were made using the 200-keV-thick target and a bombarding energy of about 2.2 MeV. The absorptions obtained were $(17.8\pm2.5)\%$ and $(22.9\pm3.5)\%$ for the 1- and $1\frac{1}{2}$-in. absorbers, respectively. The weighted mean for $g\Gamma_0$ then becomes (0.92 ± 0.10) eV.

Not too much weight has been placed on the evaluation of Γ_0 from the scattering experiment, principally

[11] F. R. Metzger, Progr. Nucl. Phys. **7**, 54 (1959).

because of the difficulty in determining $N(E_R)$. However, to be sure that the results are reasonable and to assure ourselves that only one level is involved, such a calculation is worthwhile. As pointed out earlier, if more than one level is excited but not observed because of the finite resolution of the detector, then all that is observed is an increase in the resonance effect; i.e., the resonance effect will be the sum of the effects for the individual levels. Since one measures a ratio in the self-absorption experiment, however, this result will give an average level width.

Determining $N(E_R)$ involves, first, the relative intensities of the 6.91- and 7.12-MeV radiations in the incident beam, second, the angular distribution of the 7.12-MeV gamma rays relative to the proton beam and, third, the α-γ correlation. Since no measurements have been made on the α-γ correlations, isotropy has been assumed, and this, then, is the principal uncertainty in this evaluation. The relative intensities of the 6.91- and 7.12-MeV radiations may be obtained from the data of Trail and Raboy.[8] For the mean angle of about 30° relative to the proton beam used in the scattering experiment, this gives about 84% of the radiation as 7.12 MeV. The second was taken care of in that the intensity of the incident radiation was measured at the same angle relative to the proton beam. Applying then the ratios of 0.84 for the percentage of 7.12-MeV radiation and 0.63 for the ground-state branching ratio, $g\Gamma_0$ was calculated to be (1.10 ± 0.06) eV, where the error represents only the statistical uncertainty in the data. Considering the assumptions made, this is in reasonable agreement with the value obtained from the self-absorption experiment.

VI. SPIN AND PARITY

The geometry used in these studies is also shown in Fig. 1. Moving the NaI crystal from directly in back of the attenuator to a position 7 in. back changes the scattering angle from about 140° to about 90°. A third angle of about 115° is obtained with the crystal halfway back. Great care had to be taken in all of these measurements to be sure the energy calibration was stable. This was necessary since only part of the full energy peak could be used in the analysis to be sure that none of the 6.66-MeV radiation resulting from the branch to the 440-keV state was included. A fit to the data obtained gives $W(\theta)=1+(0.47\pm0.09)P_2+(0.32\pm0.03)P_4$. The requirement of the P_4 then immediately eliminates $\frac{1}{2}$ and $\frac{3}{2}$ as possible spin assignments for this state. One may consider $\frac{7}{2}$, but a fit to the data would require a fair amount of mixing. This, however, would not give reasonable agreement with the lifetime of the state, i.e., the octupole component required would have to be enhanced by the order of 10^4. This leaves only $\frac{5}{2}$ as the possible spin. Figure 4 gives a plot of A_2 versus A_4 for values of δ, the quadrupole to dipole amplitude ratio, from 0 to $\pm\infty$, and the shaded region shows the experimental value with errors. The intercepts give two regions for δ, and these are $-1.8>\delta>-2.2$ and $2.5<\delta<3.0$. The large value of δ along with the large width requires that the mixture be $E2$–$M1$ rather than $M2$–$E1$, and this further defines the parity of the state as positive.

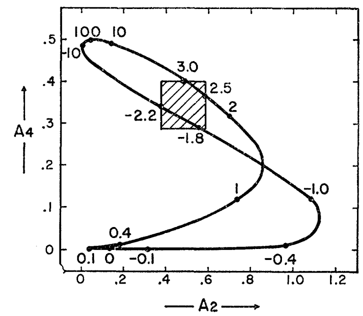

FIG. 4. A_2 versus A_4 for values of δ from 0 to $\pm\infty$. The shaded region gives the results of this experiment.

One may also look at the angular distribution of the 6.66-MeV radiation by stripping out the 7.1-MeV pulse-height distribution. This was done using the spectrum obtained with the water scatterer as in Sec. II, and the angular distribution so obtained was consistent with that expected for a $\frac{5}{2}$-spin assignment for both the 7.1-MeV and 440-keV states. However, the fit was not inconsistent with other possible spin assignments. The angular distributions for the remaining radiations could not be determined because of the poor statistics.

VII. CONCLUSION

From the above we see that the energy of this level in Na^{23} has been measured to be (7.10 ± 0.02) MeV and the spin and parity to be $\frac{5}{2}+$. Although the energy is somewhat lower than that given by others,[2] the spin and parity are in agreement.

The spin of $\frac{5}{2}$ for this state determines the weighting factor g for the ground-state transition as $\frac{3}{2}$, and, therefore, the partial width for the decay to the ground state becomes (0.62 ± 0.07) eV. The mixing ratio δ^2 has been measured to be 6 ± 3 which defines the $E2$ and $M1$ components of the width to be about 0.5 and 0.1 eV, respectively. In terms of the Weisskopf unit, $\Gamma_{\gamma W}$, $|M|^2=\Gamma_\gamma/\Gamma_{\gamma W}$ becomes 0.014 for the $M1$ part. On the basis of the full independent-particle model[12] in intermediate coupling, one expects that $|M|^2$ will have a value of about 0.15 to a factor of about 20 each way, and the above value is certainly within this region. The $B(E2)/B(E2)_{SP}$ calculated from Eq. (IV.3) and (V.1) of the review article of Alder *et al.*,[13] but correcting for the statistical weight differences, becomes 8.3 which indicates an appreciable enhancement.

The observed branching ratios were 63% to the

[12] D. H. Wilkinson, *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, Chap. 5.

[13] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

ground state, 22% to the 440-keV first-excited state, 12% to the 2.64-MeV state, and 3% to the 2.98-MeV state. The possibility that the 4.78- and 4.43-MeV states are involved cannot be definitely ruled out but the energy differences would favor the scheme given.

In general, the agreement between this work and that of Singh *et al.*[3] and Braben *et al.*[4] and, in fact, between these two groups themselves is rather poor, but this can easily be accounted for by the difficulties associated with the analysis of data from (p,γ) reactions. In particular, for this case the difference in energy between the resonance state at 9.75- and the 2.64-MeV state is just the energy of the 7.10-MeV state. Since the decay of the 9.75-MeV state to the 2.64-MeV state is probably preferred,[4] the observation of the decay to the 7.10-MeV level and its subsequent decay would be very difficult. Of course, it is possible that different states are involved in the two cases, but this seems quite unlikely.

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$Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$ Reactions from 0.4 to 28 GeV*

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Cross sections for the $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{111}$ reactions have been measured in the energy region from 0.4 to 28 GeV. The (p,pn) cross section decreases to a value of ≈ 50 mb in the GeV region. The $(p,2p)$ cross section shows a significant rise between 0.4 and 1 GeV and then a gradual decrease. Correlations between these data and the total cross sections for $p-p$ and $p-n$ interactions are discussed.

INTRODUCTION

THEORETICAL treatments of nuclear reactions between high-energy particles and complex nuclei have generally made use of the "impulse approximation"[1] in which the bombarding particle interacts with only one of the target nucleons at a time. Monte Carlo calculations based on this model[2–4] give reasonably good predictions for many of the features observed in high-energy nuclear reactions. For very simple reactions, those involving a single collision between the bombarding particle and a target nucleon, it is expected that the elementary-particle cross sections will play a more obvious role in determining the shapes of excitation functions than they would for more complex reactions. That this is the case has been clearly shown for the $C^{12}(\pi^-,\pi^-n)C^{11}$ reaction.[5,6] Here, observed structure including a pronounced peak at 190 MeV in the (π^-,π^-n) cross section corresponds to the general features of the free-particle π^-n total cross section.

(Nucleon, 2 nucleon) reactions are a class of simple high-energy reactions that have been studied extensively; the experimental data and interpretation are the subject of a forthcoming review[7] and compilation.[8] Unfortunately, no structural features as pronounced as the pion-nucleon resonances occur in the nucleon-nucleon cross sections. The pp and pn total cross sections as summarized by Barashenkov and Maltsev[9] are shown in Fig. 1. The most pronounced feature is the factor of two rise in σ_{pp} between 0.3 and 1 GeV due to inelastic processes involving meson production. Reeder[10] has measured cross sections for the $Fe^{57}(p,2p)Mn^{56}$ and $Zn^{68}(p,2p)Cu^{67}$ reactions to see whether a corresponding feature could be observed. Although a rise was observed in both cross sections between 0.4 and 0.72 GeV, its significance is marginal because of the magnitude of the experimental errors.

The present experiment, a study of (p,pn) and $(p,2p)$ reactions on Ce^{142}, was undertaken to further examine to what extent the cross sections, particularly the $(p,2p)$ cross section, could be correlated with the elementary-particle cross sections. This target system has been the subject of previous investigations[11–15] as

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