# Possible production of highly excited $\pi^-$-Ne atoms in collisions of 70-GeV protons with Mg nuclei

M. P. Gur'ev, A. S. Denisov, A. V. Zhelamkov, Yu. M. Ivanov, L. P. Lapina, P. M. Levchenko, A. A. Petrunin, Yu. P. Platonov, A. G. Sergeev, A. I. Smirnov, V. M. Suvorov, and O. L. Fedin

*Institute of Nuclear Physics, Russian Academy of Sciences, 188350 Gatchina, Leningrad Region, Russia*

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The possible production of $\pi^-$ atoms in the decay of hadron resonances is discussed. This mechanism should lead to a filling of states with $l\neq0$. It might be observed through the detection of characteristic x radiation. An attempt has been made to measure the intensity of the $3d$–$2p$ line of the $\pi^-$-Ne atom emitted by a Mg target in a 70-GeV proton beam. A crystal-diffraction spectrometer for measuring the x-ray emission of hadronic atoms was used. A peak at a level $\approx 2.4$ errors was observed; the corresponding cross section is $\approx 0.5$ mb. This value is interpreted as an experimental upper limit on the magnitude of the effect.

The production of $\pi^-$ mesons at nuclei in bound states has been discussed for several reactions—photoproduction[1] $(\gamma,\pi^-)$, electroproduction[2] $(e,e'\pi^-)$, and "pion transfer"[3] $(n,p\pi^-)$—but has yet to be seen experimentally. It has been predicted that $\pi^-$ mesons should be produced preferentially in $s$ states (near the nucleus, atomic wave functions with orbital angular momenta $l\neq0$ are small) and that it might be possible to study these states by detecting an emitted particle.

It has now been confirmed that in the inelastic interaction of a high-energy proton with a nucleus a significant fraction of the $\pi$ mesons form in the decay of hadron resonances. One result, in particular, is an enrichment of the soft part of the momentum spectrum of the secondary particles.[4] It is easy to see that the decay of a resonance might—depending on the width and momentum of the resonance—occur at a significant distance away from the residual nucleus (for example, the decay length of an $\eta$ meson might be comparable to an atomic radius). The existence of a decay gap makes possible a production of $\pi^-$ resonances with large orbital angular momenta with respect to the residual nucleus even when the $\pi^-$ meson has a small momentum. It also leads to a natural mechanism for the filling of $\pi^-$-atom states with an orbital angular momentum $l\neq0$. The decay of such states should be accompanied by the emission of characteristic x radiation, which might be utilized as a signal.

In the absence of detailed data on the cross sections for the production of hadron resonances, it is difficult to calculate a probability for this process. A simple calculation as in Ref. 5 yields values on the order of 0.01 mb for light nuclei. This can be no more than a very crude estimate, since it is based on an extrapolation to small momenta of the experimental cross sections for $\pi^-$ production and on the assumption

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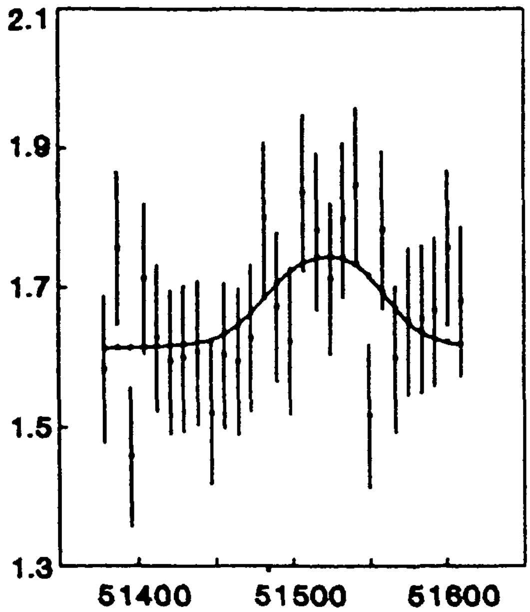


FIG. 1. Measured region of the electromagnetic spectrum of a Mg target near the energy of the $3d$–$2p$ transition in $\pi^-$-Ne. The radiation energy, in eV, is plotted along the abscissa. The number of counts per $10^{12}$ protons incident on the target is plotted along the ordinate. The smooth curve is a fit for the case of four (stable) isotopes of Ne with equal weights. .

that all the $\pi^-$ mesons with kinetic energies smaller than the binding energy (assumed to be 0.1 MeV) are captured by the residual nucleus.

These circumstances stimulated an attempt to use a Cauchois crystal-diffraction spectrometer to observe emission on the $3d$–$2p$ transition of a $\pi^-$-Ne atom in the electromagnetic spectrum of a thick (17-cm) magnesium target in a beam of 70-GeV protons at an accelerator of the Institute of High Energy Physics. We selected neon because it is definitely not present in a target of pure magnesium. A transition energy of 51 519 eV was calculated through a numerical solution of the Klein–Gordon equation. This is an average over the various Ne isotopes. The luminosity of the spectrometer and the resolution of this energy are $1.3\times10^{-9}$ and 34 eV, respectively (the aperture of the working crystal was $8\times8$ cm, its thickness was 1.1 mm, the 130 planes were used for reflection, the radius of curvature was 5 m, and the measure of elastic quasimosaic structure was 14″). The experimental apparatus, the measurement procedure, the data analysis procedure, and the calculations of the transition energies are described in more detail in Refs. 6 and 7.

Limitations on the time allotted for the measurements forced us to acquire data as in Ref. 7, in only one of the two possible positions of the spectrometer corresponding to symmetric reflection of the x radiation with respect to the quartz planes. The spectrometer was calibrated with the help of $\gamma$-ray lines of $^{182}$Ta. Figure 1 shows the result of a 5-h scan of the region of the spectrum near the calculated transition energy. The approximating curve here was drawn through the experimental points with $\chi^2/\nu=0.72$. It is the sum of a flat background and a peak having the instrumental lineshape (the isotopic composition of the Ne was taken into account here). The total intensity of the isotopic components is $0.36\pm0.15$ of a count per $10^{12}$ protons. The position of the peak corresponds to an energy of 51 521 ± 14 eV; its width does not exceed ≈100 eV. The statistical significance of the peak is 98.4%. A variation of the isotopic composition of the Ne (with up to six isotopes differing in weight) during the fitting of the points had no effect on $\chi^2$.

We studied possible explanations for the measured peak. We verified that there were no atomic lines, mesic-atomic lines (other than that of the $3d$–$2p$ transition of $\pi^-$-Ne), or $\gamma$-ray lines in the measurement interval. Among the latter lines, according to Ref. 8, the only possible candidates with similar energies (within a few keV—this is roughly the error within which the energies of nuclear levels can be determined from the level schemes) are $\gamma$ transitions between highly excited states in $^{13}$B and $^{20}$F, but the probabilities for these transitions are negligible.

The good agreement between the experimental energy of the peak and that calculated for the $3d$–$2p$ transition in $\pi^-$-Ne is an argument in favor of this interpretation. Taking the inelastic cross section for the $p+$Mg interaction to be 373 mb, correcting for the target thickness, and knowing the luminosity of the spectrometer, we find from the line intensity that the cross section for the production of the $\pi^-$-Ne atom should be ≈0.5 mb in this case. From the shape of the line we can conclude that the Doppler broadening (the residual nuclei have recoil momentum) could not exceed ≈100 eV, so the kinetic energy of the $\pi^-$-Ne atom at the instant the $3d$–$2p$ photon is emitted would have to be less than ≈10 keV. Since the initial kinetic energy of the Ne nucleus must be on the order of 1 MeV (Ref. 9, for example), we conclude that the $\pi^-$-Ne atom should live long enough to be slowed down. This situation would be possible only if there were an initial filling of states with large quantum numbers. This conclusion in turn suggests that the effective source of $\pi^-$ mesons should overlap significantly with corresponding atomic wave functions, so it should be larger than the nuclear length scales. This conclusion agrees with the mechanism for the production of pionic atoms in the decay of hadron resonances which we discussed at a qualitative level at the beginning of this article. The possible objection to the interpretation of this peak as a $\pi^-$-Ne line on this basis of the small theoretical cross section can be overruled in view of the crude nature of the calculation and the lack of information on the cross sections for $\pi^-$ production in the kinematic region $p_{\pi^-} < 5$ MeV/c, which is the region of importance to this experiment.

Finally, we cannot rule out the possible explanation of the measured peak as a statistical fluctuation. Its probability is ≈1.6%. It is for this reason that we believe that the value of 0.5 mb which we found should be regarded as an experimental upper limit on the cross section for the production of a highly excited $\pi^-$-Ne atom as the result of the collision of a 70-GeV proton with a Mg nucleus.


[1] C. Tzara, Nucl. Phys. **B18**, 246 (1970).
[2] V. F. Dmitriev, JETP Lett. **14**, 81 (1971); J. Nieves and E. Oset, Phys. Rev. **C43**, 1937 (1991).
[3] H. Toki and T. Yamazaki, Phys. Lett. **B213**, 129 (1988).
[4] V. S. Murzin and L. I. Sarycheva, *Interactions of High Energy Hadrons*, Nauka, Moscow, 1983.
[5] Che Ming Ko, *Particles and Nuclei, Tenth International Conference, Book of Abstracts* (Heidelberg, 1984), p. J4.
[6] A. S. Denisov, A. V. Zhelamkov, Yu. M. Ivanov *et al.*, JETP Lett. **54**, 558 (1991).
[7] M. P. Gur'ev, A. S. Denisov, A. V. Zhelamkov *et al.*, JETP Lett. **57**, 389 (1993).

[8]R. J. De Meijer *et al.*, At. Data Nucl. Data Tables **13**, 1 (1974); R. J. De Meijer *et al.*, At. Data Nucl. Data Tables **15**, 391 (1975).
[9]L. Winsberg *et al.*, Phys. Rev. C**22**, 2108 (1980).

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